A Novel Numerical Model of Surface Water Flow and Freezing for Glaze Ice Accretion with Runback

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Abstract—**In this paper, we examine numerical simulations of glaze and runback ice accretion made using our original icing modelling approach. Whereas traditional icing models consider continuous fluxes of impinging droplets and water flow along the ice surface, our morphogenetic approach considers the three-dimensional stochastic behaviour of an ensemble of fluid elements, which impinge individually, move along the icing surface following random walk rules, and freeze on the surface. For specified atmospheric conditions, the model can emulate the flow of water in rivulets and their gradual freezing, leading to the formation of ice ridges. In addition, as a result of the model's intrinsic randomness, it is able to provide measures of the inherent stochastic variability of the rough ice ridges forming along rivulets. If the water flux is sufficiently high, the entire surface can be covered with an ice layer of variable roughness. To illustrate the innovative capabilities of our three-dimensional model, the simple case of ice formation on a horizontal cylinder as a result of freezing rain is examined.**

I. INTRODUCTION

The behaviour of unfrozen water on a surface prior to freezing has a direct impact on the resulting ice shape due to redistribution of the impinging water mass. Runback ice accretion typically occurs with a flux of water along the surface that exceeds the locally impinging water flux. It is of particular interest for in-flight icing applications. Runback ice accretion can form on surfaces equipped with thermal anti-icing systems, when the system is not evaporating 100% of the water impinging on the surface. In this case, the water runs back to the point where the added heat no longer maintains the water film above its freezing temperature. The water then begins to freeze, developing a ridge line and leaving the leading edge clean. Although appearing inconsequential in terms of its mass, wet glaze with runback ice accretion can significantly alter the aerodynamic characteristics (lift and drag) of the structure (Whalen et al. 2005). The experimental results described by Hansman and Turnock (1989) highlight the importance of surface water behaviour to the icing process in the glaze ice regime. Numerical models (Fortin et al. 2004 and Croce at al. 2009) have been developed to simulate water bead growth and the possible transition to rivulets and continuous flow. They provide information about initial ice roughness that is important for heat flux calculations.

The objective of this paper is to demonstrate that the morphogenetic model could be used to predict three-dimensional glaze ice accretion with runback. In this paper, we extend the glaze ice formulation of the morphogenetic model to 3D. The morphogenetic model has already been extended successfully into 3D for rime and wet-rime applications (Szilder et al. 2006 and Szilder 2007). Accurate prediction of the formation of ice beads, ice ridges, rivulets or finally of a rough glaze ice surface is important for a variety of engineering applications. In this paper we will focus on a comparatively simple case of ice formation on a cylinder exposed to freezing rain, with heat transfer conditions leading to glaze ice formation. Such a case is of great interest to the power line icing community.

II. THREE-DIMENSIONAL NUMERICAL MODEL

In this section we describe the main characteristics of the three-dimensional morphogenetic model that will be used to simulate surface water flow and freezing leading to the formation of glaze ice accretion. We will start with a description of a simple example, when ice is formed on a cylinder as a result of freezing rain. To examine this case, we will make major simplifying assumptions for a number of reasons. We wish not merely to emulate the complex processes of glaze ice accretion but rather to understand them by first dissecting the problem into its components. In this way, we want to capture their essence without the confusion of unnecessary and often unknown details. We also wish to identify the main physical parameters determining the glaze ice accretion and present the results in a concise form.

Let us consider a simplified case of ice accretion when drops move along straight vertical lines, and, once they hit the cylinder without splashing, they freeze along the surface under homogeneous heat transfer conditions. The impinging water flux is given by the precipitation mass flux, w (kg m^{-2} s^{-1}). Although we recognize that the total heat flux consists of convective, evaporative, sensible and radiative terms, we do not specify them individually here. In addition, we assume that this total heat flux is not a function of location. Consequently, the mass freezing rate, m (kg m^{-2} s^{-1}) remains constant at locations where there is sufficient water available to freeze.

Let us define the dimensionless number S, which we will call the runback factor, as the ratio of the impinging mass flux on a horizontal surface, w, to the freezing mass flux, m. When $0 < S \leq 1$, all impinging water freezes on impact and there is no surface flow of unfrozen water. Simple integration of water mass balance on a cylinder surface reveals that when $\frac{1}{2}\pi \leq S \leq \pi$, runback water flows from the upper stagnation line to a location on the lower surface of the cylinder given by $\alpha = S$ where α is the angle (in radians) measured from the upper stagnation line. For details refer to Szilder et al. (2002).

Now we will discuss briefly the new features of the three-dimensional morphogenetic model developed for glaze ice accretion. For a detailed description of the model characteristics, please refer to previous publications (Szilder and Lozowski 2002 and 2004).

In the new three-dimensional algorithm for water motion on a surface, a fluid element moves from cradle to cradle location at each time step. The next cradle location is sought within an ellipsoid volume given by $x^2/a^2 + y^2/b^2 + z^2/b^2 = 1$ where: a is the downward and b cross-stream motion step parameter, x is directed along the mean local flow and is locally tangential to the surface, y is perpendicular to the mean flow and is tangential to the surface, and z is perpendicular to the surface. The unit distance corresponds to the cell size. When searching for the next cradle location, the ellipsoid is positioned so that the present fluid spot is located on the ellipsoid surface at (-a, 0, 0). The ellipsoid centre and its orientation change at each step.

For each discrete location within the ellipsoid, a number of already existing neighbours is computed. A weight is assigned to distinguish the type of neighbour and the geometry of contact. To enhance coalescence, neighbour weight is increased from the ice-free surface to the ice. This assumption leads to new element preferential attachment to the ice structure. In addition, the type of contact with a neighbour plays a role and increasing weight is assigned to point, line and surface contact. The total cumulative weight for each discrete position within the ellipsoid is computed and the location where it is a maximum determines the cradle location. However, if there is more than one location of the maximum, the final location is chosen randomly among them.

After a fluid element moves to a new cradle location, a random number is generated and compared with the local probability of freezing to determine the possibility of freezing. After an element freezes, the motion of the next element is examined. This process continues until all elements corresponding to the total precipitation have been considered.

III. MODEL RESULTS AND DISCUSSION

In this segment, we will examine the influence of the governing parameters on the glaze ice accretion process with runback as predicted by the three-dimensional morphogenetic model. To illustrate the main features of our novel approach, a simple case of ice formation on a horizontal cylinder as a result of vertically falling freezing rain will be considered.

Time evolution of glaze ice accretion for different values of the runback factor and motion range parameter is examined. The following geometrical values have been assumed: cylinder radius 50 mm, cylinder length 150 mm, cylinder extent on which impingement occurs 100 mm, and size of the computational cell 0.5 mm. For clarity only one side of the cylinder is displayed. Fluid elements are released at random locations above the cylinder and they fall vertically downwards until they encounter the cylinder or already formed ice structure. Once on the surface, the elements move along the surface until they freeze.

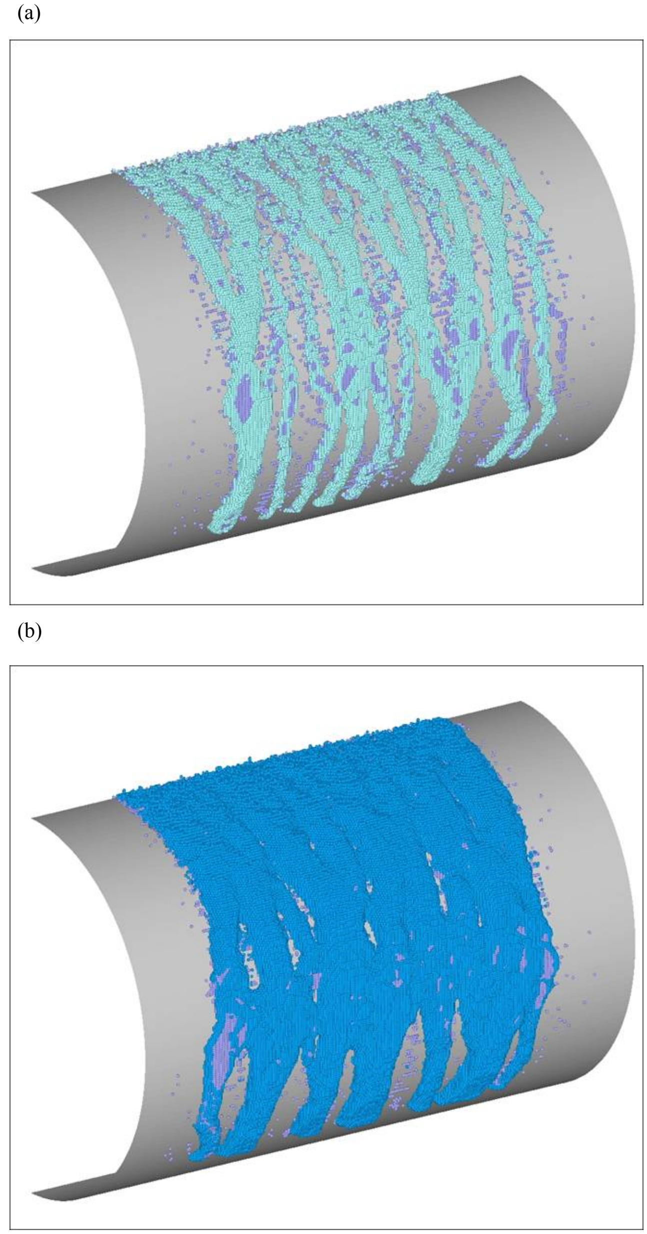
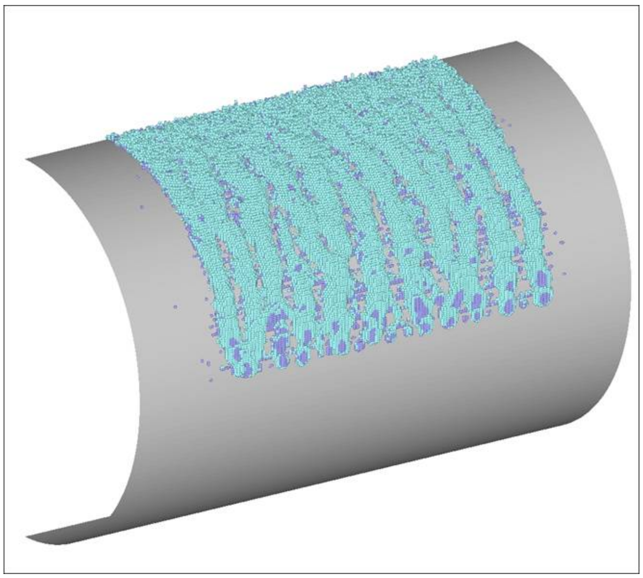


Fig. 1. Glaze ice accretion on a cylinder for a runback factor of ¾ π and downstream and cross-stream motion range parameters of 2.5 and 4.5, respectively. Different colours distinguish the first and second half of the simulation.
(a) total precipitation 2 mm
(b) total precipitation 10 mm.

Figure 1 shows the formation of meandering ice ridges on a cylinder for a runback factor S = ¾ π. As discussed above, for this condition the analytical model predicts a homogenous ice layer within a range of ¾ π radians from the upper stagnation line. However, the morphogenetic model predicts a more complex and, at the same time, a more realistic looking glaze ice accretion. Initially, ice ridges form along the main path of water flow on the surface and they thicken with time. The figures show only ice; they do not show the moving fluid elements. However, looking at the ice structures, one can envisage the unfrozen drop trajectories. It may be noticed that the drops are “advected” downstream while being “diffused” outward. On the upper cylinder where the drops impinge, ice ridges tend to be less pronounced then underneath the cylinder. This occurs because, on the upper surface drops can impinge at any location whereas underneath they tend to move along ice ridges. In addition, as a result of the model's intrinsic randomness, each ice prediction for the same conditions is different. The ice shape variation displayed in Figs. 1a and 1b is not just a result of the total precipitation amount but also the different sequence of random numbers that was used to obtain the solution.

(a)



(b)

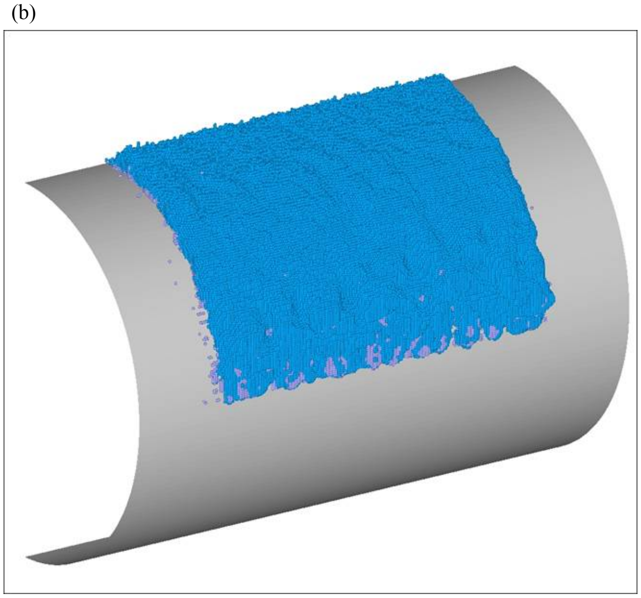
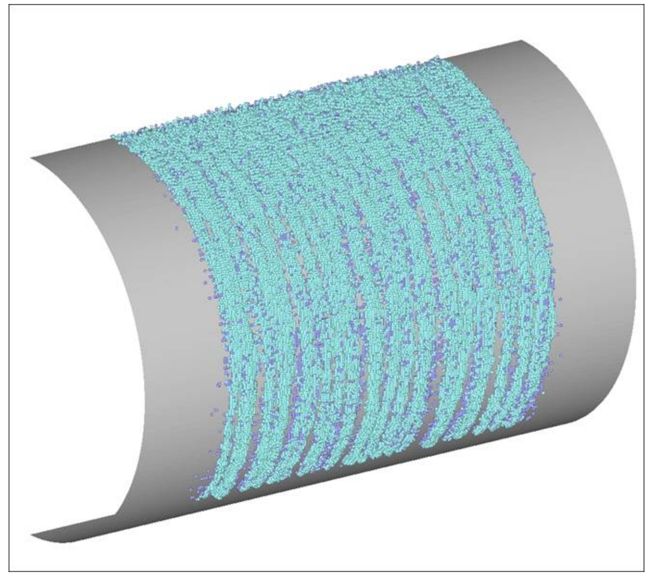


Fig. 2. The same as Fig. 1 but the runback factor is ½ π.

(a)



(b)

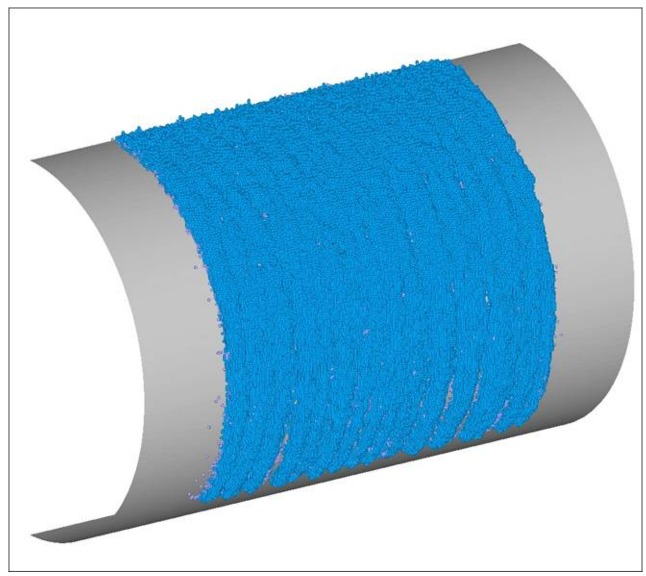


Fig. 3. The same as Fig. 1 but the cross-stream motion range parameter is 1.5.

Figure 2 shows model prediction for a runback factor of ½ π when heat loss is just large enough to freeze all the liquid on the upper cylinder surface. However, water still moves along the cylinder surface to redistribute the impingement flux and form an ice layer of approximately constant thickness. The morphogenetic model predicts an initially random distribution of ice beads that is followed by the formation of ice ridges, Fig 2a; finally, a rough ice layer covers the entire upper surface, Fig 2b.

A comparison between Figs. 1 and 3 sheds light on the influence of the motion range parameter on the details of the ice accretion shape, while keeping the overall ice characteristics like extent and average thickness unchanged. When the cross-stream motion parameter decreases, the ice ridges are straighter and their meander diminishes. In addition, ridges are formed closer to each other and they tend to be smaller. From a physical point of view, the magnitude of the motion range parameter depends on the magnitude of the forces acting on the moving water beads. The character of this relationship will be the focus of further research. For now we can only hypothesize that a relative increase of the downward force tends to increase the ratio of the downstream to cross-stream motion range parameters.

IV. CONCLUSIONS

The exploratory research described in this paper deals with numerical modelling of three-dimensional glaze ice formation, including ice ridges and runback, on a cylindrical surface under uniform heat transfer conditions. The results obtained using our innovative approach are encouraging. In the model, once the droplets impinge on the surface, they move downstream until they freeze. In the initial stages, fluid elements tend to freeze at random locations. However, once more ice is accreted, new drops tend to freeze in the vicinity of already frozen ice. For large precipitation amounts, the rough glaze ice layer covers the entire surface.

In the future, we plan to examine more challenging cases with complex drop impingement patterns, varying heat transfer conditions and complicated geometry. In addition, cases with smaller impinging droplets, applicable to in-cloud icing, will be considered by decreasing the cell size.

V. REFERENCES

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