# NUMERICAL SIMULATION OF COMPLEX ICE SHAPES ON SWEPT WINGS

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## Abstract

*In this paper, we present a three-dimensional, morphogenetic model that simulates discrete rime ice accretion structures forming on a swept wing. Rime is an ice deposit caused by the impingement and freezing, in situ, of supercooled cloud droplets at ice accretion temperatures below 0°C. Depending on conditions, the droplets may freeze as spheres or deform on the surface, but for rime to form, surface liquid flow is limited or non-existent. In our model, roughness elements that develop initially on the wing surface evolve into rime feathers and other complex, three-dimensional structures. On swept wings, these resemble the so-called "lobster tails" or "scallops" that are observed in wind tunnels and in flight. We show the results of numerical model sensitivity tests, performed as a function of two model parameters: sweep angle and freezing range parameter. This exploratory research indicates that the model can predict realistic-looking, three-dimensional ice structures on swept wings. To the best of our knowledge, this capability does not exist in any current in-flight ice accretion models.*

## 1 Introduction

Icing has long been recognized as a critical flight safety problem. Ice accumulation on aerodynamic surfaces can have a considerable influence on aircraft performance and handling qualities, and consequently on aircraft safety. A wide variety of ice accretions shapes are possible depending on the geometric configuration and atmospheric conditions. Potential ice accretions include rime ice, glaze ice and runback ice. In this paper, we will focus our attention on three-dimensional, discrete rime structures forming on swept wings that are often called "lobster tails" or "scallops" [1-3].

Over the past few years, we have developed a unique approach to numerically simulate aircraft icing and we call this method morphogenetic modelling [4-6]. The essential innovation of our approach is its ability to simulate the shape, structural details and physical properties of aircraft ice accretions by emulating the behaviour of individual fluid elements. Wind tunnel experiments and in-flight observations show that the form of aircraft ice accretions is often rough, highly convoluted and discontinuous, with evident three-dimensional features. Nevertheless, most current icing models predict accretion shapes that are relatively smooth and coherent. In addition, existing models do not predict ice density, which may decrease rather substantially under rime conditions. Morphogenetic simulation, on the other hand, predicts accretion density and has the inherent ability to simulate rough and discontinuous ice structures due to the model's discrete formulation. This original capability of the model is exploited and enhanced in this paper in order to demonstrate its advantages over traditional continuous models.

The objective of our present research is to show that the morphogenetic modelling approach can be extended to three-dimensional, in-flight icing. In this paper, we will focus on the simulation of three-dimensional, discrete rime structures forming on swept wings under conditions where experiments produce ice structures called "lobster tails" or "scallops."

Lobster tail ice accretions appear only on swept wings under certain conditions. Scallop growth in icing wind tunnels and under in-flight conditions has been discussed, for example, in [1-3]. Potapczuk [7] summarizes these observations by saying that lobster tails form at high sweep angles when discrete ice feathers develop and merge sufficiently close to the attachment line. A recent review [8] of the experimental basis for numerical modelling of ice accretions on swept wings discusses the need to advance the numerical prediction of ice scallops.

There have been a few previous attempts to model lobster tail formation. Recently, a study was conducted to examine the use of two-dimensional icing software to simulate ice shapes on swept wings [7]. This work had rather limited success because complete lobster tail structures are highly three-dimensional. Earlier, a ballistic, two-dimensional approach to simulating lobster tail icing had been sketched out [9]. That model was based on the differences between the heat exchanged at the top of the lobster tail and the heat transfer on the side of scallops.

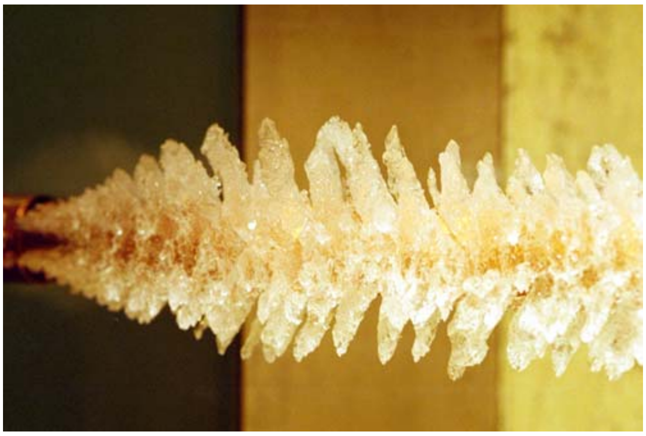


Fig. 1. Experimental lobster tail ice shape (courtesy of M. Oleskiw of NRC, Canada).

## 2 Three-Dimensional Morphogenetic Ice Accretion Model

The model used here is a descendant of a two-dimensional model originally conceived by Szilder [10] for freezing rain applications. Recent two-dimensional versions designed for in-flight conditions [4-6] are more complex than the original model, taking into account the effect on collision efficiency of non-linear droplet trajectories, considering more realistic droplet sizes, specifying the heat transfer distribution to the airstream, and working with the airfoil geometry. Some of our fully three-dimensional modelling of ice accretion applied to marine icing has been summarized in [11]. Here, we will describe only the main characteristics of a three-dimensional version of the model applied to in-flight icing on swept wings.

The three-dimensional numerical model consists of three components: an airflow solver, a droplet trajectory solver, and a morphogenetic ice growth model. Below, we briefly describe these three elements of the ice accretion model.

The velocity field of the flow is computed using the full Navier-Stokes equations for compressible flow. The temperature field is obtained from the energy equation coupled with the mass conservation and momentum equations. The conservation equations are discretised using a finite volume technique. To avoid resolving the smallest scales of turbulence, the conservation equations are time-averaged and the resulting equation set is closed with the single-equation Spalart-Allmaras turbulence model [12], which is used to calculate the turbulent kinetic energy in the flow. The flow field is assumed to be three-dimensional and steady-state. The Structured Parallel Research Code (SPARC) from the Department of Fluid Machinery at the University of Karlsruhe [13] is used to solve the equations. The spatial discretisation is based on the Jameson-Schmidt-Turkel method. The solution is deemed to have converged when the residuals of the governing equations are reduced by at least four orders of magnitude.

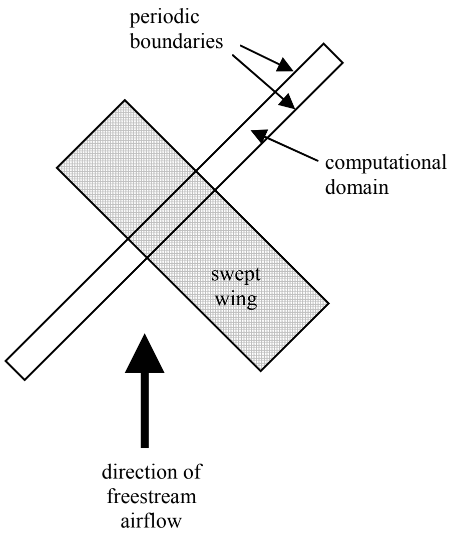



Fig. 2. Top view of swept wing and computational domain (not to scale).

The computational domain is aligned with the sweep angle of the wing, as shown in Fig. 2. Periodic boundary conditions are used in the spanwise direction so that the width of the modelled domain is only 0.1*c*, where *c* is the wing chord. A C-shaped grid generated using the ANSYS ICEM CFD software package [14] is wrapped around the wing. The first grid point normal to the surface is located at a non-dimensional distance $y^+ < 1$, where $y^+ = y\, U_\tau / \nu$ and $y$ the distance normal to the wing surface, $U_\tau$ is the friction velocity, and $\nu$ is the kinematic viscosity. Grid points are clustered near the stagnation line in front of the wing to provide the necessary resolution for the ice accretion model. The ratio used to increase the distance between successive grid points in either direction does not exceed 1.2. This gives approximately 35 grid points in the resolved boundary layer normal to the wing surface. A typical mesh contains $250 \times 120 \times 21$ grid points. The local surface roughness of the wing surface is not considered.

The three-dimensional air velocity field, which is the output of the flow field solver, is an input to the droplet trajectory solver. Unlike the flow field, the droplet trajectories are computed using a Lagrangian approach. It is assumed that the water droplets are spherical and that they do not disturb the airflow. The only force considered to act on the droplets is aerodynamic drag due to their motion relative to the airstream. The equations of droplet motion used in our model are similar to those used in other models and discussed in the literature [15]. Initially droplets are placed one chord upstream from the leading edge of the swept wing on a surface perpendicular to wing's chord. It is assumed that the initial droplet velocity equals the computed airflow velocity at that point. The flow solver calculates values of the air velocity at grid locations that are passed to the droplet trajectory solver. Because the droplet trajectory code requires the airflow velocity at three-dimensional off-grid locations, the air velocity components at a given location are calculated as a weighted average of the values at the eight grid locations within which the droplet velocity is calculated. The weightings are proportional to the inverse distance between the droplet and the grid point. Computation of the droplet trajectories and droplet impact locations leads to the local collision efficiency distribution for the clean airfoil, which is passed to the morphogenetic model. The droplet impact angle distribution is also passed to the morphogenetic model. It should be stressed that in this study, the computation of airflow and droplet trajectories was performed only once for the clean swept wing. In future work, we plan to relax this limitation and recalculate the airflow and droplet trajectories as the shape of the ice accretion evolves with time.

A number of simplifying assumptions have been made in the development of the present morphogenetic model. Before detailing them, we wish to stress that the objective of this paper is simply to demonstrate that the morphogenetic modelling approach has the ability to simulate complex, three-dimensional ice structures, specifically lobster tails. Our continuing goal has been to develop the simplest possible numerical model that is able to capture the essential physical processes that govern the development of complex ice structures. Using such a model may help to identify just what these physical processes are. For the present, we make no claims concerning the quantitative accuracy of the model.

In the model, the mass flux of impinging droplets is divided into fluid elements that are typically larger than individual cloud droplets. Consequently, we think of them as consisting of ensembles of cloud droplets, all of which undergo identical histories. A three-dimensional, rectangular lattice defines the accretion domain. By building the accretion one particle at a time, a morphogenetic model simulates the time evolution of the accretion shape in a natural way that mimics the real world. What we have yet to implement in the present model is the time evolution of the air and aerosol flow.

In our model, the fluid elements are allowed to impact randomly on the wing surface or on the existing ice structure in such a way that their mass distribution is consistent with the collision efficiency distribution computed for a single drop size on a clean wing at given sweep angle. As a result, the model, in its present form, is best applied to early stage icing, when the accretion does not appreciably change the airflow and droplet trajectories. Nevertheless we apply it here to fairly large accretions, thereby sacrificing the potential for quantitative verisimilitude in exchange for gaining an improved qualitative understanding of lobster tail icing.

Because we are simulating rime here, the fluid elements freeze in the vicinity of their impact location. Once a fluid element impinges on the clean wing or existing accretion, a "cradle" location is sought in the neighbourhood of the impact grid cell. This neighbourhood is defined by a sphere centred on the impact cell with a radius expressed in grid cell lengths called the "freezing range parameter." The freezing fluid element is moved to the empty cell within this sphere where it has the maximum number of occupied neighbours. If there is more than one such location, the final site is chosen randomly from among them. While this limited mobility approach to fluid motion on the surface was designed to simulate rime icing, it could also be appropriate for simulating those particular glaze or spongy ice accretions in which there is little surface flow. This is especially important since we wish to simulate lobster tails, which apparently arise out of glaze feather formations [7] with limited droplet spreading and limited liquid film formations [9].

It could be argued that the freezing range parameter should depend on the Macklin parameter [16], defined as the product of median volume droplet radius and droplet impact speed divided by mean surface temperature. However, at this stage we will not venture to establish a quantitative relationship. Instead, we simply argue qualitatively that greater values of the freezing range parameter are associated with warmer atmospheric conditions.

The model is sequential, so that as soon as a particular fluid element freezes, the behaviour of the next element is considered. The total number of impinging fluid elements is determined by the freestream velocity, liquid water content, sweep angle, fluid element size, duration of the icing event, and spatial distribution of the collision efficiency. In summary, the model has the following input parameters: wing type and size, sweep angle, angle of attack, freestream air velocity, liquid water content, median volume droplet diameter, air temperature and ice accretion time. In addition to these physical variables, the morphogenetic model requires a freezing range parameter that is as yet an undetermined function of the Macklin parameter.

## 3 Model Results and Discussion

In this section we examine ice accretion on a NACA 0012 wing with a 0.382 m chord length and sweep angles of 15°, 30° and 45°. The following parameters have been assumed: airspeed, 67 $ms^{-1}$; liquid water content, 0.75 $gm^{-3}$; median volume droplet diameter, 20μm; angle of attack, 0°. The values of the parameters correspond to experimental cases reported in [1]. It could be argued that two minutes of icing under these conditions should not significantly change the airflow and droplet trajectories, but it is nevertheless long enough to allow scallop-like structures to develop. Back-of-the-envelope calculations for straight line trajectories, zero sweep angle and a compact ice structure give a maximum ice thickness at the stagnation line of approximately 6.5 mm.

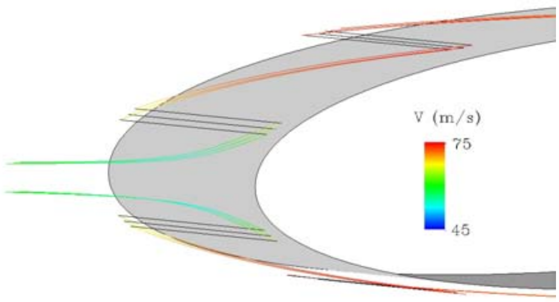
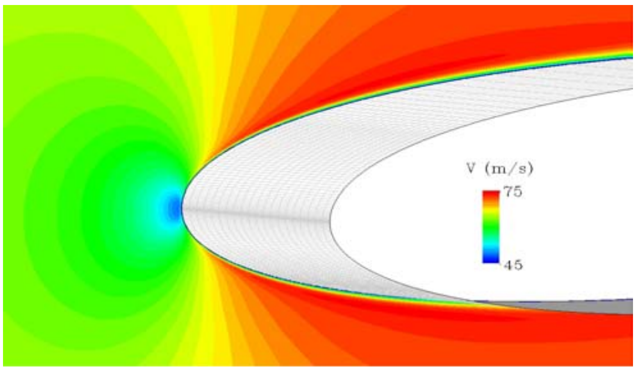



Fig. 3. Predicted streamlines coloured according to the flow velocity for a sweep angle of 45°.

(a)




(b)

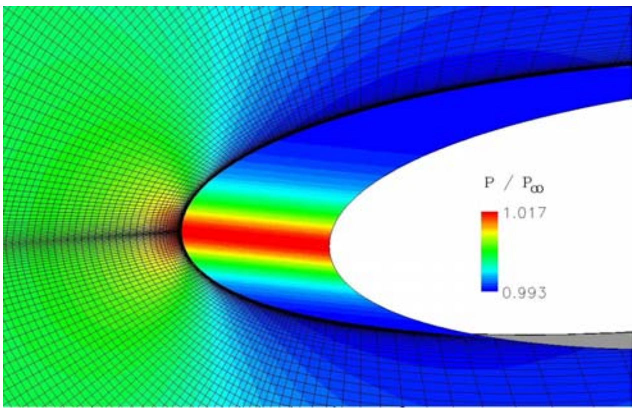



Fig. 4. Predicted flow field for a sweep angle of 45°. The computational grid used for the simulation is also shown.
(a) velocity contours at the periodic boundary
(b) pressure contours at the periodic boundary and wing surface

We will first discuss the results from the airflow solver. Figure 3 shows predicted flow streamlines for the 45° swept wing. The contours are coloured according to the velocity of the flow. The planar periodic boundaries are located at the edges of the wing shown in the figure. Due to the alignment of the computational domain, the streamlines run from the far to the near periodic boundary and then reappear at the far periodic boundary, as indicated by the black lines in the figure (giving the streamlines a zig-zag appearance). The wing is at 0° angle of attack and the streamlines displayed are symmetric about the chord.

Figures 4a and 4b display the predicted flow field for the 45° swept wing. Figure 4a shows the flow velocity contours consisting of all three components of velocity. Although not indicated in the figure, the flow in the clearly visible boundary is zero at the wing surface, and the flow is accelerated to 75 $ms^{-1}$ above the boundary layer. The contours of pressure normalized by the freestream pressure shown in Fig. 4b indicate increased pressure at the stagnation line and lower surface pressures downstream. The computational grid used for the surface of the wing and along the periodic boundaries is shown in Figs. 4a and 4b, respectively.

We will now focus on predicting the ice accretion. Morphogenetic model simulations were performed on a three-dimensional cubic lattice consisting of 150 × 150 × 300 cells (the latter in the spanwise direction along the leading edge) with a grid size of 0.25 mm. The fluid elements are cubes, each occupying one grid cell (0.015625 $mm^3$) after freezing.

We first analyze the influence of sweep angle on the ice accretion shape, setting the freezing range parameter to 3.0. Ice accretion on a wing section of 55 mm spanwise length is displayed in Fig. 5. Colours have been used to help visualize the three-dimensional ice structure. Ice accreted in the first half of the simulation is depicted in blue, while ice accreted in the second half is shown in red. In addition, a translucent surface, parallel to the leading edge and at a distance of 2.5 mm, is used to slice through the accretion. The colours fade as light penetrates the translucent plane. The view angle is 30° from a plane perpendicular to the leading edge and 10º above the horizontal plane of symmetry of the wing.

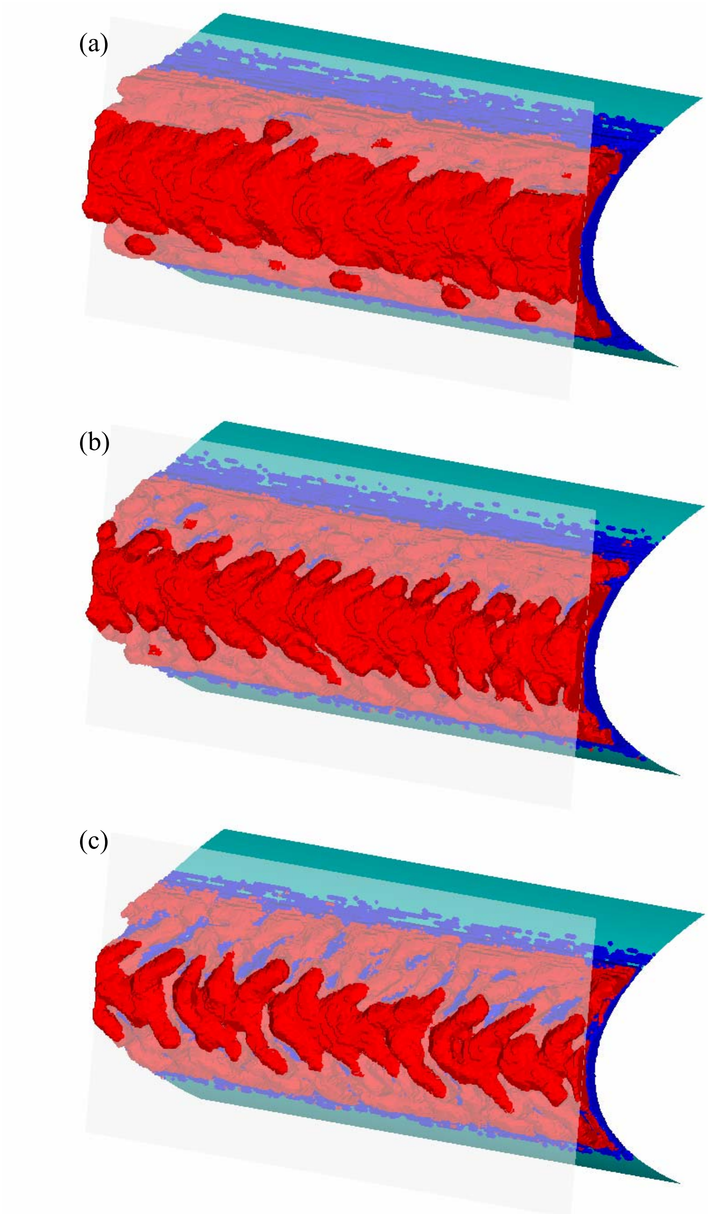



Fig. 5. Predicted lobster tail (scallop) ice shapes forming on a swept wing with a freezing range parameter of 3.0 and varying sweep angle.
(a) Sweep angle 15°
(b) Sweep angle 30°
(c) Sweep angle 45°

Examining the ice structure along the leading edge, it is apparent that the accretion has well developed three-dimensional features. The structure appears to exhibit significant variability over a wide range of spatial scales, with a dominant scale of about 4.5 mm, which appears not to depend on sweep angle. A consistent feature at this scale is the formation of ribs that result from shadowing. The ribs become more pronounced and tend to be distinctly separated from their neighbours as the sweep angle increases. Finally, the ribs are concave in the upstream direction (this is not merely the result of the viewer's perspective). These qualitative properties of the ribs in the model, and their variation with sweep angle, compare well with the properties of the lobster tail features described in [1] and [3]. The reader may also wish to compare them, qualitatively, with the lobster tail features seen in Fig. 1.

Figure 6 shows the influence of the model's freezing range parameter on the ice accretion structure. Physically, an increasing freezing range parameter implies that the impinging fluid elements spread further from their point of impact before freezing. This could result from an increasing median volume droplet diameter, increasing droplet impact speed or increasing ice surface temperature. However, since the first two parameters are assumed constant in the simulations presented here, an increasing freezing range parameter should be associated with an increasing ice surface temperature resulting from an increasing air temperature. Consequently, in the model, the accretion is transformed with rising air temperature, as individual feather like structures, Fig. 6a, merge into coherent scallops or lobster tail type structures, Fig. 6b and Fig. 6c, and finally congeal into a compact rime structure, Fig. 6d. An increase in the freezing range parameter, or equivalently of air temperature, allows fluid elements to move farther from the impingement location, making the ice structure more compact near the leading edge with less pronounced ribs away from it, Fig. 4c. This result is in qualitative agreement with the experimental results described in [2]. It should be kept in mind that the maximum distance between the

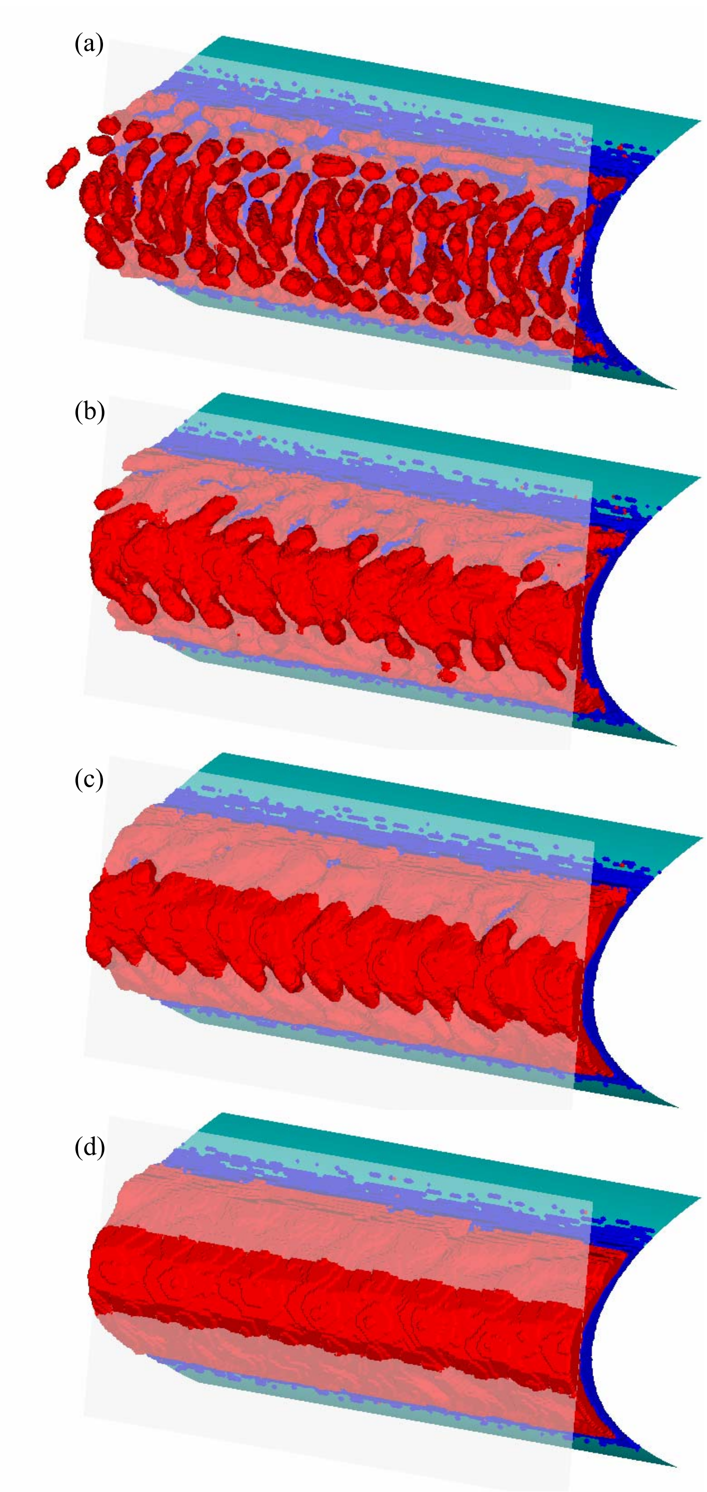



Fig. 6. Predicted lobster tail (scallop) ice shapes forming on a swept wing with a sweep angle of 30° and varying freezing range parameter.

(a) Freezing range parameter 2.5
(b) Freezing range parameter 3.0 with different sequence of random numbers than Fig. 5b
(c) Freezing range parameter 3.5
(d) Freezing range parameter 4.0

impingement location and final droplet position increases from 0.625 to 1.000 mm in Fig. 6, with the assumed grid size of 0.25 mm. It is interesting that such a comparatively small increase in the freezing range parameter leads to very substantial changes in model predicted ice shapes.

The only model input difference between the simulations in Figs 5b and 6b is a different sequence of random numbers. By comparing these two structures, one can obtain an appreciation of the stochastic variability of the model simulations. Since the random number sequence controls the details of fluid element impingement and freezing, a different sequence of random numbers is numerically equivalent to performing a new wind tunnel experiment in which the macroscopic conditions remain the same but the microscopic details, which cannot be controlled, have changed. This has important implications for comparing model and experimental results, because they are both, intrinsically, stochastic. What we still need to determine is whether or not the model's case-to-case variability is comparable with the experimental case-to-case variability.

## 4 Conclusions

Our research has shown that the morphogenetic model predicts realistic-looking, three-dimensional ice structures on swept wings. This capability does not exist in current in-flight ice accretion models. In future an analysis could be performed as a function of wing geometry, sweep angle, free stream velocity, liquid water content and droplet size. The influence of air temperature can be analysed through variation of the freezing range parameter. However, this relationship has not been quantitatively established yet, and this will be a topic of future research. In the future, we also plan to include in the simulation the temporal variation of airflow and droplet trajectory as the ice accretion structure forming on the wing evolves. Nevertheless, even this simple version of the model is able to produce discrete structures with a strong resemblance to experimentally observed lobster tails. This outcome suggests that the main requirements for lobster tails are shadowing and three-dimensional geometry with sweep. There is no need to invoke a flow instability in order to explain lobster tails, although, in wet icing, there could be a growth instability in which the flow perturbations induced by the scallops enhance the local heat transfer in such a way as to promote their continued rapid growth.

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