A LAYER PAVEMENT MODEL TO SIMULATE ROUGHNESS FEATURES IN ICE ACCRETION NUMERICAL SIMULATION

Wang Y. *,*****, D. W. Hammond** ****, Lin G. P.** ***

*** Beijing Aeronautical Technology Research Center, Beijing, 100076, China,**
**** Cranfield University, Bedfordshire, MK43 0AL, UK**
***** Beihang University, 100083, China**

Keywords: *ice accretion, glaze ice, roughness, CFD*

Abstract

This paper focuses on the simulation of ice accretion shape with roughness features during a Computational Fluid Dynamic (CFD) procedure. A new tentative approach called layer pavement model, or icing mosaic method, is described. In-flight ice accretion is a complex phenomenon, while rime icing is well known and can be adequately simulated, glaze icing however is harder to predict to a satisfactory standard. Rime ice shapes tend to be uniform in their surface roughness. Glaze ice shapes may be very irregular. Previous studies have proved that by using a non-uniform roughness distribution on an iced surface, it is possible to improve the accuracy of the simulation. In different areas on a real iced surface, the roughness should behave as different patterns or textures, according to geometric configuration and atmospheric conditions. The icing mechanism and their patterns or textures could be ultimately classified as here the layer pavement method presented. Alike the typography technology, by layer pavement method each surface grid discrete in CFD would be given an appropriate 'type' during each ice build-up iteration step. When the height of local roughness somewhat exceeded the local grid size in certain proportion, which means new facets occur and the ice growth will has new foundations and directions. Hereby rapid-growing ice branches and feathers could be introduced into the CFD process better, so the irregular ice shape such as so-called 'lobster tails' or 'scallops' observed in wind tunnels and in flight will be likely to established in CFD simulations.

1 Introduction

> *'The haunting contours and textures of the physical world'*
>
> *--Joyce Carol Oates*

Aircraft's in-flight icing problems have long been a serious concern in aviation safety and it has been implicated in a number of serious aircraft accidents. In-flight ice accretion, especially in the glaze ice case, is a complex phenomenon and the physical processes involved in it are non-completely understood. [7] From the view of morphogenetic correlation, rime ice shapes tend to be relatively uniform in their surface roughness; glaze ice shapes however may be very irregular. The freezing rate of impinging droplets and water flowing over the ice or airplane surface, to form glaze ice, is strongly dependent on the rate of heat transfer, along with the tendency of water to be retained or to move freely over icing surface. The ice surface roughness is known to make an important contribution to the convective heat transfer and surface water mass flow. Unfortunately, our understanding of the relationships driving these individual processes and the relationship between these processes are still blurred.

At first glance, an iced surface may appear chaotic. The perceptive observer will discern some semblance of order, the existence of recognizable patterns and of distinctive ice types, all of which, in their infinite variety of shape and form, are somehow expressions of the way in which the air has blown to fashion them. Even just a realistic-looking is earnestly long for in icing numerical simulations.

The long-accepted Messinger model, with some empirical extension and the mesh refinement technology, is widely adopted in current CFD simulations of ice accretion. These methods do not take account of variations in ice roughness very well. Overall, they do a reasonable job for rime ice but are less reliable for glaze ice shapes. Compared with experiment, the variation between predicted and observed ice for complex cases such as 3D scallop ice and some 2D horn ice shapes is significant.

Fig. 1. A mosaic artwork (part)

Fig. 2. Letter punches (movable types)

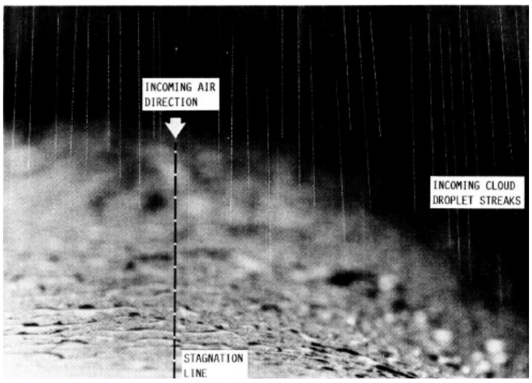
Since it seems that the sufficient understanding of icing processes still has a long way to go, we suppose that we can just measure and ‘cut’ pieces of pattern from real ice, pave these fragments at the appropriate position into computational mesh to substitute any artificial icing model which currently constituted by complicated functions, just as a mosaic had done. A mosaic artwork is usually a picture or decorative design made by setting small coloured pieces, as of stone or tile, into a surface, and it can mimic most of nature with lifelikeness. Moreover, probably while sets of icing ‘letter punches’ could be founded, we can ‘print out’ any realistic ice patterns and simulate the ice growth by repeating the ‘printing’ operation layer over layer. Although the quantity of ‘letter punches’ must be enormous, modern computer science could be competent for the workload as our aid.

2 Past Work on Icing Roughness

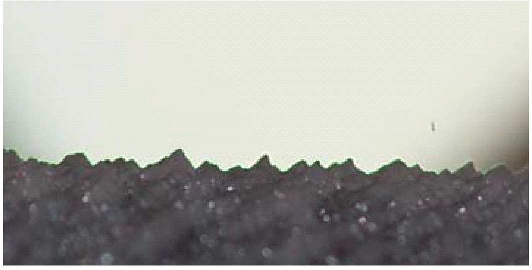
2.1 Recordings of Roughness

To understand the basics of most physics processes, observation, where possible, is usually the best and first aid to research. This seems very reasonable the case in icing research. A number of techniques dominantly are close-up photography and urethane casting, have been developed to observe and record ice shapes and roughness for the numerous IRT and flight-test experiments, which have been undertaken. Some of these allow the evolution of the ice to be observed. These told us some of what we want to know. Based on the results obtained from Kind, Anderson, Hansman, Olsen, Tsao, and Vargas et al, there have been several significant studies to increase an understanding of the ice growth. Moreover, although some studies are only observational and qualitative, sometimes they contribute significantly to progresses.

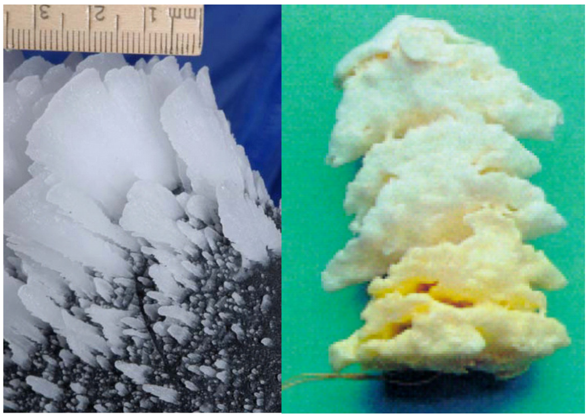
Some qualitative close-up observation, including the Close Range Photogrammetry technique [4] and stereo photography [12], show evidence that the capture of three-dimensional ice shapes with subtle small-scale patterns is possible.



A close-up photograph on a stagnant area



Side view of ice ridges



Scallop ice and its urethane casting

Fig. 3. Examples of ice recording results from references

2.2 Effects of Roughness

Hansman et al [5, 6] revealed that in the rough zone in a glace ice case, unfrozen water coalesced to form nearly hemispherical beads, instead of a liquid film people had postulated. The beads appear to act as aerodynamic roughness, which is well known to increase convective heat transfer substantially. Subsequently they are driven downstream a small distance and freeze into closely spaced, approximately hemispherical roughness elements. The possibility of splashing and the absence of runback in the actual ice accretion (and locally enhanced heat transfer) may explain why some of computational results predict less ice near the stagnation point than is found in actual measured ice shapes. The observations also show relatively rapid growth of ice thickness just down stream of the discrete-bead zone where indeed ice horns were found to develop.

Vargas et al [20, 21] provided a more detailed view of how feathers develop from roughness elements in the formation of a complete scallop. The observations uncovered some previously unknown processes in the formation of the feathers and initial scallop tips in the complete scallop case. Hemispherical shaped roughness element forms on the surface of the ice accretion; the roughness element on the ice accretion freezes in a pointed shape, with a facet at an angle in the upstream side; the front facet grows outwards creating the actual feather, in Fig 4 it is an individual feather. Fig 4 shows the processes involved in the formation of feathers from roughness elements in the main ice accretion of a complete scallop.

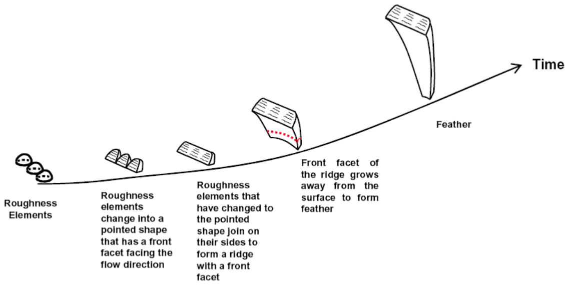


Fig. 4. Vargas' illustration to show how roughness elements grow into individual feather

2.3 Morphogenetic Model

Morphogenetic model [14] is unique, which can predict realistic-looking, three-dimensional ice structures on swept wings. This capability does not exist in other familiar in-flight ice accretion models. It produces discrete structures with a strong resemblance to experimentally observed lobster tails. This outcome mainly derives from its sacrificing of the quantitative verisimilitude of the local water deposit. The final freezing sites of the impact fluid elements are chosen randomly from so-called ‘cradle’ locations, instead of their exact impact locations. For the first time, there is no need to invoke 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. This introduction of chanciness or uncertainness is quite similar to some of our ideas.

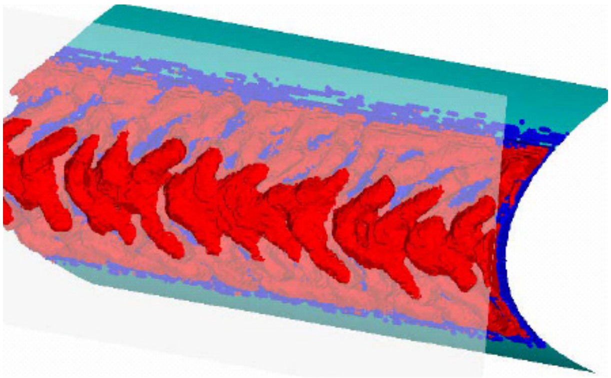


Fig. 5. Predicted Scallop Ice by Morphogenetic Model

3 Technical Method

3.1 Overview

Parameters such as local temperature, local impingement angle, local air velocity, droplet or ice particle size or its distribution, the amount of runback water from upstream grids, and the substrate characteristics as well, control the final roughness pattern of ice surface. There is no reason to doubt, if all variables are the same, the local ice pattern or roughness feature in a computational grid will be different, no matter it locates on an airfoil, an airplane frame, or even on the tip of an ice horn or branch. Some people may argue that roughness parameters at the same position of an airfoil are evidently different during icing processes, as Fig 6 shows. We should point out here we are discussing is restrict only in one tiny computational grid; all parameters had been localized, so as the icing process progressed, its roughness pattern should be redefined. However, the ice pattern, which had been chosen as the initial stagnant line, will also be suitable for any stagnant area on each tips of succeeding ice feathers.

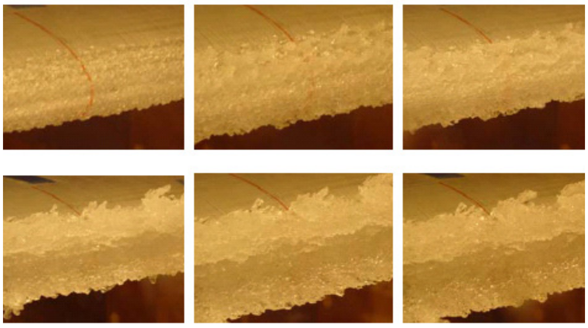
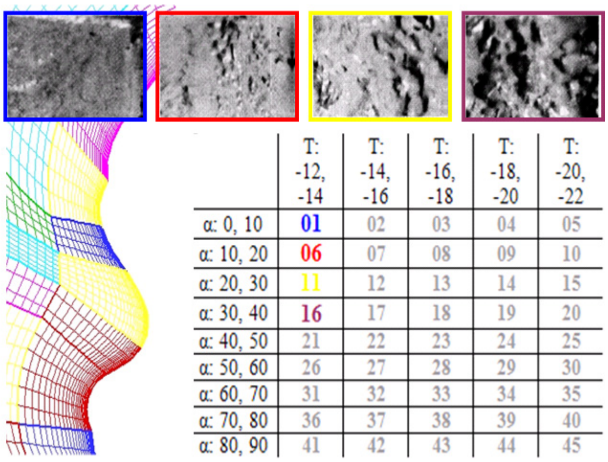


Fig. 6. Evolution of the ice on an airfoil



	T: -12, -14	T: -14, -16	T: -16, -18	T: -18, -20	T: -20, -22
α: 0, 10	01	02	03	04	05
α: 10, 20	06	07	08	09	10
α: 20, 30	11	12	13	14	15
α: 30, 40	16	17	18	19	20
α: 40, 50	21	22	23	24	25
α: 50, 60	26	27	28	29	30
α: 60, 70	31	32	33	34	35
α: 70, 80	36	37	38	39	40
α: 80, 90	41	42	43	44	45

Fig. 7. Scheme of definition and application of a set of ice ‘movable types'

In the Layer Pavement Model or Method, each surface grid will be given an appropriate type during each iteration step. For instance, if there is an icing leading edge which its stagnant point temperature is -12ºC (a nearly rime ice regime) and the lowest static temperature in all the iced area is -22ºC (quite a low velocity), and the impingement angle of the droplet should always range from 0º to 90º (neglect the sign) in most situations. After one ice growth iteration we label all grids which their static temperature are between -12 to -14ºC and droplet impact angle between 0 to 10º as type No. 01. Grids with temperature -12 to -14ºC and impact angle 10 to 20º as type No. 02, etc, until type No. 45 the temperature is -20 to -22ºC and impact angle 80 to 90º. Thereafter, in case of the size of all grids are uniform, we must define the thickness (which is depended on the time step of the ice growth iteration) and surface pattern or texture (roughness characteristics) for every type which accordingly should have the same size with the grids. What the CFD module be fed back are the macro geometrical shape change and different aeronautical and thermodynamic characteristics of every grid due to different type number with different pattern. The latter kind of micro geometrical information is recorded outside the CFD module and can be used to reconstruct the full ice shape with roughness characteristics as final or when needed.

3.2 Chanciness and Uncertainness

The first important question about aforementioned instance is how does this method produce irregular ice shape on a straight airfoil when the temperature and impact angle distribution will be all parallel, and what if during general CFD mesh construction when it is impossible to keep all grids have same size and shape. The answer should be owed to the chanciness or uncertainness. When a type was defined by whatever any method, it should be provided as a block (as showed on the top of Fig 7) much larger than all the grids in the CFD case, so different size and shape can be cut off from it to pave different grid. Then for example in the near stagnant point area when a glaze ice is accreting, when the deposit ice growth regime is dominant (ice grow from the interface between water film and substrate ice, without affect of water droplets impact), so the roughness pattern be got on the block will has a large size, maybe larger than some grids. When a particular type is cut off from the block with such pattern, there is a chance maybe it will be cut on a roughness peak so it has a bigger thickness, or maybe it has possible to be cut on a roughness valley so it has a thinner thickness. Then during that iteration, even though some grid has the same temperature and impact angle and the same type number, they will gain different ice growth thickness in one iteration step. The subsequence ice growth in CFD will be affected by this incipient difference. Another example to explain this kind of chanciness may be in the rear icing area where the feather ices accrete. The early ice growth may be dominated by the condensation or upstream droplets splash, which has merely a small chance to deposit in one pavement time step. So in all the grids in the same situation, there may be only some of grids have the chance to capture some water to produce the early ice nodule as a roughness, and to have different aeronautical of water collection performance in next iteration. Then the irregular feather ice will be produced.

3.3 Foundation of the Types Set

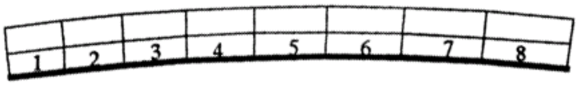
The second and the most important question here is how to found this type. Of course, it is not just as simple as narrated in the instance by different temperature and impact angle. Things will always never as simple as that, and this is a question will be answered only after some attempts were validated. However, some deductions can be presented now:

- MVD and LWC should be on top of all conditions which be used to choose a series of types.
- Then division of static temperature, air velocity (maybe also the impact velocity), impact angle, local water film characteristics (conformation, thickness, velocity, etc), local substrate roughness, local freeze fraction, local water collection coefficient, and so on, will determine the particular type in the series.
- Of course how many type should be divided will be determined by the accuracy demand.
- What parameters should be chosen to construct the coordinates of the movable types is a key issue. Obviously some of variations are correlative, as static temperature and local air velocity and Re number. So maybe to select some non-dimensional parameters which combined several variations will be preferred plans.

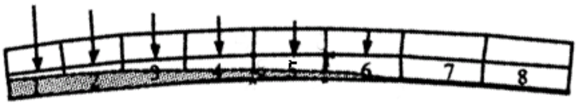
As previous works presented by Anderson and Shin, they had measured the size and height of roughness elements in the transition area of ice-accreted models, and found the parameter to be a function of unitary freezing fraction and accumulation parameter of that airfoil. Local Re numbers with character length of water film thickness, roughness height or size, and other non-dimensional parameter should be considered. How to combine these finite local non-dimensional parameters is negotiable and it is still difficult to say which plan will affirmatively be better than others will. However, as our opinion now, impact angle and temperature (velocity, and may be combined in any kind of Re number) are two unavoidable parameters, append an already exist local freezing parameter or a new combined one.

After talking about the division of the types in the series, there is still a question on how to found the block for types. Experimental method would be an ultimate solution, but that must need the consuming of money and time.

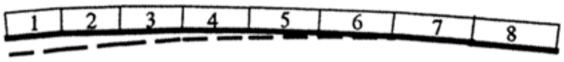
3.4 Icing Mosaic



Original computational mesh



Scheme of water collection



New mesh for iteration after ice accretion

Fig. 8. Scheme of current ice accretion models

Current ice accretion models use the mass and energy conservation law to get equations to calculate the mass of ice in a control volume in every time step. After the new outline of the leading edge is obtained, the computational mesh for the next time step can be regenerated on the new boundary. Most of roughness characters are lost.

However, with icing mosaic model we adaptively cut types with different size and thickness from a prepared block. While average thickness is still determined by water deposit in the element, its roughness characters will affect the final geometrical immediately. The inclined facet we are expecting for should be introduced to calculation earlier. Therefore, the local impact angle and other parameters are all different with previous method; ice feathers may prematurely build-up in early stage. This mechanism will appear more significant when the roughness pattern has more embossment character.

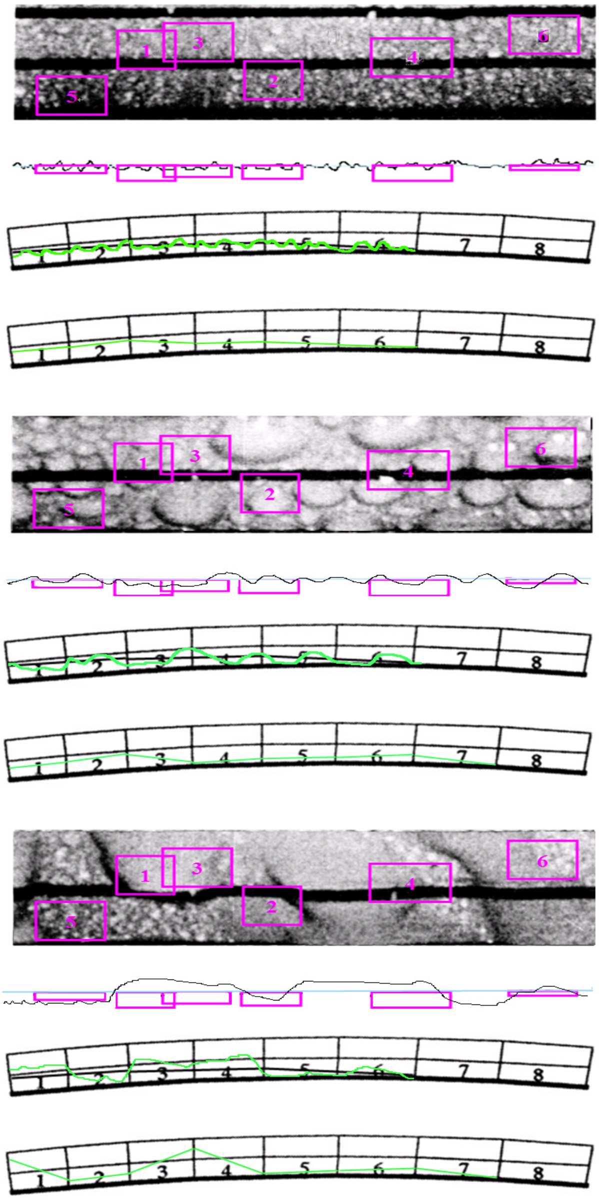


Fig. 9. Scheme of icing mosaic; patterns and their profile, random cutting, new neutral ice surface

3.5 Layer pavement

As our research starts, the preliminary work should firstly put into practice by constructing some limited and coarse series of types, and get some CFD ice growth result. However, utilizing exist literature result we can only get some macro roughness (close to millimetre) information. The low-grade roughness pattern measurement is still a technical obstacle nowadays. Considering these challenges, what we can do is depending on some analysis and boldly supposing.

In different areas on a real iced airfoil the roughness will behave as a different pattern or texture, and the icing mechanism and their pattern or texture can may be classified as follows, (with different roughness degree and the smoothest first):

a) The degree of shielding from droplet impact is small and restricted to short times. The ice is growing or melting under a thick layer of water. The condensation, sublimation, or solidification processes dominate the ice growth, should leading to a smooth ice surface or smallest roughness structure. Roughness height and size is less than the droplet diameter.

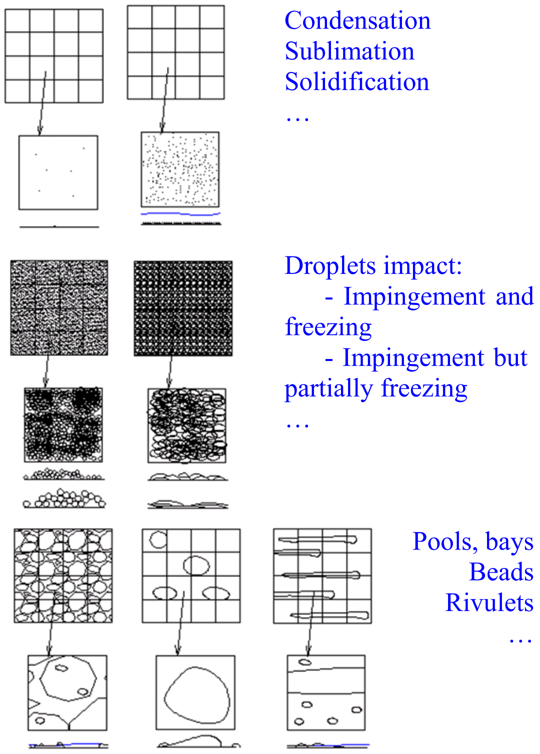


Fig. 10. Mechanisms and their patterns (deduction)

b) In the droplet impingement area where the droplets will partially freeze, the roughness size is affected mainly by the droplets' size, even though other aspects as velocity and impact angle will influence the accumulation pattern. Roughness height and sizes is of the same order of magnitude as droplet diameter.

c) In the runback area where the water film breaks into rivulets and beads, or is confined as small pools or shallow bays (smaller than the grids' size), these build the largest sub-grid scale roughness. Generally, its size and height will be larger than the droplet diameter but smaller than several millimetres.

As ice class a, b and c may be built synchronously at a given grid location at same time, so in one iteration step a component for each class may be included to describe the state of that point, like a chromatic printing had done. Pavement should be done suggested not only one layer in one ice-growth iteration step. Through this method, even mixed-phase icing, icing with Super cooled Large Droplets (SLD) and their splashing secondary droplets, icing in a non-uniform cloud, or other complex situation could be all included in one method.

While the roughness growth exceeds the grid size in CFD process, its affects can be captured by the fluid functions solver.

4 Prospects and Propositions

How to develop a technology to record the ice shape with all-grade roughness information would be very important, and how to test in the IRT to produce an ice shape isolated from other factors disturbs.

On the computational aspect, Tsao's triple-deck Theory to produce the roughness formation may be considered, and some kind of roughness as the incipient nodule produced by the condensation mechanism, as they are too tiny to expect on the experimental to record and analysis them, these kind of situation may only depend on numerical experiment to help to build the model.

However, both above two aspects all seem have much more difficulty and cannot present a result in a short term.

Acknowledgement

The authors would like to acknowledge the China Scholarship Council for the financial support upon their academic communion. Great gratitude to Dr Robin A. Stanfield for his valued experimental results and inspirations, as well as other colleagues in Cranfield icing Research tunnel (IRT) team.

References

[1] Anderson, D. N., Shin, J. (1997). Characterization of Ice Roughness from Simulated Icing Encounters. NASA TM 107400 and AIAA 97-0052. In: *AIAA 35th Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 6-10.

[2] Anderson, D. N., Hentschel, D. B., Ruff, G. A. (1998). Measurement and Correlation of Ice Accretion Roughness. NASA CR 2003-211823 and AIAA 98-0486. In: *AIAA 36th Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 12-15.

[3] Blackmore, R. Z., Lozowski, E. P. (1998). A Theoretical Spongy Spray Icing Model with Surficial Structure. *Atmospheric Research*, 49, p. 267-288.

[4] Collier, P., Dixon, L., Fontana, D., Payne, D., Pearson, A. W. (1999). The Use of Close Range Photogrammetry for Studying Ice Accretion on Aerofoil Sections. *Photogrammetric Record*, 16(94), p. 671-684.

[5] Hansman, R. J., Jr., Turnock, S. R. (1989). Investigation of Surface Water Behavior During Glaze Ice Accretion. J *Aircraft*, 2(26), p. 140-147.

[6] Hansman, R. J., Breuer, K. S., Hazan, D., Reehorst, A., Vargas, M. (1993). Close-up Analysis of Aircraft Ice Accretion. NASA TM 105952 and AIAA 93-029. In: *31st Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 11-14.

[7] Kind, R. J., Potapczuk, M. G., Feo, A., Golia, C., Shah A. D. (1998). Experimental and Computational Simulation of In-flight Icing Phenomena. *Progress in Aerospace Sciences*, 34, p. 257-345.

[8] Linder, Wilfried. (2006). *Digital photogrammetry: a practical course* (2nd ed), Berlin, Springer.

[9] Lozowski, E. P., Oleskiw, M., Blackmore, R. Z., Karev, A., Kolar, L., Farzaneh, M. (2005). Spongy Icing Revisited: Measurements of Ice Accretion Liquid Fraction in Two Icing Wind Tunnels. AIAA 2005-658. In: *AIAA 43rd Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 10-13.

[10] Mikkelsen, K. L., McKnight, R. C., Ranaudo, R. J., Perkins, P. J., Jr. (1985). Icing flight research: aerodynamic effects of ice and ice shape documentation with stereo photography. NASA Report TM 86908 and AIAA 85-0468.

[11] Olsen, W., Walker, E. (1986). Experimental Evidence for Modifying the Current Physical Model for Ice Accretion on Aircraft Surfaces. NASA TM 87184. In: *3rd International Workshop on Atmospheric Icing of Structures*, Vancouver, Canada, May 6-8.

[12] Orr, D. J., Breuer, K. S., Hansman, R. J., Jr. (1995). Quantitative analysis of Ice Accretion Roughness Using Spectral and Stochastic Techniques. AIAA 95-0888.

[13] Shin, J. (1994). Characteristics of Surface Roughness Associated With Leading Edge Ice Accretion. NASA TM 106459 and AIAA 94-0799. In: *AIAA 32nd Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 10-13.

[14] Szilder, K., McIlwain, S., Lozowski, E. P. (2006). Numerical Simulation of Complex Ice Shapes on Swept Wings. In: *25th International Congress of the Aeronautical Sciences*, Hamburg, Germany, September 3-8.

[15] Tsao, J. C., Rothmayer, A. P. (2002). Application of Triple-deck Theory to the Prediction of Glaze Ice Roughness formation on an Airfoil Leading Edge. *Computers & Fluids*, 31, p. 977-1014.

[16] Tsao, J. C. (2003). Cross Flow Effects on Glaze Ice Roughness Formation. AIAA 2003-1219. In: *AIAA 41st Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 6-9.

[17] Vargas, M., Reshotko, E. (1998a). Physical Mechanisms of Glaze Ice Scallop Formations on Swept Wings. NASA TM 1998-206616 and AIAA 98-0491. In: *AIAA 36th Aerospace Sciences Meeting and Exhibit*, Reno Nevada, January 12-15.

[18] Vargas, M. (1998b). *Ice Accretion on Swept Wings at Glaze Ice Conditions* (PhD thesis). UMI 9833923. Case Western Reserve University, Cleveland, Ohio, United States.

[19] Vargas, M., Broughton, H., Sims, J. J., Bleeze, B., Gaines, V. (2005). Local and Total Density Measurements in Ice Shapes. AIAA 2005-657. In: *AIAA 43rd Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 10-13.

[20] Vargas, M., Tsao, J. C. (2007a). Observations on the Growth of Roughness Elements into Icing Feathers. AIAA 2007-0900. In: *AIAA 45th Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 8-11.

[21] Vargas, M., Tsao, J. C., Rothmayer, A., (2007b). Review of Role of Icing Feathers in Ice Accretion Formation. In: *2007 Aircraft & Engine Icing*

International Conference, Seville, Spain, September 24-27.

Copyright Statement