# RECENT DEVELOPMENTS IN SCALING METHODS FOR ICING WIND TUNNEL TESTING AT REDUCED SCALE

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**Keywords:** *icing testing; reduced scale; scaling methods*

## Abstract

*This paper is concerned with reduced scale testing of in-flight ice accretion on aircraft surfaces. A basic description of the icing process is presented and the reason for occurrence of two types of icing, rime and glaze, is explained. Important physical phenomena are highlighted, including phenomena whose importance is not widely recognized. The implied modelling requirements are outlined and discussed. It is shown that the requirements can be readily satisfied for rime icing conditions and that good reduced scale test results can be obtained. For glaze icing on the other hand, not all of the scaling requirements are known. Recent developments in this area are outlined and discussed in the light of experimental results obtained by the authors and others.*

## Nomenclature

- $Ac$ accumulation parameter, eqn. (2)
- $c$ chord length
- $C_f$ skin-friction coefficient, $\tau_0/0.5\rho V^2$
- $C_w$ specific heat of liquid water
- $d$, $D$ droplet diameter, diameter of body nose region
- $h_c$ convective heat transfer coefficient
- $h_{fs}$ latent heat of fusion of water
- $\underline{K}$ droplet trajectory parameter, eqn. (1)
- $\ell$, $L$ a general length scale; body length scale
- $LWC$ liquid water content
- $n$, $n_0$ freezing fraction, freezing fraction at stagnation point
- $p$ static pressure
- $q_e/q_c$ ratio of evaporative to dry convective heat transfer
- $t_w$ thickness of liquid water film, eqn. (3)
- $T_i$ temperature of ice accretion surface (0°C for glaze icing)
- $T_\infty$, $T_R$ Static temperature and recovery temperature of freestream air
- $u_w$ mean velocity in liquid water film
- $V$ freestream air velocity
- $We_t$ Weber number based on water film thickness, $\rho V^2 t_w/\sigma$
- $\beta$ local droplet-collection efficiency
- $\Delta C_p$ change in pressure coefficient in the nose region of the body
- $\theta$ position angle in nose region of body
- $\mu$, $\mu_w$ viscosity of air, viscosity of liquid water
- $\rho$, $\rho_w$ density of air, density of liquid water
- $\sigma$ surface tension of liquid water
- $\tau$ icing test run time
- $\tau_0$ aerodynamic shear stress exerted on the surface of the water film

subscripts *mod* and *ref* denote the model and the reference cases, respectively.

## 1 Introduction

In flight-icing is one of the most important flight safety issues and is the subject of intense international research and development effort. Both physical and computational modelling are used in the design, development and certification of aircraft for flight in icing conditions. While computational methods for predicting in-flight ice accretion are available, the reliability of their predictions is somewhat limited, particularly for glaze icing [1]. Testing in icing wind tunnels is thus a vital tool and the ability to test at reduced scale would be particularly desirable in view of the relatively limited size of available icing wind tunnels. Scaling requirements are not, however, fully established for all icing régimes. This paper discusses recent developments in this area. Recent experimental results obtained by the authors and others are used to illustrate the discussion.

To provide essential background, the paper begins with a brief physical description of the in-flight icing process. As will be seen, there are two types of icing, rime and glaze. Glaze icing is particularly complex and the physics of it are not fully understood. Scaling requirements are discussed in the light of the physical processes that are, or may be, important. Reflecting the incomplete understanding of glaze icing, scaling requirements for it are not well established. Recently proposed additional scaling requirements [2, 3] are outlined and are discussed and assessed in the light of experimental and computational results.

## 2 Basic Description of the In-Flight Icing Process

A brief description of the ice accretion process, as currently understood, will be useful as background for the ensuing discussssion. This description is based mainly on papers by Messinger [4], Hansman & Turnock [5], Bilanin [6], Hansman *et al.* [7] and Hansman *et al.* [8].

In-flight icing occurs when an aircraft flies through clouds in which droplets of supercooled liquid water are suspended. This of course requires an air temperature below freezing, i.e. below 0°C . Droplets tend to strike upstream-facing surfaces on the aircraft. At steady state these surfaces can be assumed to be adiabatic. Immediately upon impact the droplets freeze either partially or completely. The latent heat of fusion is released from the water which freezes and this tends to warm the accreted ice and underlying solid surface towards 0°C. This warming tendency is counteracted by convective heat loss to the ambient air. The steady-state temperature in the impact region is thus mainly the result of a balance between the rate of latent heat release and the convective heat transfer rate to the ambient air. In cold temperatures with low liquid water content (*LWC*) the temperature of the accreted ice remains below 0°C and the impacting droplets freeze completely upon impact. On the other hand, with high *LWC* and/or air temperatures only slightly below 0°C the surface temperature of the accreted ice is 0°C and only a part of the liquid water freezes upon impact; that is, the freezing fraction, $n$, is less than unity. The unfrozen water tends to run back along the surface and it too will eventually freeze. In such conditions the freezing fraction tends to be less than unity because the rate of convective heat loss is insufficient to remove all of the latent heat that would be released if the liquid water were to freeze completely at its impingement point. With low *LWC* and low temperature, on the other hand, convection has the capacity to remove the latent heat released by freezing of all of the impinging liquid water so that the freezing fraction is unity and the temperature of the accreted ice can be less than 0°C. It should be noted that in this paper the term *convection heat transfer* includes heat transfer associated with evaporation of water from the ice-accretion surface into the ambient air; the evaporative heat loss is of comparable magnitude to the 'dry' convective heat loss.

Conditions in which the freezing fraction is unity (e.g. cold air, low *LWC*) are known as rime icing conditions. The rime ice accretion process is relatively simple because the impinging droplets freeze completely upon impact and remain where they strike the surface. In modelling work it is thus only necessary to correctly simulate the droplet trajectories and to ensure that the temperature of the accreting ice remains below 0ºC .

When the freezing fraction is less than unity, glaze icing conditions are said to prevail. Glaze icing is much more complex than rime icing because of the unfrozen water which is present in the impingement zone. As already mentioned, this water runs back and tends to freeze somewhat downstream of where it impinged on the surface. Complex ice shapes tend to develop, often with large horns in two-dimensional cases and complex three-dimensional 'lobster tail' shapes on swept surfaces.

Recent research by Olsen & Walker [9], Hansman & Turnock [5], Hansman *et al.*[7] and Yamaguchi & Hansman [10] indicates that in glaze icing the detailed behaviour of the runback water has a very important influence on the shape of the ice deposits. The runback water appears to exercise this influence in part through its effects on the rate of convective heat transfer from the surface to the ambient air. More freezing will occur where this heat transfer rate is high. Close-up video observations [7] show that the liquid water forms an approximately uniform film on the accreted ice layer near the flow stagnation point but that farther back the liquid film breaks down and the water collects into discrete beads on the surface. Olsen & Walker [9] first observed these beads and recognized their probable significance. The beads appear to act as aerodynamic roughness which is well known to substantially increase convective heat transfer coefficients [11, 12]. The observations show relatively rapid growth of ice thickness just downstream of the discrete-bead zone. Indeed ice horns were found to develop there. The breakup of the liquid film into discrete beads may be associated with transition from laminar to turbulent flow in the air boundary layer. Of course roughness would tend to have an influence on the transition location. The discrete-bead zone is observed to migrate slowly upstream as icing test runs progress.

Hansman *et al.* [7] have also noted that the runback water tends to form into rivulets. The rivulet flow behaviour can be expected to have an important influence on ice accretion shapes both by virtue of influencing the convective heat transfer rate and by virtue of determining where the runback water moves to and eventually freezes. Bilanin [6] suggests that splashing in the impingement region and perhaps aerodynamic stripping of liquid water from the surface may also be important. On the basis of a correlation published by Walzel [13], Kind [2] argues that splashing probably occurs in typical glaze icing conditions. Kind and Oleskiw [14] actually observed aerodynamic stripping in some of their test runs where relatively large amounts of liquid water were present and large drops tended to form at the edges of the ice accretion.

In the light of the two preceding paragraphs it appears that surface tension would play an important role in glaze icing and should be recognized in modelling work. Indeed Hansman & Turnock [7] and Bilanin & Anderson [15] have shown that addition of surfactants to the water can have a dramatic effect on the shape of ice accretions in glaze icing tests. Viscosity effects in the liquid water flow can also be expected to be important.

## 3 Modelling Considerations and Similarity Requirements

In light of the preceding section it is easy to list the main physical factors which are important to in-flight icing. They are the airflow pattern, the droplet trajectories, the convective heat transfer from the ice-accretion surface to the ambient air and, for glaze icing, the behaviour of the liquid water on the surface of the ice accretion, including splashing and aerodynamic stripping, and the phase-change or freezing process. The convective heat transfer is, as outlined above, strongly coupled to the behaviour of the liquid water, as well as to the developing shape and roughness of the ice accretion.

Correct modelling of the airflow and of the droplet trajectories is sufficient for rime icing because the supercooled droplets can be assumed to freeze completely at their impact position. Although convective heat transfer is important to the physical process, there is no need to accurately simulate either it or surface water flow in the case of rime icing. For glaze icing, on the other hand, accurate simulation of the convective/evaporative heat transfer, and thus of all the factors mentioned in the preceding paragraph, is crucial. Since icing encounters tend to occur at relatively low Mach number, compressibility effects can usually be neglected.

In physical modelling the strategy is to try to produce, in controlled experiments, conditions dynamically similar to the reference conditions, that is the aircraft flight and icing conditions that are of interest. The most straightforward way of doing this is to use a full-scale model and to subject it to the same airspeed, ambient temperature, droplet diameter, *LWC*, etc. as in the reference case. This is not always possible due to constraints on model size imposed by available icing wind tunnel size. Reduced-scale testing is thus very desirable. To attain dynamic similarity in reduced-scale testing it is necessary to match (i.e. to have values in the model test equal to values in the reference case) relevant non-dimensional ratios of lengths, velocities and forces. Judicious physical reasoning is required to identify the minimum set of non-dimensional parameters that must be matched.

As is well known, dynamic similarity of the airflow pattern and of aerodynamic forces can be ensured by using a correctly scaled model and matching the Reynolds number. It is seldom possible to actually match Reynolds number but there are well established techniques for recognizing and alleviating problems that may stem from this. In fact the typically bluff shapes of glaze ice accretions tend to define separation locations, thus reducing sensitivity to Reynolds number.

Similarity of droplet trajectories requires matching the ratio of drag to inertia forces on the droplets. Bragg [16] has done the most thorough analysis of this problem and has shown that trajectories are very well scaled if the droplet inertia parameter, $\bar{K}$, is matched, that is

$$\bar{K}_{\mathrm{mod}} = \bar{K}_{ref} \qquad (1)$$

where $\bar{K} = (1/18)\,(\rho_w/\rho)\,(d/L)\,(\rho V d/\mu)^{0.65}$

The volume of liquid water impinging on the model must also be correctly scaled. Provided that eqn. (1) is satisfied, this is ensured by matching the accumulation parameter, that is

$$Ac_{mod} = Ac_{ref} \qquad (2)$$

where $Ac = LWC\ V\,\tau\,/(L\,\rho_w)$

The foregoing scaling requirements are now fairly well accepted and used by the icing-test community. For rime icing they are the only requirements that need to be satisfied and this is easily done by choosing *LWC*, freestream airspeed, *V*, and run time, $\tau$, to satisfy eqn.(2), and droplet diameter, *d*, to satisfy eqn.(1). Of course for rime icing the freestream air temperature in the icing wind tunnel must be sufficiently low that all droplets freeze immediately upon impact. Even for reduced scale tests good similarity of rime ice shapes is obtained when these scaling requirements are satisfied. Figure 1 shows two examples.

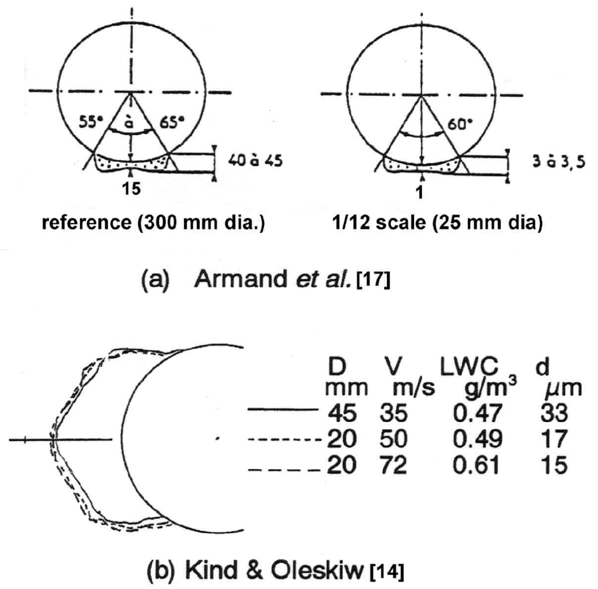


**Fig. 1** Examples of scaling for rime icing.

For glaze icing a number of additional scaling requirements must be satisfied in addition to those outlined above. The additional requirements are not well established and considerable research effort is being devoted to identifying them. The goal is to correctly scale the distribution of mass of water that freezes at all corresponding points on the model and reference bodies, since this would yield the correct ice shape on the model. The additional requirements are thus concerned with ensuring that the correct mass of liquid water arrives, and that the freezing fraction has the same value, at all corresponding points.

Because validated scaling laws for glaze icing are not presently available, glaze icing tests for aircraft design and certification purposes are currently done at full scale, sometimes with some distortion of the aft portion of the model to mitigate size constraints. A substantial amount of testing at reduced scale has, however, been done in attempts to identify suitable scaling laws, for example [14, 15, 18 - 25]. In these research-oriented tests there has been a consensus that, in addition to satisfaction of eqns. (1) and (2), the freezing fraction should be matched. The approach has been to match the calculated value of the freezing fraction, $n_0$, at the stagnation line of the model and reference bodies. In reduced scale tests with matching $\overline{K}$, $Ac$ and $n_0$, scaling success has sometimes been good and sometimes poor. There is a consensus that one or more important scaling parameters have yet to be identified. The following paragraphs outline some recent efforts to remedy this deficiency.

## 4 Recent Progress in Identification of Additional Scaling Requirements

As discussed earlier, surface tension effects are clearly important and should be correctly scaled. This requires matching of the ratio of aerodynamic- or inertia-forces to surface-tension forces. The Weber number, $We = \rho V^2 \ell / \sigma$, represents this ratio. The length scale, $\ell$, in the Weber number must be appropriate to the physical process whose scaling is being considered. As will be seen, the water flow on the surface of glaze ice accretions is typically very thin and viscous stresses in the water flow are significant. Correct scaling of these effects requires matching of the ratio of viscous forces to surface-tension forces. This ratio is represented by the capillary number, $Ca = \mu_w u_w / \sigma$, where $\mu_w$ and $u_w$ are viscosity of the liquid water and a measure of its velocity, respectively.

The need to match a Weber number has been recognized by some researchers in recent years, for example [15, 20, 24], but there is disagreement regarding a suitable choice for the length scale, $\ell$. Possible candidates are the overall body size, $L$, the supercooled droplet mean diameter, $d$, or some measure of the thickness of the water flow on the ice-accretion surface. Since the requirement is to correctly scale the surface water flow dynamics, the appropriate length scale would seem to be a measure of the thickness of this flow; since this thickness is very small, the body size, $L$, should be of little direct relevance. Also the droplet diameter, $d$, should be of little direct relevance to this flow because the droplets disappear as distinct entities upon impact. However, the droplet diameter, $d$, as well as the water flow thickness would be relevant to splashing, and the water density, $\rho_w$, should be used in the Weber number that relates to splashing.

Thus far other researchers have not recognized the possible importance of the Capillary number, $\mu_w u_w / \sigma$.

As mentioned earlier, the liquid water that is present on the surface of glaze ice accretions generally forms a thin film in the stagnation region. Although this film breaks up into beads and rivulets a short distance downstream, its thickness could be used as a measure of water-flow thickness for scaling purposes. Indeed the film thickness is presumably an important parameter in determining where and how the film breakup occurs. Since the film is very thin it is reasonable to assume laminar equilibrium flow, with negligible inertia effects [26 - 28]. This means that the flow in the water film can be considered as a superposition of two-dimensional Couette and Poiseuille flow, since it is driven by the shear stresses and pressure gradients imposed on it by the airflow. Using a relation for water-mass conservation and a superposition of the classical Couette and Poiseuille flow solutions, Kind [2] derived expressions for the capillary number, $\mu_w u_w/\sigma$, and for the water film thickness, $t_w$. The expression for $t_w$ is

$$t_w^2 = \frac{\mu_w LWC\, V\, \beta(1-n)(D/2)Sin\theta}{\rho_w(0.5\rho V^2)(C_f/2 + 0.42\Delta C_p t_w/D)} \qquad (3)$$

For working purposes the values of $\beta$, $D$, $\theta$, $C_f$ and $\Delta C_p$ were set to 1.0, chord times thickness-to-chord ratio, 45deg., 0.003 and -2 respectively for evaluation of Eqn. (3). It should be noted that scaling results are insensitive to these estimated values because we are primarily concerned with ratios for model to reference cases; $\beta$, $\theta$, $C_f$, $\Delta C_p$ and also $n$ should have the same values for the model and reference cases so that they largely cancel out of the ratios. Values of $t_w$ calculated from eqn. (3) for typical glaze icing conditions are very small, of order $10^{-5}$ m. It is interesting that the expression for the capillary number, $\mu_w u_w/\sigma$, is identical to that for the Weber number $\rho V^2 t_w/\sigma$ when the analysis outlined here is used to determine $u_w$ and $t_w$. Upon reflection, this is not surprising since the analysis for the water film thickness, $t_w$, includes a model of water viscosity effects so requiring the film capillary number to match does not introduce any new requirements. Thus matching of $\rho V^2 t_w/\sigma$ automatically ensures matching of $\mu_w u_w/\sigma$, which is fortunate. Viscous forces in the water film are found to be of the same order as surface-tension forces.

Kind [2] examined numerous scaling tests reported in the literature and found that for most test runs which produced good scaling of the ice accretion shape the Weber number $We_t = \rho V^2 t_w/\sigma$ was approximately matched to the reference value, even though that was not a conscious test requirement. The converse was approximately true for test runs for which scaling success was weak. Figure 2 illustrates this finding, which of course offers some support for $We_t$ as an important scaling parameter for glaze icing. Other proposed scaling parameters were assessed in the same way; their correlation with scaling success was significantly poorer than that seen in Fig. 2.

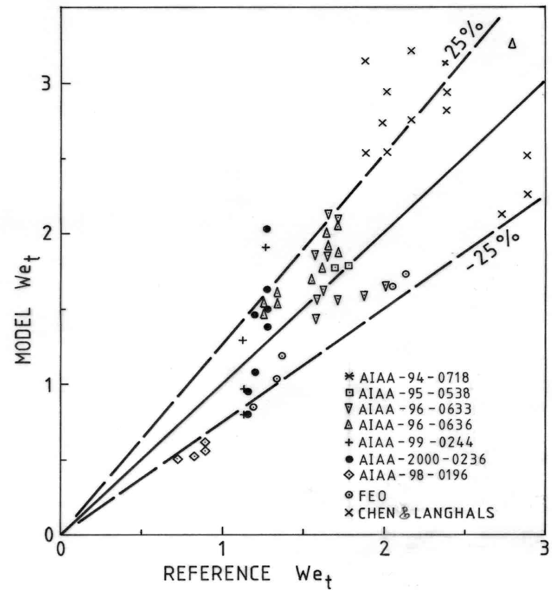


**Fig. 2** Correlation of good scaling success with matching of $We_t$.

Kind and Oleskiw [14] carried out icing tests specifically directed at assessing the validity of the proposed Weber number, $\rho V^2 t_w/\sigma$, as a scaling parameter for reduced scale glaze icing tests. 45 mm diameter circular cylinders were tested to provide reference ice shapes and 20 mm cylinders were tested to provide reduced scale results for comparison. Test conditions for the runs with the 20 mm cylinders were chosen such that $\bar{K}$, $Ac$ and $n_0$ always had the same values as for the corresponding reference run; this determined the values of droplet diameter, $LWC$ and run time. The airspeeds, $V$, were chosen to make one of the following non-dimensional parameters equal for the reduced-scale and corresponding reference run: capillary number, $\mu_w V/\sigma$ or Weber number based on overall length scale, or droplet diameter or water film thickness, $\rho V^2 D/\sigma$ or $\rho V^2 d/\sigma$ or $\rho V^2 t_w/\sigma$ respectively. Freestream air temperature, $T_\infty$, remained a free parameter that could be chosen arbitrarily, but was made equal to that in the reference run in most cases. Tests were done for five different sets of reference conditions. The results for two of these are shown in Figures 3 and 4 which show tracings of the ice accretion cross section at mid-span of the models at the end of the test runs; these results are typical of the others.

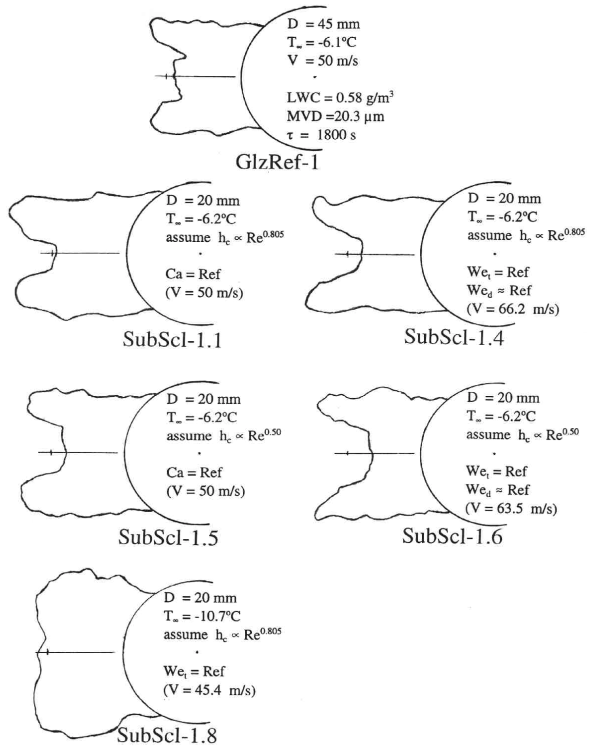


**Fig. 3** Results of scaling tests on circular cylinders[14]; $n_0 = 0.38$ The uppermost tracing is the reference case, $D$ = 45 mm; $D$ = 20 mm for the sub-scale cases. Tracings are at midspan unless otherwise noted.

Perhaps the most obvious observation from examination of Fig. 3 and 4 and the other test results for the circular cylinders, is that all of the sub-scale test runs which used the same freestream static temperature, $T_\infty$ , as the reference case produced reasonably good matches to the reference ice shape. This indicates that if the droplet inertia parameter, $K$, the accumulation parameter, $Ac$, the calculated freezing fraction at the stagnation line, $n_o$ , and the freestream static temperature, $T_\infty$ , are matched, then the ice accretion shape is not particularly sensitive to freestream velocity within the range of these tests, that is, $V_{ref} \leq V \leq 1.5V_{ref}$. Conversely, when the reduced-scale and reference freestream static temperatures differed substantially, there was a marked deterioration in the similarity between sub-scale and reference ice shapes, as can be seen in the lowermost tracings in Fig. 3 and 4.

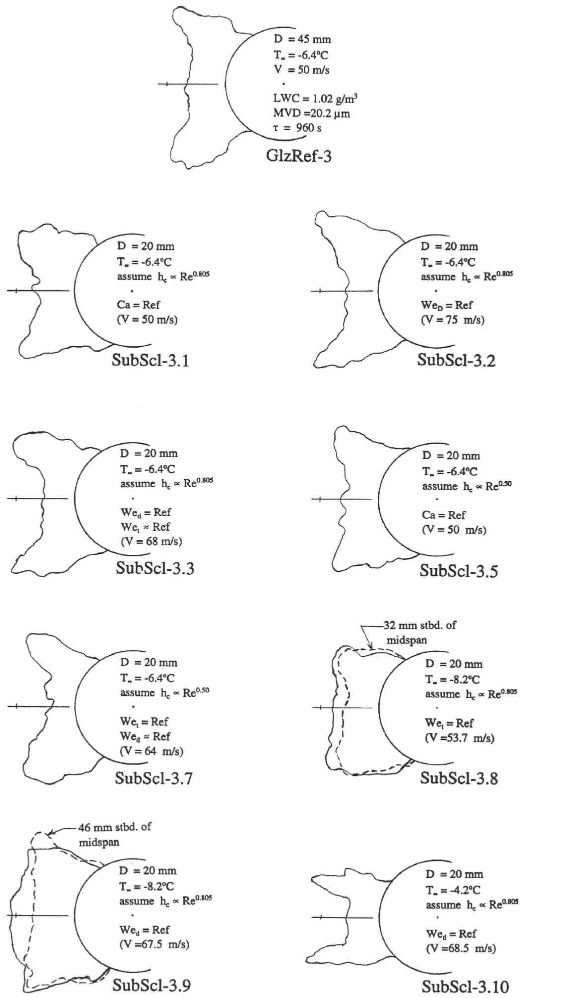


**Fig. 4** Caption as for Fig. 3, except $n_0 = 0.26$

More recently Oleskiw *et al.*[25] conducted icing tests on NACA 0012 airfoils with the same objectives as the tests on circular cylinders. The reference and reduced scale airfoil models had chord lengths of 500 and 222 mm, respectively. Fig. 5 shows a typical set of results. The results of these tests also indicated that the ice accretion shapes were insensitive to freestream velocity within the range tested, that is $V_{ref} \leq V \leq 1.6V_{ref}$, with $V_{ref}$ = 67 m/s. In contrast to the circular cylinder results, there was no obvious sensitivity to freestream temperature changes but the temperature changes were limited to rather small values (< 3°C) due to constraints on attainable operating conditions in the icing wind tunnel. The results suggest that airfoil shapes may be relatively insensitive to changes in icing conditions, as compared to circular cylinders.

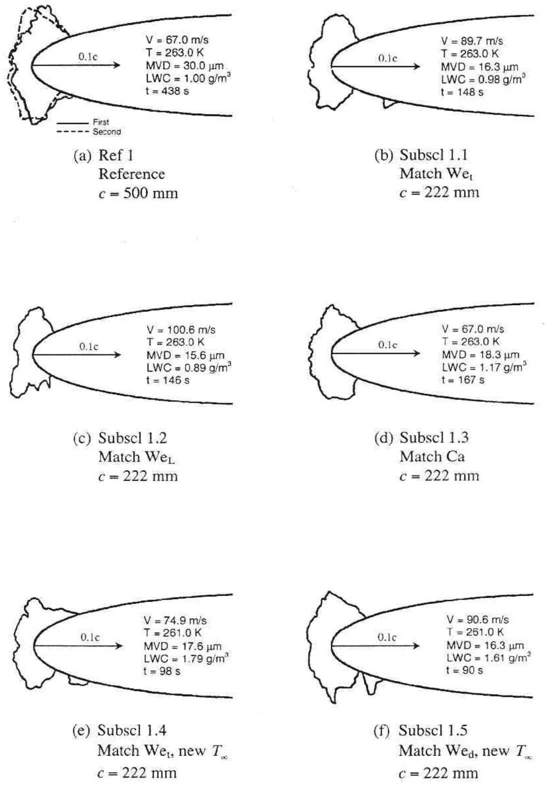


**Fig. 5** Results of scaling tests on NACA-0012 Airfoils [25]; $n_0 = 0.25$ The uppermost tracing is the reference case, $c$ = 500 mm; $c$ = 222 mm for the sub-scale cases.

As mentioned earlier, the current consensus amongst icing-scaling researchers is that the non-dimensional parameters $\bar{K}$, $Ac$ and $n_0$ should be matched for glaze icing tests. This can be achieved by choosing suitable values for droplet diameter, $LWC$ and run duration. Freestream velocity can be chosen by matching the proposed Weber number. This procedure leaves the freestream static temperature, $T_\infty$, as a free parameter. However, as mentioned above, Kind and Oleskiw [14] observed that their scaling results for circular cylinders were distinctly poorer when the freestream air temperature differed from the reference value. This was the most striking of the results of those tests and no explanation was apparent at that time.

Kind [3] recently suggested the following explanation. Using the Messenger[4] model, the expression for the freezing fraction can be shown to consist of the sum of two non-dimensional terms, that is (e.g. [29])

$$n = A + B/\beta \qquad (4)$$

where $A$ = sensible/latent heat ratio
$= C_w(T_i - T_\infty - V^2/2C_w)/h_{fs}$

$B$ = convective/latent heat ratio
$= (1 + q_e/q_c)h_c(T_i - T_R)/(LWC\ V\ h_{fs})$

To simplify the discussion, the runback mass flowrate has been omitted from eqn. (4); symbols are defined under Nomenclature. Note that $A$ has a constant value while $B$ varies with position in the ice-accretion region because the convective heat transfer coefficient, $h_c$, of course varies. Thus the $B$ term in eqn. (4) represents a distribution, with a particular value, $B_0$, at the stagnation point. If we require that $n_{0mod} = n_{0ref}$ and choose $T_{\infty mod} = T_{\infty ref}$, then $A_{mod} = A_{ref}$ and $B_{0mod} = B_{0ref}$ and it is reasonable to expect that the $B$ term in eqn. (4) will make the same contribution to the distribution of $n$ as in the reference case. On the other hand, if $T_{\infty mod} \neq T_{\infty ref}$ then $A_{mod} \neq A_{ref}$ and $B_{0mod} \neq B_{0ref}$; then $n_{mod}$ will equal $n_{ref}$ only at the stagnation point and the distributions of $B$ and $n$ will differ from the reference case. This explanation is supported by computations carried out using the icing codes TRAJICE2 [30] and LEWICE2 [31], results of which are shown in Figs. 6 and 7. It would thus appear that the values of the sensible/latent and convective/latent heat ratios, $A$ and $B$, should be individually matched at the stagnation point. In practice the freezing droplets are water in both the reference and the reduced scale cases so matching of $n_0$ and of $T_\infty$ is equivalent to matching of $A$ and $B$.

Another observation of Kind[2] and Kind and Oleskiw [14] was that when the Weber number $We_t = \rho V^2 t_w/\sigma$ and the freestream air temperature, $T_\infty$, were matched to their reference values, then the Weber number $We_d = \rho V^2 d/\sigma$ was also approximately matched to its reference value It is not clear at present if this is purely coincidental but it would indeed be fortuitous if this is generally the case because then the Weber

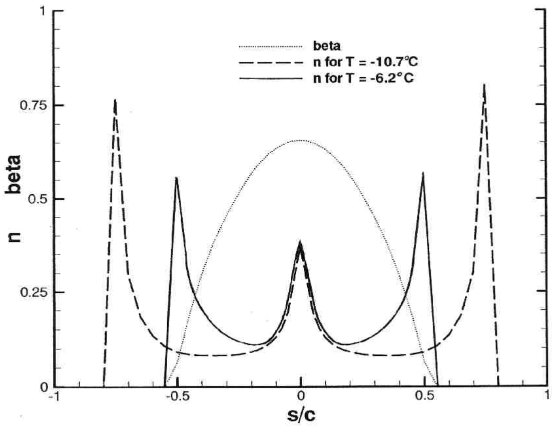


**Fig. 6** Collection efficiency and freezing fraction predicted by TRAJICE2 for 20 mm dia. cylinders with same $K$, $Ac$, $We_t$ and $n_0$ but different $T_\infty$ [30].

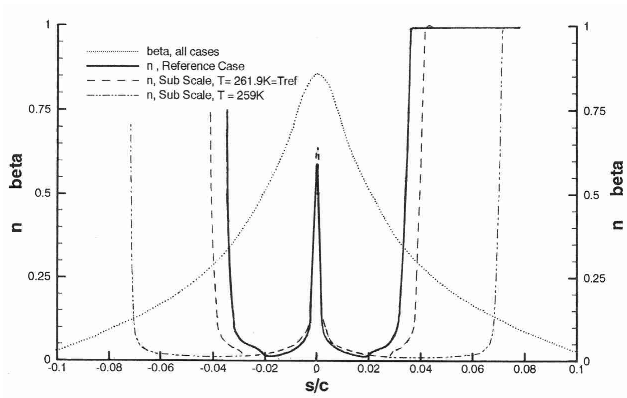


**Fig. 7** Collection efficiency and freezing fraction predicted by LEWICE2 for NACA-0012 airfoils at $\alpha = 0$ with same $K$, $Ac$, $We_t$ and $n_0$ but different $T_\infty$ ($c$ = 500 mm for reference, 222 mm for sub-scale cases) [31].

number appropriate to splashing, $\rho_w V^2 d/\sigma$, would be matched as well. Then all of the scaling requirements that have been proposed would be satisfied, at least approximately. In summary, the work outlined above suggests that satisfactory results may be obtainable from reduced-scale glaze icing tests if the non-dimensional parameters $K$, $Ac$, $We_t$ , $A$ and $B$ are matched to their reference values. The scaling requirements for splashing may be ‹automatically' satisfied, at least approximately, if the foregoing requirements are satisfied. Matching of $n_o$ and $T_\infty$ ensures matching of $A$ and $B$ in practice. Ice accretion shapes may be relatively insensitive to the value of freestream velocity, $V$, meaning that approximate matching of $We_t$ would be adequate. All of these conclusions are tentative and much additional experimental work is required in order to thoroughly assess them. Tests are required for a variety of body shapes, including airfoils at angle of attack, and for a wide range of icing conditions. Most testing to date has been done using droplet sizes corresponding to ‹classical' icing, that is $d$ ~ 20 μm; testing with the larger droplet sizes ($d$ ~ 200 μm) corresponding to supercooled large droplet (SLD) icing conditions is a particular need.

## 5 Conclusions

The discussion in this paper suggests the following conclusions.

Successful physical modelling of rime icing is possible at reduced scale and requires only that Reynolds-number effects be small and that the droplet inertia and accumulation parameters be matched to their reference values.

In glaze icing the flow behaviour of the liquid water on the surface of the ice accretion is very important both by virtue of its strong influence on the convective heat transfer rate and by virtue of determining where the runback water moves to and eventually freezes. Both surface tension and water viscosity have significant effects on this behaviour. Scaling requirements should take this into account. A Weber number based on water-film thickness has been proposed for this purpose and preliminary assessment suggests that it may be a valid scaling parameter.

The freestream air temperature in both full-scale and reduced-scale glaze icing tests should be equal to that in the reference case. If this requirement is not respected the distribution of freezing fraction will not match that in the reference case even if the freezing fraction at the stagnation point is matched.

Satisfactory results may be obtainable from reduced-scale glaze icing tests if the non-dimensional parameters $K$, $Ac$, $We_t$ , $A$ and $B$ are matched to their reference values. This is a very tentative conclusion and much additional experimental work is required in order to enable a thorough assessment of it.

## Acknowledgements

This work was partially supported by a Natural Sciences and Engineering Research Council research grant.

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