THE DETERMINATION OF ICE DEPOSITION ON SLENDER WINGS: AN EXPERIMENTAL TECHNIQUE AND SIMPLIFIED THEORY

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Abstract

A slender wing at incidence generates strong vortices above the upper surface that can entrain water droplets and create ice deposits on that upper, or leeward, surface. Such deposits cannot be as accurately reproduced in icing tunnels as the more usual deposits on the forward facing, or windward surfaces, and purely theoretical predictions would seem to require a very detailed knowledge of the flow around the wing to predict droplet trajectories.

A novel technique has been evolved that uses a water tunnel with small glass beads representing the supercooled water droplets. This technique can be shown to simulate full scale trajectories more accurately than those in conventional icing tunnels, and deposition rates have been deduced from study of bead impingement. There are, however, errors associated with the measurement of the position of impingement, and the technique becomes difficult to apply when icing rates are low. For these conditions a simplified theory has been evolved; the theory predicts the motion of droplets relative to the air in the vicinity of the wing, where the conditions near the wing are deduced from surface flow visualisation pictures obtained from conventional wind tunnel models. The theory gives good agreement with experiment and enables a much greater understanding of the effects of various parameters to be obtained.

Introduction

The deposition of ice is a hazard that any aircraft may encounter, and one that needs full investigation - particularly for civil aircraft. The atmospheric conditions under which icing may occur are fairly well established, and for conventional aircraft those parts most susceptible to icing are well defined. The supercooled water droplets normally impinge on the windward surfaces (e.g. wing leading edges), although ice build-up may occur on the leeward surfaces to a limited extent if the water runs back appreciably before freezing. Laboratory techniques have been developed to determine ice patterns utilising icing tunnels - wind tunnels run at temperatures below freezing, into which minute water droplets are introduced. To represent full scale conditions reasonably accurately, the droplets need to be very small unless, as can often be done, a part only of the aircraft is represented. Droplet size may not, however, be too critical for windward surfaces in that over-large droplets would result in a higher deposition than would be met full-scale. This would give a pessimistic prediction which, if designed to, would result in some safety margin.

New shapes tend to bring new problems, and this seems particularly so for aircraft with 'slender' or low aspect-ratio delta wings. The strong vortex pattern generated above such wings can bring droplets down towards the upper (leeward) surface, possibly leading to the build-up of substantial ice-ridges. This was dramatically demonstrated by Rush(1) for delta wings of unity aspect ratio and 4 ft chord. Large ice ridges were formed on the wing upper surface inboard of the vortices, and particularly at high incidence. One of his photographs for an incidence of 20°, is shown as Figure 1. It should be noted that with delta wings the whole wing needs to be tested as the deposition on any one part is very much affected by the strong vortices generated by the whole wing. Now for an accurate representation of full-scale conditions at this scale very small droplets should be used, and the use of over-large droplets may result in an optimistic picture with no indication as to how optimistic. Rush's results therefore need careful interpretation and extension, and this was in part done by Rush himself in tests on a 10 ft delta wing(2).

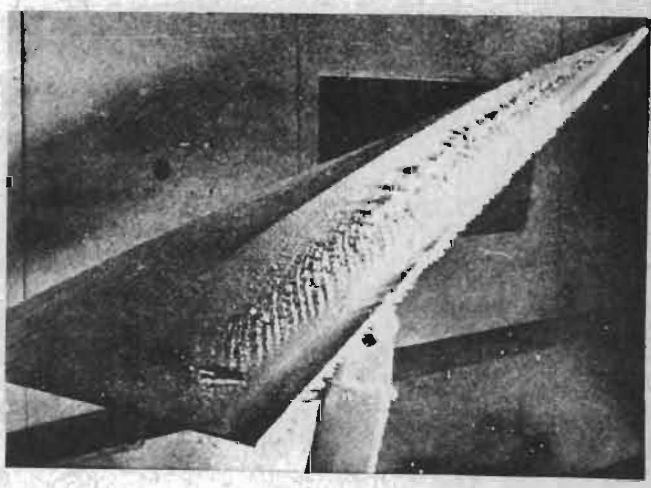

Figure 1. Typical Result of Icing Tunnel Test on Delta Wing(1).

Wind Speed	80 m.p.h.
Temperature	-5°C
Water	1.0 gm/m^3
Drops	20 micron
Incidence	20°

The implications of possible ice build-up on wing uppersurfaces are far-reaching: the position of the ice is critically dependent on the strength of the vortices or wing incidence, and hence protection for a range of realistic flight conditions suggests that large areas of the wing upper surface might need protective devices. The relevance to aircraft such as the BAC/Sud Aviation Concorde is obvious, and has attracted the attention of various people using various techniques and facilities.

This paper describes one novel experimental technique that was developed for this problem, and a simplified theory that was devised to fill the substantial gaps left by the experimental technique. In order to appreciate the advantages and disadvantages of both experimental and theoretical approaches, some of the background to icing work and factors affecting droplet trajectory are first discussed.

Laboratory Representation of Full-Scale Icing Conditions

The small water droplets that create ice deposits on aircraft are of the order of 20 microns in diameter. Their rate of fall under gravity is very small, and in a laboratory representation of icing the effect of gravity is usually ignored. The deposits occur when the flow is curved, the droplets being thrown out by centrifugal force. Typically for an aircraft flying at 500 ft/s and with a local radius of curvature of the flow of, say, 5 ft the acceleration on a droplet following the flow might be about 300 times gravitational acceleration. The force necessary to give this acceleration is aerodynamic and comes from a relative cross-flow velocity. For similar trajectories the ratio of cross-flow velocity to free stream velocity must be the same for model and full-scale. If conditions were such that the drag characteristics of the droplets could be represented by a constant drag coefficient, then the condition for similarity can be written as:-

$$\left(\frac{d_m}{d_f}\right)\left(\frac{l_f}{l_m}\right)\left(\frac{\rho_f}{\rho_m}\right)\left(\frac{\rho_w - \rho_m}{\rho_w - \rho_f}\right) = 1 \qquad (1)$$

where suffix m refers to model conditions and f to full-scale conditions,

d = droplet diameter
l = length
ρ = free stream density
and ρw = droplet density.

It is convenient for later work to express this in the alternative form

$$\left(\frac{d_m}{d_f}\right)\left(\frac{l_f}{l_m}\right)\left(\frac{\sigma_m - 1}{\sigma_f - 1}\right) = 1 \qquad (2)$$

where $\sigma_m = \rho_w/\rho_m$ and $\sigma_f = \rho_w/\rho_f$.

Now the assumption of constant drag coefficient is most unrealistic for small droplets. Reynolds numbers in the range 1 - 100 are perhaps to be expected as against Reynolds numbers greater than 1000 for comparatively constant C_D - Figure 2 shows the variation of C_D with Reynolds number. A more reasonable assumption might be that appropriate to Stoke's Flow - i.e. that C_D varies inversely as Reynolds number. The condition for similarity then becomes:-

$$\left(\frac{V_m}{V_f}\right)\left(\frac{d_m}{d_f}\right)^2\left(\frac{l_f}{l_m}\right)\left(\frac{\nu_f}{\nu_m}\right)\left(\frac{\sigma_m-1}{\sigma_f-1}\right) = 1 \qquad (3)$$

where V = free stream velocity
and ν = kinematic viscosity.

A more complete background to these equations is given elsewhere by the author[3] and Avison[4].

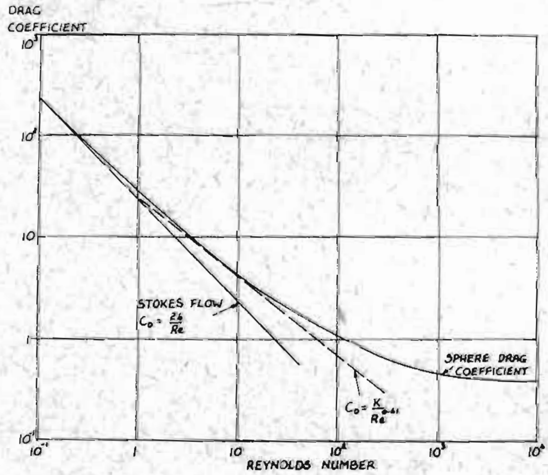

Figure 2. Sphere Drag Coefficient ~ Reynolds Number.

Intermediate Reynolds numbers may be catered for by assuming drag coefficient variations of the form[4]:-

$$C_D = \frac{K}{Re^n} \qquad (4)$$

where K is a constant, Re is Reynolds number, and n is some power less than 1. The condition for similarity then becomes:-

$$\left(\frac{V_m}{V_f}\right)^n\left(\frac{d_m}{d_f}\right)^{1+n}\left(\frac{l_f}{l_m}\right)\left(\frac{\nu_f}{\nu_m}\right)\left(\frac{\sigma_m-1}{\sigma_f-1}\right) = 1. \qquad (5)$$

Rush[1] uses a formula virtually equivalent to using n = 0.61, while Avison[4] in his work justifies a value of n = 0.8.

It is apparent that in principle the condition for similarity will be different for different model sizes, test velocities, and droplet size, and in fact for one droplet at different parts of its trajectory.

The errors associated with assuming a constant similarity law are, however, in many cases only of the same order of magnitude as errors stemming from the test technique itself, although this point is discussed later.

Now the form of the similarity laws show that, for a particular model, simulation of full-scale may be achieved with various combinations of droplet size and tunnel velocity. Alternatively a model test may be said to represent at full scale velocity and droplet size a particular size of aircraft, and this has been used[3] to aid in the interpretation of Rush's results[1]. One of the wings tested by Rush was a plane delta wing, and for such a wing the flow pattern is substantially 'conical' in form - i.e. the conditions (of velocity and pressure) at various longitudinal positions are similar and this might also be expected to be largely true for the second wing tested. If individual model tests are then said to represent a wing of a particular length, or that length from the apex of the full-size wing, then pictures such as that for 15° incidence, shown in Figure 3, emerge. The small lines indicate the distance from the apex represented by individual tests. The main features of the ice pattern are shown in Figure 3, and this perhaps helps to put the results in perspective - the major ice deposit is inboard of the vortices and over about the first third of the length of the wing, except for the apex, where all droplets are thrown out by the high curvature, leaving the extreme apex clear of ice.

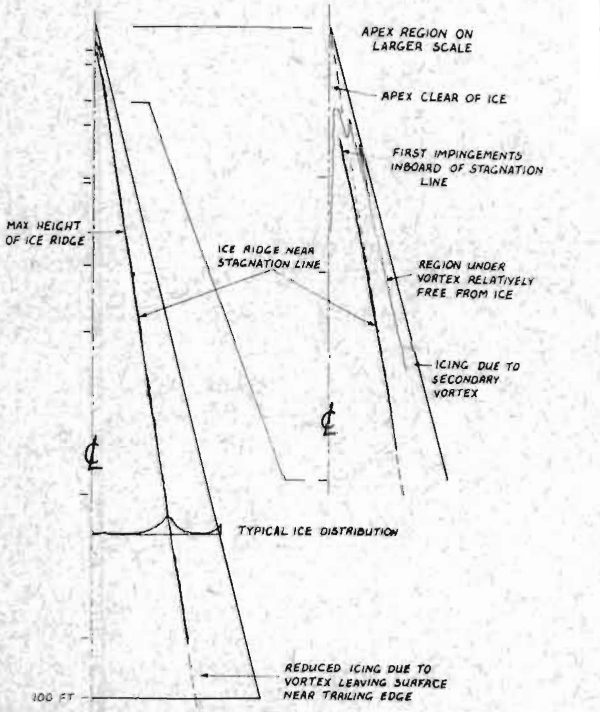

Figure 3. Icing Pattern on Wing Upper Surface - 15° incidence

It is apparent that fully representative icing conditions are difficult to achieve in the laboratory; these are in part the temperature conditions to get the correct ice form and in part the conditions necessary to reproduce the correct droplet trajectories and hence impingement rates. At reasonable drop size it requires either very large models (implying large wind tunnels that can be used for icing tests), or models of more modest size operated at low speeds, where Reynolds number effects may become important and the fall of droplets under gravity significant. Some alternatives can, however, be deduced if the trajectories only are simulated, and no attempt is made to obtain directly the ice build-ups. This could well be reasonable for the large expanses of upper surface on a large slender-winged aircraft, where the distance of run-back before freezing is small compared with other distances.

Consider, for example, equation (3), but where the media used are not necessarily air and water. With wind tunnels solid particles might be considered instead of water droplets, and water tunnels could provide a large change in stream density. The possibilities are best illustrated by the nomogram shown in Figure 4. All parameters are shown as ratios of model to full scale - thus full scale conditions are represented by unity on each scale. For convenience the dynamic viscosity, μ, is used rather than the kinematic viscosity. Icing tunnels - using the same media as full scale, but covering a different speed range at different scale - are shown, and it can be seen that droplets should in general be below the 20 micron full scale size. Larger wind tunnels would be advantageous, as might be the use of powders instead of water droplets. Also shown are lines representing the use of water and glycerine tunnels. The latter is rather unrealistic, but would nominally represent full scale if lead shot of about 1 mm diameter were used. More realistically, water tunnels using the small glass beads that are readily available down to 50 micron diameter might be used. A comparison of typical Reynolds numbers (Table 1) shows that while model conditions are not as well represented in water tunnels, 'droplet' conditions seem rather better represented.

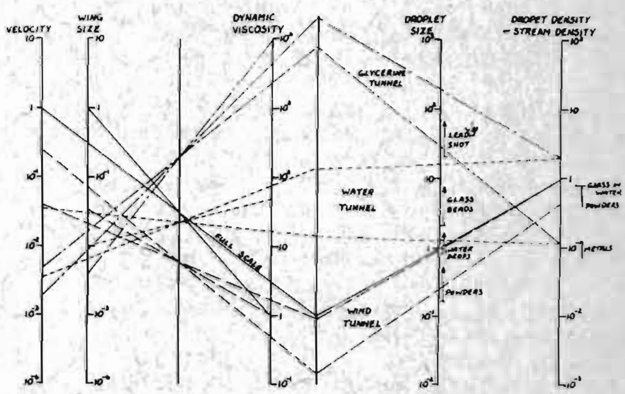

Figure 4. Comparison of Particle Sizes Required for Similar Particle Paths Using Different Media.

TABLE 1

Typical Reynolds Numbers

	Full Scale	Icing Tunnel	Water Tunnel
Model	$3x10^8$	10^6	10^5
Droplet	20	2	10

Water tunnels would seem to offer other advantages - notably the ability to determine more accurately the size of particle used, and to test using a much smaller size range. There are, however, a number of disadvantages, including the virtual impossibility of arranging for the particles to stick on impact, and the resulting difficulties in then having to track the particles. The idea seemed, however, promising, and Ministry support was obtained for the work of Avison(4) and Hale(5).

Water Tunnel Tests

A water tunnel was built at the University of Bristol for use in icing studies. The build of the tunnel and the development of a technique are described by Avison(4); the main features of the tunnel are the large settling chamber with smoothing devices set below the 1 ft x 1 ft octagonal working section, with 6 in diameter return circuit and centrifugal pump. A vertical working section was chosen to minimise the effect of gravity on the trajectories and reduce access time by minimising the volume of water above the working section. Ice deposits were deduced assuming that the 'droplets' would freeze on impact, and a technique was developed that would give the rate of impact at various points. The technique was to introduce a bead/water mixture via a hypodermic tube aligned with the stream direction, to note the impingement point of the beads, and then to traverse the tube relative to the model, again recording the impingement points. The impact points corresponding, say, to four injection points on the corners of a square would define an area on the wing within which all droplets full scale, passing through the equivalent square full scale, would impact; this would then give a rate of icing for that area.

The impact points were obtained by photographing the wing and bead trace through mirrors, such that simultaneous side and plan views were obtained, and a typical photograph is shown as Figure 5. The recorded impact points for an incidence of 15°, tunnel velocity of 1.2 ft/s and a bead size of 110 microns is shown in Figure 6(a) and the deduced levels of icing in Figure 6(b). Note that in Figure 6(a) the shaded area represents the cross-section through the upstream flow that includes all the beads that impinge on the upper surface of the wing; droplets outside this area full scale would miss the wing, and the total ice catch on the upper surface would correspond to the total droplets passing through this area. The contours in Figure 6(b) show percentages of full catch rate, where full catch is the depth of ice that would be deposited on a surface normal to the stream with no droplet deflection by the stream.

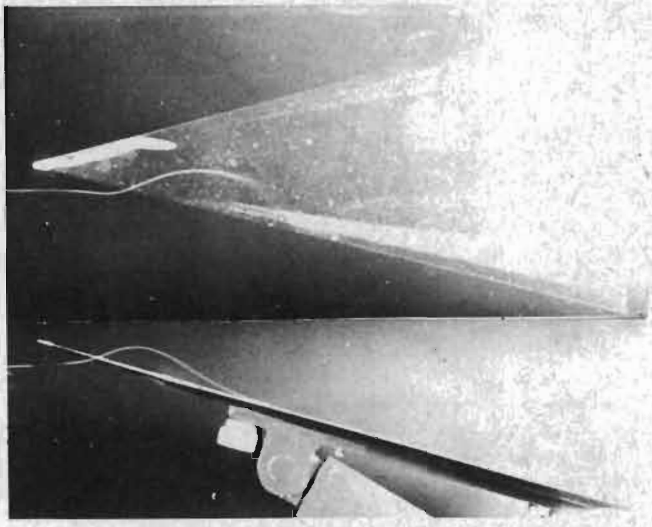

Figure 5. Typical Photograph of Bead Trace(4).

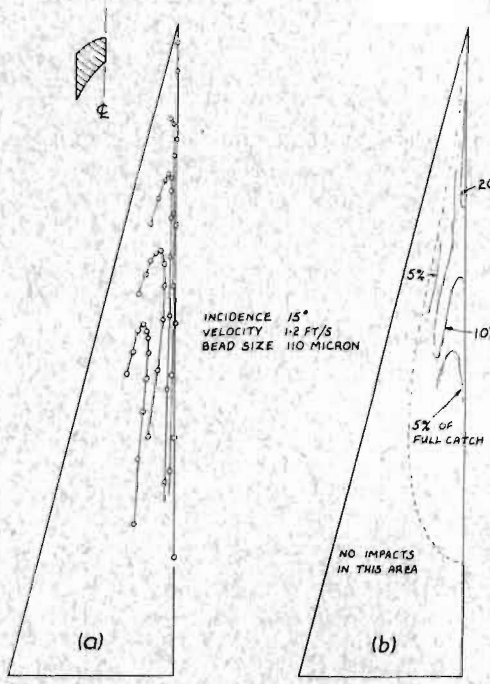

Figure 6. Typical Results for Delta Wing in Water Tunnel(4)
(a) Impact Points
(b) Deduced Icing Levels

The results obtained by Avison are impressive and are in line with Rush's work, showing an ice ridge being formed inboard of the vortices. They seem to indicate that icing levels on the upper surfaces of full scale slender wings are unlikely to be serious, but these results are not conclusive for various reasons:-

> Full similarity with full-scale required either a higher tunnel velocity or larger bead size. Tunnel velocity was limited by the flow around the injection hypodermic - larger velocities caused instabilities which affected the bead stream. Larger bead sizes would have required larger diameter hypodermic tubing that would have been limited to lower tunnel speeds.
>
> Some unsteadiness in the tunnel flow led to some uncertainty in impact position.
>
> The low 'icing levels' encountered over most of the wing meant that the impact angle was low, hence the precise impact point was difficult to measure. The 'icing levels' would be even less at a more realistic (lower) incidence.

Conclusions from Avison's work were that regions likely to suffer heavy icing could be determined using a water tunnel technique, but that these regions would probably be comparatively small in extent, and for the larger regions of low icing the technique had definite limitations. The research was, however, continued by Hale[5] using a modified technique, to extend results on the delta wing down to a more realistic incidence of 10^o, and to obtain results on a Concorde model. A modified technique was used for two main reasons. Firstly, larger beads and/or higher tunnel velocities were required in order to represent more accurately full scale conditions, and Avison's technique had limitations in these directions. Secondly, the smoothing devices in the tunnel were proving troublesome, with contamination from the tunnel circuit creating some blocking of the gauzes, and a technique less sensitive to smoothness of flow was desirable. Now for other reasons a simplified theory for the prediction of low icing levels was being evolved (described later), and the background to this theory suggested that local ice catch could be adequately determined on the upper surface simply from the angle of impact. The technique tried by Hale was therefore to introduce a cloud of beads into the upstream flow and record angles of impact, where an impact angle of, say, 0.1 radians would imply an icing level of 0.1 x full catch. The impact angles were recorded by photographing the wing in side view with only a narrow spanwise section of the wing illuminated. The angles were taken direct from the photographs, with corrections made for any substantial lateral velocity. The photograph for the plane delta wing shown as Figure 7 is an enlargement showing only part of the length of the wing, but even so it is apparent that measurement of angle requires a finite length of trace which, because of the curvature of the flow, is always pessimistic, usually to the extent of at least 2 degrees or 4 to 5% of full catch.

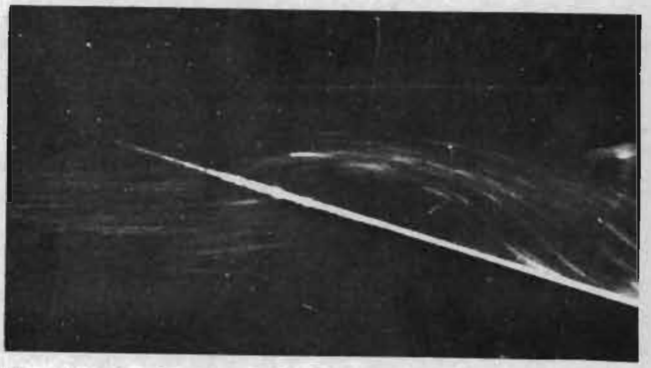

Figure 7. Typical Photograph of Bead Traces in Narrow Illuminated Plane[5].

Examples of icing levels obtained from Hale's results are shown in Figure 8 where interpretation has used the simplified theory described later. Figure 8(a) relates to the same conditions as Figure 6. The levels of icing predicted by Hale are greater than those of Avison although the differences can largely be accounted for by experimental error. The patterns are similar, and the boundary forward of which no icing is predicted is virtually the same. Figure 8(b) shows the case for the same bead size and tunnel speed, but with incidence reduced to 10^o. Impacts were rare and relatively few were recorded, and hence the contour lines are tentative, but the large difference between the 15^o and 10^o patterns is very noticeable.

The second model tested by Hale was of the Concorde, the 1/144th scale model (shown in Figure 9) being constructed by the British Aircraft Corporation Ltd. Tests were performed for conditions representative of full scale, mainly at 10^o incidence. The results of one series of tests are shown in Fig. 10. The more complex wing shape obviously gives rise to a more complex icing picture.

Hale compares the Concorde model results with icing results obtained in France in a large wind tunnel, and one photograph from these results (velocity 150 ft/s, 20 micron droplets, 12^o incidence) is shown as Figure 11. The French results do not in fact record actual thicknesses of ice but do demonstrate conclusively that upper surface icing is not a problem with Concorde. Comparison with Hale's results reveals some interesting areas of agreement and disagreement. Both feature the thickest ice deposits inboard of the vortices, some icing in the wing body junction and no icing near the wing apex. The French results do, however, show some icing under the vortices and near the wing leading edges, whereas no particle impingments were noted in this region by Hale. The levels of icing are also different, but the higher level predicted by Hale is due to the technique leading to an overestimate rather than underestimate.

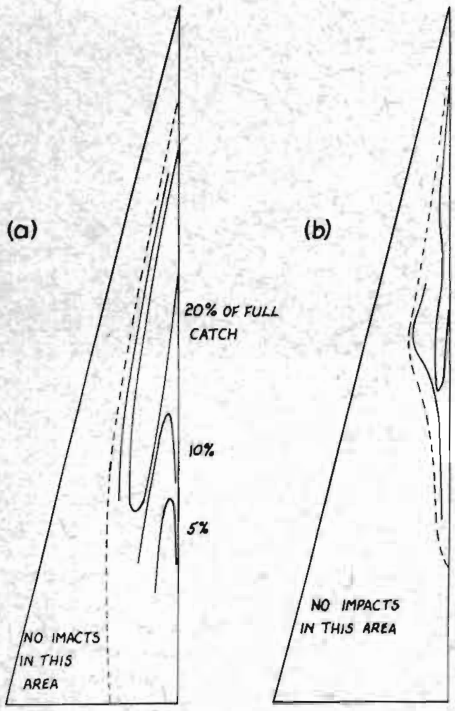

Figure 8. Typical Results from Individual Impacts in Water Tunnel[5].
(a) 15° Incidence
(b) 10° Incidence

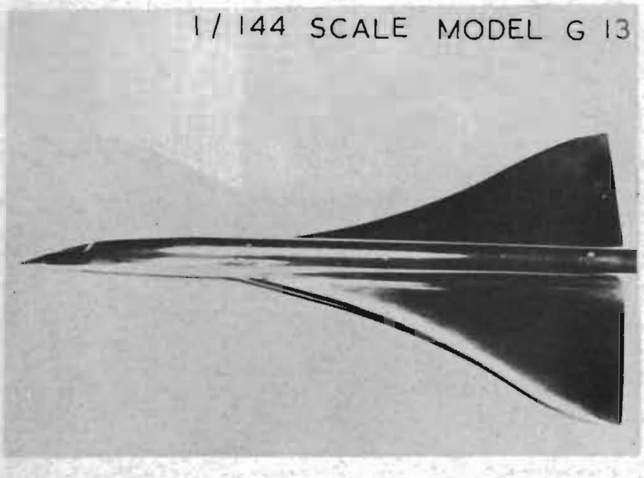

Figure 9. Concorde Model used for Water Tunnel Tests.

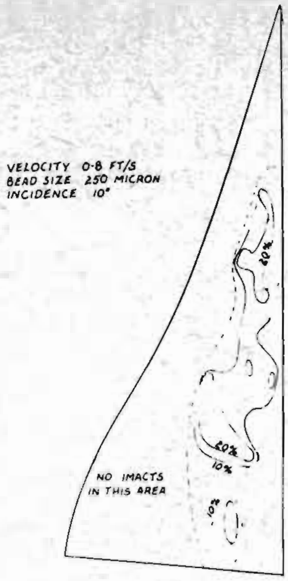

Figure 10. Typical Results for Concorde Model in Water Tunnel.

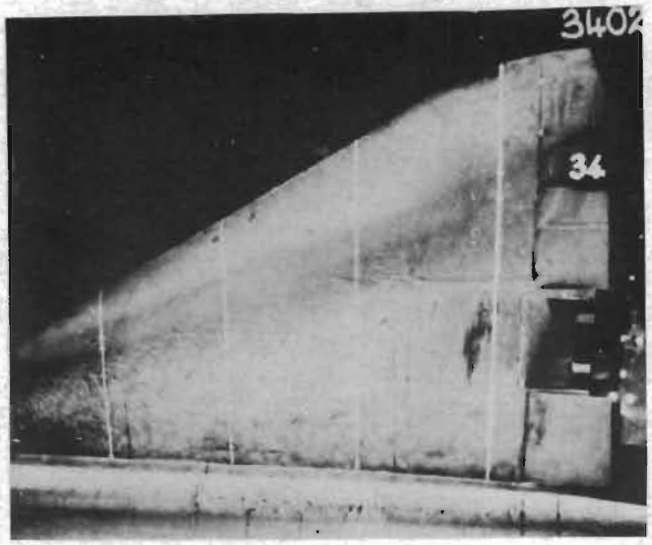

Figure 11. Concorde - Icing Pattern from Large Scale Tunnel Tests.

A Simplified Theory

The underlying assumption behind the use of a water tunnel for the prediction of ice deposition was that the representation of the correct droplet trajectory is the single most important aspect in icing studies. The same assumption suggests that a completely theoretical prediction might be made, where, if a flow pattern is known, the trajectories of droplets of various size can be computed by some step-by-step procedure. This technique has been used for leading-edge icing[6], icing on cylinders[7] and in certain other cases, but it does require a full knowledge of the flow pattern, and for this pattern to be expressable in convenient terms. The flow past a simple, plane, delta wing is, however, complex; the flow separates from the leading edges, forms strong vortices above the wing, and certainly cannot be described accurately in mathematical terms. The more complex curved, cambered, twisted wing-body combinations such as Concorde generate even more complex flow patterns, and immediate reaction is to assume that theoretical prediction of ice deposition is completely impossible. The results of the water and icing tunnel tests suggest, however, that icing levels are probably low, and that certain important simplifications can be made. These lead to a new approach that uses a computational procedure based on results from conventional wind tunnels.

Let us consider first conditions close to the wing surface, and assume that the droplets are distributed in the same way as they are in the undisturbed stream, i.e. the number of droplets per unit volume is the same as for the free stream. Let us assume further that the droplet velocity parallel to the surface is substantially that of the flow adjacent to the surface. A low icing level would correspond to the droplets being spread out over a large area of surface, a high icing level to the droplets being spread over a small area (see Figure 12). The low icing levels observed over the larger areas of the slender wings therefore imply a shallow angle between droplet trajectory and surface (about 1° for 2% of full catch) - or a small velocity (compared with stream velocity) perpendicular to the surface and hence to the local flow. But originally the droplet velocity, and the free stream were in some other direction. This means that both have changed direction by similar amounts, or that the final small difference between the two is unlikely to be very dependent on conditions a large distance from impact, but very dependent on conditions near impact. This suggested that predictions might be made based only on local conditions, and to this end droplet motions were computed for a one-dimensional flow and then related to two and three-dimensional flows.

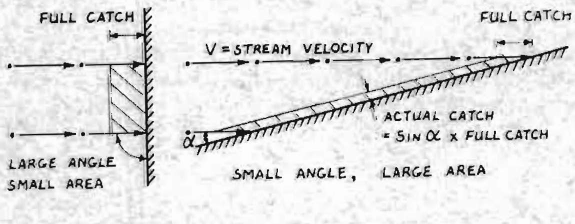

Figure 12. Relation between Angle of Impact and Level of Icing.

A one-dimensional step-by-step computation requires only a statement of the forces acting on a droplet and knowledge of the droplet mass. The variation of drag coefficient, C_D, with Reynolds number was expressed as

$$C_D = \frac{24}{Re} + \frac{5}{Re^{(1/2)}} + 0.4. \qquad (6)$$

This is a fairly good approximation, and comparison with the values used by Bergrun[6] is shown in Figure 13. Impact velocities were computed assuming various values for velocity gradient towards the surface, with zero velocity at the surface. Other parameters varied were droplet size, initial position and velocity for the droplet relative to the air, and an accelerating force to represent flow over a curved surface (or a gravity component). Figure 14 presents the impact velocities for 20 micron droplets in air at sea level: the large effect of velocity gradient can be seen, and the relatively small effect of initial conditions (or conditions distant from the surface) for low impact velocities (equivalent to low icing levels). Small curvature has very small effect under conditions equivalent to high icing levels - a somewhat larger effect at low icing levels. In all cases the effect of curvature with a convex surface would be to reduce icing; hence if a pessimistic view only is required the effect of curvature might be ignored.

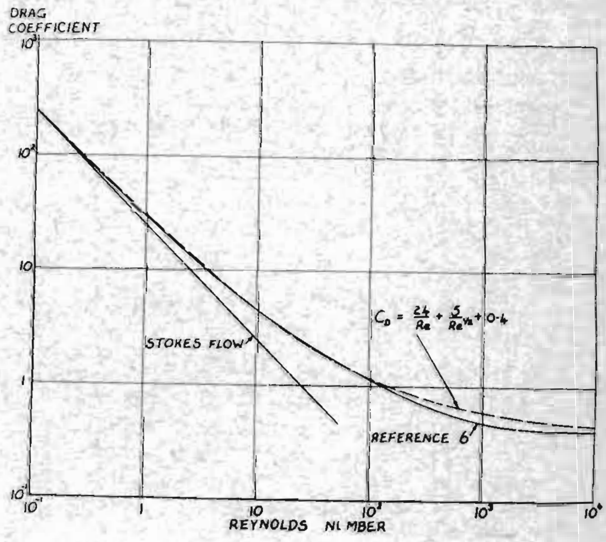

Figure 13. Comparison of Sphere Drag Coefficients ~ Reynolds Number.

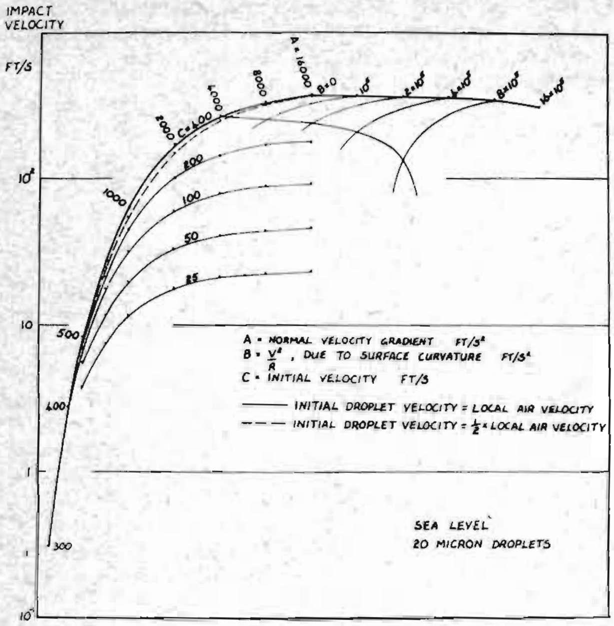

Figure 14. Impact Velocities for 20 Micron Droplets.

Droplet trajectories in two dimensions can be deduced from the one-dimensional if forces in the two directions can be considered independent. This would be so for Stoke's Flow at low Reynolds number where $C_D = \frac{24}{Re} = \frac{A}{V}$ for a particular droplet where A is some constant and V the velocity. If the component velocities in the x and y directions are u and v, then the force in the x direction would be

$$F_x = \frac{1}{2}\,\rho V^2 .\ C_D .\ \frac{u}{V}$$

$$= \frac{1}{2}\,\rho V^2 .\ \frac{A}{V}\ .\ \frac{u}{V} = \frac{1}{2}\,\rho A u \qquad (7)$$

independent of v, and similarly for the force in the y direction. Now for low icing levels the Reynolds numbers would in fact be approaching those where Stoke's Flow applies, and for any higher Reynolds numbers the resulting forces in two dimensions would be slightly greater than that implied by the above assumptions, and hence result in lower velocities and icing rates. The velocity component parallel to the surface and the curvature of the surface together determine the centrifugal acceleration on the droplets.

The one-dimensional droplet impacts can therefore be related to real flows if local conditions (flow velocity, velocity gradient, etc.) are taken. This approach has been applied to several cases, but some comments about the initial assumptions should first be made.

It was assumed that the number of droplets per unit volume was as for the free stream. Certainly at the extremes of particle size this would be the case: very small droplets would flow with the stream, having virtually no velocity relative to the stream, whilst very large drops would maintain free stream velocity throughout the flow, being virtually unaffected by the changing flow directions. Intermediate cases, however, need some justification. Consider droplets in Stoke's Flow in a stream of velocity V turning with a radius of curvature r. The droplet velocity relative to the stream, v, would be proportional to the acceleration $\frac{V^2}{r}$, or equal to $K.\frac{V^2}{r}$, where K is some constant. The distance thrown out in turning say, one radian would be $vr = KV^2$, i.e. independent of radius, or the spacing between droplets in the radial direction remains unaltered. This would not necessarily be the case for higher Reynolds number where Stoke's Flow is no longer a reasonable assumption, or for 'shadow' regions, where drops are cut off by some solid edge, e.g. a sharp wing leading edge.

It was also assumed that the droplet velocity parallel to the surface was substantially that of the flow adjacent to the surface. Certainly at the surface the relative velocity parallel to the surface would be less than that normal to the surface when the velocity gradient along the surface was less than that normal to the surface. This would be the case on the upper surface of delta wings. For low icing levels this then means that the relative velocity parallel to the surface is small compared with the local stream velocity, or the droplet velocity is substantially that of the flow adjacent to the surface.

Application of Theory to Various Cases

The results of applying the theory to three cases is described. Occasionally the required velocity gradients may be easily determined, as in the first case described, although this is most likely for configurations where the method is rather inaccurate. In other cases the velocity gradients would have to be measured directly, or deduced from other information.

Circular Cylinder

Ice deposition on leading edges is closely related to that on circular cylinders, and the latter has been investigated in detail, notably by Brun and Mergler(7). They present, in a non-dimensional form, computed depositions for various stream velocities, droplet size, Reynolds number, and cylinder size. Some typical results are presented in Figure 15 with results from the simplified theory superimposed where the velocity gradients have been computed from potential flow. The maximum thickness of icing is, surprisingly, of the right order. The extent around the cylinder is, however, underestimated, due probably to the fact that over the cylinder conditions change rapidly in the stream direction.

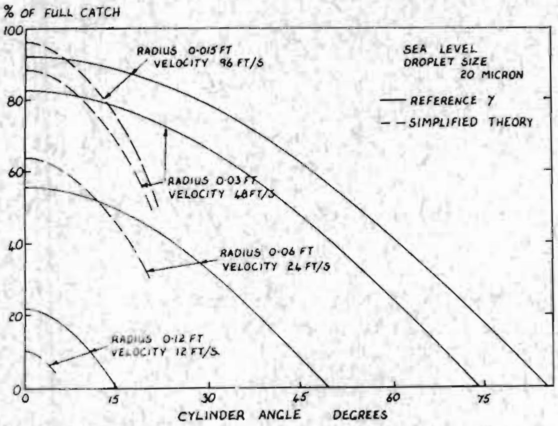

Figure 15. Comparison of Ice Predictions for Circular Cylinders.

Delta Wing of Unity Aspect Ratio

The flow over the delta wing cannot be conveniently expressed in mathematical form, and the required velocity gradients have to be obtained from experiments. A four foot long model was mounted in a wind tunnel at an incidence of 10 degrees, and two methods were used to extract velocity gradient. The first model used a yawmeter, which was traversed laterally, longitudinally, and vertically. The second method aimed at using the type of information that might already be available, vis. a surface flow visualisation picture.

Consider the rectangular-section stream-tube shown in Figure 16. As the width increases so the depth decreases. Hence for constant velocity, knowledge of the divergence of streamlines in a horizontal plane implies knowledge of the convergence of streamlines in a vertical plane. If the velocity is not constant, but the variation is known (e.g. from pressure measurements), then vertical variation can still be inferred. Now for the plane delta wing a surface-flow visualisation picture was obtained. For simplicity conical flow was assumed, but the derived velocity gradients agreed well with those obtained from the yawmeter, and are shown in Figure 17. A contour representation of these velocity gradients is shown in Figure 18(a) where the increase in gradient towards the apex can be seen. The 'data sheets' of which Figure 14 is an example, were then used to give icing levels for different models and full-scale conditions, in particular for various droplet sizes. A typical result is shown in Figure 18(b), where to a first approximation the local velocity has been assumed to be equal to free stream velocity. Comparison with the results of Rush, Avison and Hale shows a similar ice ridge - although with no clear region near the apex and without the movement of the ice-ridge towards the centre-line near the apex. As with Avison and Hale no ice build-up is predicted between the vortex and the leading-edge.

Further results, and some implications, are discussed later.

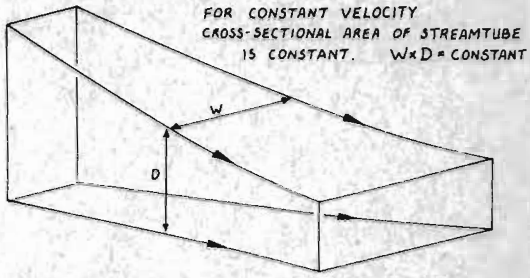

Figure 16. Relation Between Vertical and Horizontal Dimensions of Streamtube.

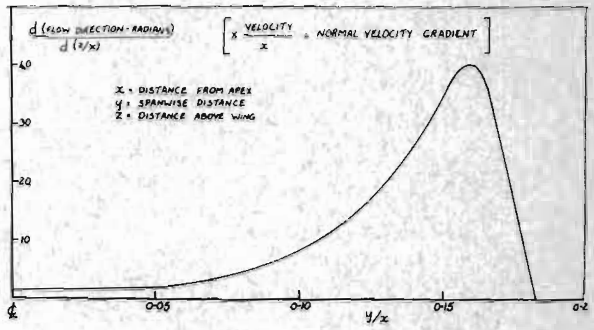

Figure 17. Normal Velocity Gradients for Plane Delta Wing at 10° Incidence.

Concorde Model

The third configuration to which the method was applied was that of the BAC/Sud Aviation Concorde, (although a detailed examination of Concorde upper surface icing might now be considered of only academic interest, as the French tests have now demonstrated conclusively that no problem exists). In this case the shape is complex, no assumption of conical flow is possible, and a full yawmeter traverse would have been difficult. Good surface-flow visualisation pictures were however available, and one for an incidence of 10.4 degrees is shown as Figure 19. Measurements of surface-flow direction were made for seven longitudinal positions; and some of these are shown in Figure 20. Contours of equal velocity gradient were then obtained, and icing levels predicted using the 'data sheets' as before. Figure 21 shows the predicted limit of icing and the 1% and 10% contours for two droplet sizes, for conditions comparable to those of Figure 11. It should be noted that in this case some icing is shown under the vortex although the level of icing is such as to be hardly noticeable. Three ice 'ridges' are shown, the main, broader, one inboard of the primary vortices, a secondary one connected with the secondary vortex near the leading edge, and a third narrow ridge between the first two. There is also some deposit in the wing-fuselage junction towards the apex, and some suggestion that the apex itself might be clear of ice. All these features are evident in the photographs of the French tests.

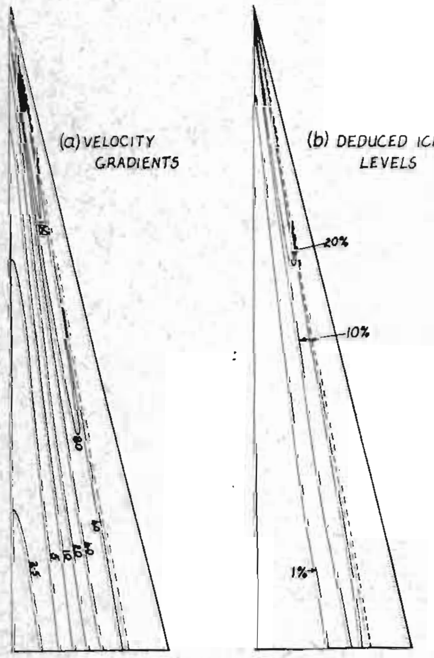

Figure 18. Typical Theoretical Results for Delta Wing.

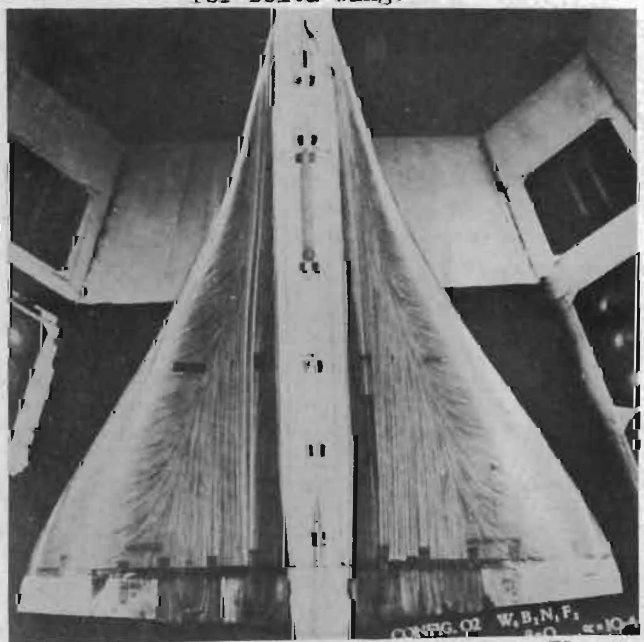

Figure 19. Concorde - Upper Surface Flow Visualisation Picture - 10.4° Incidence.

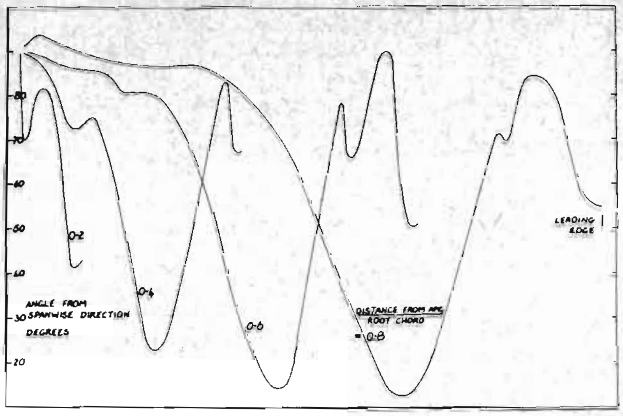

Figure 20. Typical Variations of Flow Direction with Position - Concorde.

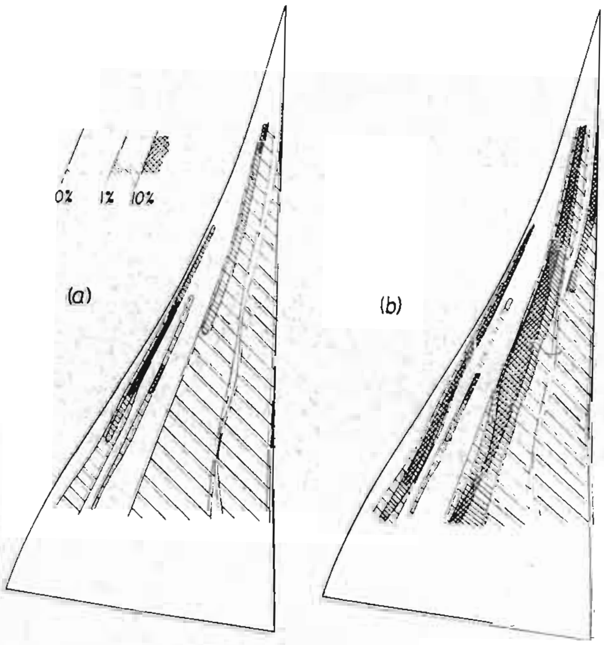

Figure 21. Typical Theoretical Results for Concorde Wing.
(a) 0%, 1% and 10% contours, 20 micron
(b) 0%, 1% and 10% contours, 40 micron.

Scope of the Simplified Theory

The theoretical results obtained for the plane delta and Concorde wings are encouraging, being in broad agreement with results obtained from special facilities. By themselves the theoretical results would not be conclusive in showing where ice protection might or might not be required. They do, however, lead to a better understanding of icing on complex configurations, and perhaps show how some errors can arise in other techniques.

Some results for the plane delta wing are presented in an alternative form in Figure 22. The results relate to conditions 50 ft from the apex of a delta wing flying at 400 ft/s at sea level, where positions closer to the apex would experience more severe icing, those further away less severe. Figure 22(a) gives the percentage of full catch predicted for droplets of 40, 80, 160 and 320 microns, plotted against spanwise position. Following earlier arguments, the lower levels of icing should be reliable, but the higher are only to be taken as an indication that severe icing would be expected. Figure 22(b) presents the same information as boundaries of 1%, 10% and 30% of full catch. Somewhat arbitrarily, icing below 1% is termed negligible, from 1% to 10% noticeable, 10% to 30% significant, and above 30% severe.

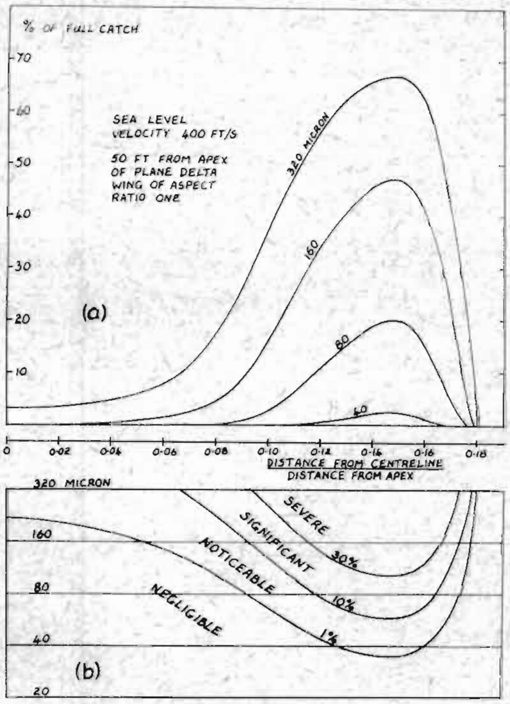

Figure 22. Effect of Droplet Size on Ice Deposition.

In this terminology, the 40 micron droplets lead only to noticeable icing over a small portion of the wing, the 80 micron to significant icing over a small portion and noticeable over about twice the area, while the 160 micron droplets would lead to severe icing over a small portion and at least noticeable over about half the wing. This does therefore show that the level of icing can be quite sensitive to droplet size, and that on occasion a doubling of droplet size can possibly lead to a tenfold increase in ice deposition.

Let us consider now a model representation of full scale. Firstly a mean droplet size of 20 micron relates to some distribution of size, typically:-

Droplet size (micron)	5	11	17	22	28	33	39	44
% by weight	3	8	20	30	20	10	5	4

The 9% by weight of droplets near 40 micron might contribute more to upper surface icing than the other 90%. A correct distribution of size at model scale is therefore important, unless the effect of the various size fractions can be separately assessed. Secondly, the range of droplet Reynolds numbers: the 40 micron droplet in areas of, say, less than 1% full catch would have a Reynolds number less than one fourtieth that of the 80 micron droplet at 20% full catch. In addition the ratio between full scale and model Reynolds numbers may be up to a factor of ten. The overall factor for droplet Reynolds numbers may therefore be around 400. Now a straight line approximation to drag coefficient (see Figure 2), as assumed in all the scaling laws, will over this range of Reynolds number lead to error in scaled droplet size of up to 2. This suggests either that different scaling laws are required for different droplet fractions, or that some help in the interpretation of icing tests is required, especially if any uncertainty exists about the actual droplet sizes generated in a particular test. The Simplified Theory seems suited to give this help.

It should be noted that this sensitivity to droplet size, and the possibility of error in scaling is almost certainly the reason for the differences in the results of the various tests.

It should also be noted that while icing tunnel tests have shown that there is no upper surface icing problem for Concorde, this will not necessarily be the case for other slender aircraft of different size with a different upper surface flow.

Concluding Remarks

The possibility of ice deposition is a hazard that has to be fully investigated, particularly for civil aircraft. Current practice is adequate for the normal type of icing on the windward surfaces of conventional aircraft. The slender delta wings of less conventional aircraft can, however, collect ice on their upper, leeward, surfaces. Correct simulation of this icing is difficult, as the full aircraft must always be modelled. The build-up is sensitive to droplet size, and droplets that are too large may lead to misleading, sometimes optimistic, results. An experimental technique that uses glass beads in water is shown to be a possible alternative to the use of an icing tunnel but is susceptible to error when icing levels are low. More particularly, a simplified theoretical approach, deducing icing levels from wind tunnel data that would normally be available for other purposes, is presented. The theory is particularly useful in areas of low icing, and is in many ways complementary to the use of test facilities. It seems useful as an aid to interpretation, and as a means of achieving a greater understanding of the method of deposition. For new configurations it could give a good indication of potential icing problems, and possibly show some saving in time and expense.

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D I S C U S S I O N

B.G. Newman (McGill University, Montreal, Canada):
1. It seems to me that your technique for analysing flow visualisation pictures might also be useful for determining snow deposit and in the development of efficient snow fences. Can you comment on this suggestion?
2. Can the effect of skin friction be added to the theory? The oil drop technique developed by Meyer gives some indication of skin friction as well as flow direction.

J.W. Flower: 1. I have certainly not as yet given any consideration to snow fences, but my first reaction is to say yes, the technique might well be useful, although certain of the basic data might have to be presented in a somewhat different way.
2. I would think not. The best that can be done is to try and demonstrate that boundary layer effects generally are small and that to ignore them gives rise to errors no larger than those inherent in icing tests at Reynolds numbers noticeably different from full scale.