more slats (lifting surfaces) could be added to a particular fin to attain a desired normal force. Complex grid-like inner fin arrangements provided increases in normal force over open geometries and a comparatively larger axial force, and may be suited to applications requiring high structural integrity, well-behaved lift characteristics, and high drag.

Results presented in Figs. 1 and 2 indicate typical characteristics of grid-fin configurations. For both cases, the square and the rectangular configurations, there is a significant increase in normal force at higher angles of attack as additional slats are added. As expected, the double-slat fin produced larger normal forces. However, the single slat and cross fins, at least over the linear range, generated approximately the same normal forces even though the cross fin had a larger lifting surface area. The 7.62×15.24-cm grid fins exhibited similar trends. Thus, the cross-configuration fin of both sizes produce roughly the same normal force as the single slat fin, and could be tailored to produce a "desired" axial force as well as a desired normal force by designing for a certain number of effective horizontal slats. These same fins, because of their low hinge actuator requirements, may be efficient as lifting surfaces when flown in the normal transverse direction but may also be used as "drag" brakes if turned to a horizontal position.

The internal arrangement of a particular grid fin appears to also influence the stall point. Generally, the more complex an internal arrangement is, the higher the stall angle of attack. As a matter of fact, for the more complex geometries, the cross and double, the stall does not occur below 18-deg angle of attack. Hinge moments (CMH) for all cases are very small and root-chord bending moments (CMRCBM) exhibit properties similar to the normal-force behavior.

Agreement between theory and experimental data was quite good for all configurations with typical results shown in Fig. 2. It is interesting to note that the slope of the C_N-alpha curve tends to increase up to approximately 8.0 deg to such an extent that the theory underpredicts the data slightly in this region, which is atypical for vortex-lattice formulations. In this case, it appears that the upper "slat" stalls before the lower slat, which produces a distinct "bump" in the aerodynamic coefficients between 4.0 and 10.0-deg angle of attack. Past 10–12 deg, there seems to be a second "stall," perhaps of the bottom or cross members. Results were very repeatable and both multiple slats and cross-slat configurations exhibited the same trends.

Tests were not run at angles of attack higher than 18 deg, so that in some cases the actual stall of the fin was never observed. Tuff tests did, however, show that the upper fin members do indeed stall with separated (reverse) flow on the top side of the upper slat. These same tests also showed that bottom slats did not stall at least up to 18-deg angle of attack. For all configurations, the hinge moments were very small and increased only slightly with angle of attack. In some cases, the slight increase was followed by a decrease in CMH, probably as a result of secondary fin-element stall. Although one cannot be certain, it appears that most of the hinge-moment contribution comes from the fact that at higher angles of attack, the lower slats (unstalled) normal-force contribution is in front of the hinge line, while the upper (stalled) normal-force contribution is behind the hinge line. Very little of the hinge moment comes from the fact that on each fin element the center of pressure is in front ($\approx$quarter-chord) of the hinge line.

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Transition Limits for Water-Droplet Crystallization with the NASA Lewis Icing Nozzle

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Introduction

SINCE ice accumulation on aircraft and engine surfaces can seriously degrade performance, icing tests are an important aspect of the development and verification tests of aerospace flight systems. The ultimate goal of a ground-based test facility is to effectively simulate icing conditions actually encountered by an aircraft in flight.

To produce the small droplets for icing-cloud simulation, high-pressure air-atomizing nozzles are used. For certain icing-test applications, such as model scaling, median drop sizes down to 5 μm are needed, which may require air-atomizing pressures greater than 3000 kPa. Isentropic expansion of the atomizing air from this pressure to atmospheric pressure results in airstream temperatures of $-160°C$, which will result in ice crystals forming in the cloud unless the air and water are heated to high initial temperatures.

The purpose of these tests was to determine the effect of atomizing air temperature and pressure on the formation of ice crystals.

The NASA Lewis standard icing spray nozzle, shown in Fig. 1, was selected because it has been extensively calibrated and is currently used in the NASA Lewis Icing Research Tunnel. The tests were conducted in the single nozzle icing research test cell at Arnold Engineering Development Center with the nozzle spraying into a bellmouth followed by a 0.91-m-diam duct. The distance from the nozzle to the measuring station was 4.42 m.

During the test, the drop-size distribution was determined with the Laser Fiber Optic System (FOS). The FOS uses a single laser beam and measures the shadow of the particle with a lens system and row of photomultiplier tubes.

A "soot slide" technique as described by Skidmore and Pavia[1] was used to indicate the presence of crystals. The impressions of the droplets in the soot coating are indicative of the state, liquid or crystal, of water droplets. A more complete description of the technique is given in Ref. 2.

Results

The effect of atomizing air temperature on droplet crystallization was evaluated by setting the atomizing air pressure between 300 and 830 KPa and lowering the atomizing air temperature from 115 to 15°C. Tests were conducted at tunnel temperatures of -13 and $-8°C$. Most of the tests were conducted at a spray-nozzle water temperature of 60°C. The tunnel Mach number was 0.3 and the liquid water content (LWC) was 0.6 g/m^3 for all of the tests.

The tunnel and spray conditions were set and a soot slide was exposed and examined under the microscope for the pres-

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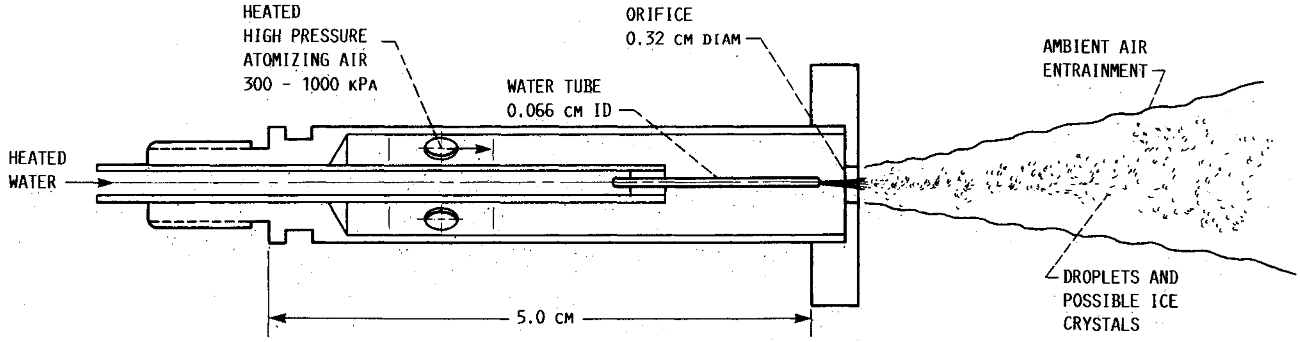

Fig. 1 NASA Lewis standard icing spray nozzle.

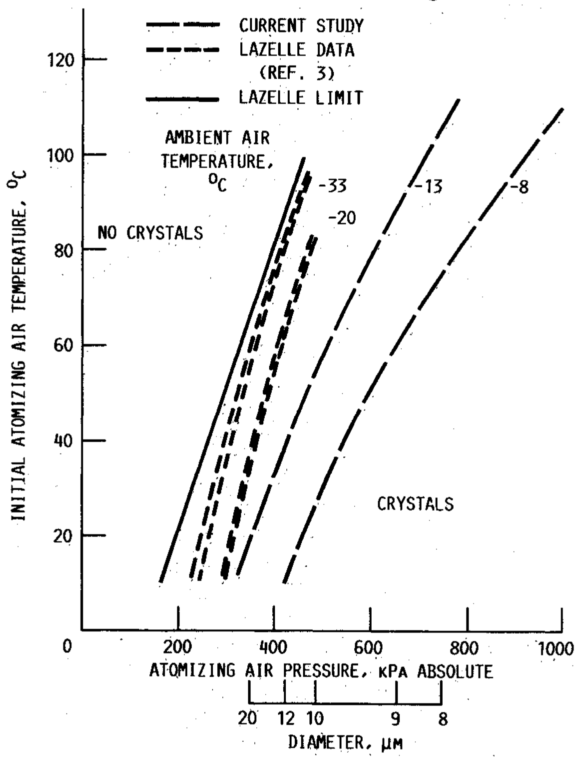

Fig. 2 Transition map for the occurrence of droplet crystallization.

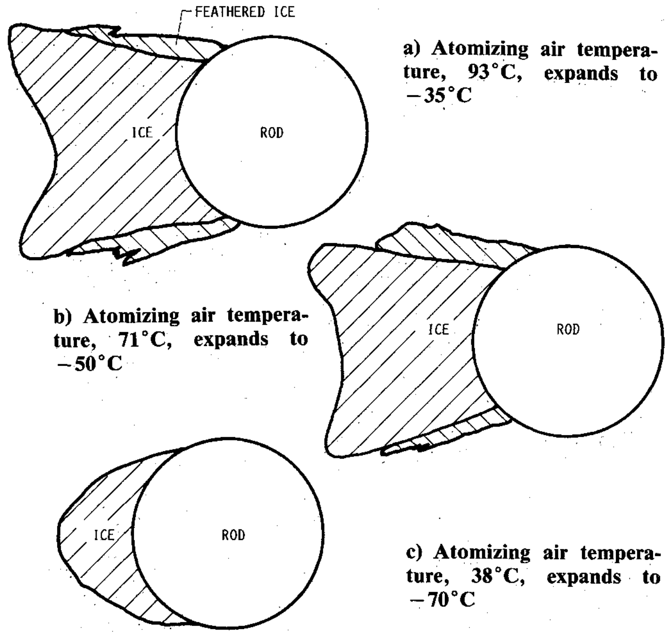

Fig. 3 Effect of atomizing air temperature (crystallization) on ice shape (2.54-cm-diam rod; tunnel ambient temperature −9°C; atomizing air pressure 450 kPa; initial water temperature 38°C; LWC 0.6 g/m³; and time 6.0 min).

ence of crystals. In most tests, a second slide was exposed for verification because the probe was operated manually and sample quality varied. If most of the droplets were observed to be crystallized on a slide, the point was marked as the transition. Then the air temperature was raised and another data point was taken. The process was repeated at various pressures until a transition line could be established.

The phenomena being studied should depend primarily on the cooling caused by the isentropic expansion downstream of the nozzle.

The transition map for droplet crystallization is shown in Fig. 2. The lines are drawn through the transition where crystals were predominant on the slide. For a given ambient air temperature, as the air pressure is increased the atomizing air temperatures must also be increased to prevent crystallization. Lazelle's data at −33 and −20°C are shown as short dashed lines.[3] Lazelle had a "rule of thumb" shown by the solid line that the nozzle air temperature in degrees Centigrade should be greater than twice the nozzle air pressure in psig.

The median volume drop size (MVD) is shown as a subscale on Fig. 2. The MVD measured by the FOS instrument did not change within experimental deviation with changes in air temperature. Even on crystallization, the FOS system did not indicate changes in drop size.

The transition curve can be closely approximated by isentropic-expansion lines of constant static air temperature at the specified atomizing air pressure.

The change in ice shape on a 2.54-cm-diam pipe with the presence of crystals in the spray is shown in Fig. 3. At the lower atomizing air temperature where the droplets have crystallized (Fig. 3), the horns have not formed and the catch is considerably reduced. Figure 3 indicates that the presence of crystals in the spray does significantly affect the ice shape formed.

Conclusions

The results of this study validate the concern over droplet crystallization, define the spray-nozzle operating conditions at which droplet crystallization occurs, and show that the resultant ice shapes on test models vary significantly if the droplets are crystallized.

The transition curve is related to the static temperature curves of the atomizing air jet. Within the scatter of the data, there was no effect of tunnel temperature on median drop size.

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