MECHANISMS RESULTING IN ACCRETED ICE ROUGHNESS

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Abstract

Icing tests conducted on rotating cylinders in the BF Goodrich's Icing Research Facility indicate that a regular, deterministic, icing roughness pattern is typical. The roughness pattern is similar to kernels of corn on a cob for cylinders of diameter typical of a cob. An analysis is undertaken to determine the mechanisms which result in this roughness to ascertain surface scale and amplitude of roughness. Since roughness and the resulting augmentation of the convected heat transfer coefficient has been determined to most strongly control the accreted ice in ice prediction codes, the ability to predict a priori, location, amplitude and surface scale of roughness would greatly augment the capabilities of current ice accretion models.

Nomenclature

a	cylinder radius
C_f	local skin friction coefficient
C_D	droplet drag coefficient
d	droplet diameter
$\hat{i},\hat{j},\hat{k}$	unit vectors of a Cartesian coordinate system
k	wave number in the direction of the cylinder axis
k_s	sand grain roughness
K_m	modified Bessel function of the second kind
LWC	liquid water content
m	integer that defines azimuthal wavelength $\lambda = 2\pi a/m$
N_u	Nusselt number
p	pressure
P_r	Prandtl number
r,θ,z	coordinates of a circular cylindrical system
R_{e_d}	Reynolds number based on droplet diameter
R_{e_λ}	Reynolds number based on wavelength λ
R_{e_a}	Reynolds number based on cylinder radius
t	time
U	free stream speed
U_x,U_y,U_z	Cartesian velocity component
$\overline{V}$	droplet velocity
$\overline{X}$	droplet position
β	local collection efficiency
ε	small number
η	surface perturbation amplitude
λ	surface perturbation wavelength
ρ	density of water or ice
ρ_a	density of air
τ	droplet adjustment time scale
τ_a	amplification time scale
τ_c	cylinder traversing time
Φ	velocity potential
ω	vorticity
Ω	cylinder rotation rate
$\propto$	proportional to

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I. Introduction

It has been known for some time now that ice roughness and the resulting augmentation of the convective heat transfer coefficient significantly alters the predictions of ice accretion codes such as LEWICE.[1] In the field, observation of ice roughness on aerodynamic surfaces is the rule rather than the exception. Many investigators have experimentally measured the augmentation of the heat transfer coefficient near or at the leading edge of aerodynamic surfaces which have been artificially roughened with hemispherical roughness. Recently Newton et al[2] have compared convective heat transfer measurements on a NACA 0012 in flight and in the icing research tunnel at NASA Lewis. Here, the surfaces were roughened by affixing roughness elements which were hemispheres of 1mm height and 2mm diameter in several patterns. Presumably the shape and scale of these roughness were selected to replicate the roughness observed on iced surfaces.

Presently, the state of the art in incorporating the effects of ice roughness in ice accretion prediction codes is semi-empirical. The code user essentially specifies the location and magnitude of roughness during code initialization[3]. Predictions of ice shape are then compared against measured data and the roughness specification is iterated upon until the agreement between predicted shape and measured shape is judged adequate.

The current work takes the position that ice roughness may be predictable. This position was motivated by some unexpected test data which was obtained during a test program which was designed to confirm ice accretion scaling laws.[4-5] During these tests, circular cylinders were slowly rotated in the BF Goodrich's icing tunnel, while the tunnel temperature was slowly allowed to rise. Repeatedly, the accreted ice surface texture on the circular cylinders had a texture which is best described as that resembling corn on the cob. The regularity in the pattern therefore begs the question: What physical mechanisms fix the scale of this corn-on-the-cob roughness?

The paper is organized as follows: in Section 2, a brief description of the tests conducted and data obtained is given. In Section 3, a mechanism for wavy surface development is postulated which involves proper phasing between