FINAL TECHNICAL REPORT

FOR NASA GRANT NAG 3-1796

Entitled

NUMERICAL SIMULATION OF INTERNAL HEAT TRANSFER PHENOMENA OCCURRING DURING DE-ICING OF AIRCRAFT COMPONENTS

Prepared for

NASA Lewis Research Center
Cleveland, Ohio 44135

by

Principal Investigator:

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for the period
10-6-95 to 9-30-96

FINAL REPORT for NAG 3-1796

The numerical simulation of the internal heat transfer phenomena occurring during anti-icing or de-icing of a layered aircraft or rotor blade with an electrothermal heat source has been a subject of intense research by University of Toledo faculty and graduate students since 1980. The present grant involved an experimental study to determine the convective heat transfer coefficient from castings made from ice-roughened flat plates. The convective heat transfer coefficient between accreted ice and the surrounding environment has long been known to be the key parameter in the energy balance that predicts the continued transient growth and shape of the resulting ice. This effort was initiated by the inability of the current ice prediction codes to accurately model glaze ice shapes. This was an intense effort in which University of Toledo faculty members and a doctoral student constructed the necessary models and ran wind tunnel tests using electrothermal heaters to measure the convective heat transfer coefficients. In a previous final report, 63 publications related to the work done by the University of Toledo de-icing group were listed. The present final report lists below the three publications resulting from the current work, which are available in the open literature. In addition, the final Ph.D. dissertation is attached. All of this material has been provided to the grant technical monitor.

Dukhan, N., G. J. Van Fossen, K. C. Masiulaniec and K. J. De Witt, "Experimental Technique and Assessment for Measuring the Convective Heat Transfer from Natural Ice Accretions," 33rd Aerospace Sciences Meeting, Reno, Nevada, 1/95, Paper No. AIAA-95-0537, 24 pgs.

Dukhan, N., G. J. Van Fossen, K. C. Masiulaniec and K. J. De Witt, "Convective Heat Transfer from Castings of Ice Roughened Surfaces in Horizontal Flight," American Helicopter Society International Icing Symposium, Montreal, Canada, 9-95, Conference Proceedings, pp. 127-140.

Dukhan, N., G. J. Van Fossen, K. C. Masiulaniec and K. J. De Witt, "Convective Heat Transfer Coefficients from Various Types of Ice Roughened Surfaces in Parallel and Accelerating Flow," 34rd Aerospace Sciences Meeting, Reno, Nevada, 1/96, Paper No. AIAA-96-0867, 20 pgs.

A Dissertation
Entitled

MEASUREMENTS OF THE CONVECTIVE HEAT TRANSFER COEFFICIENT FROM ICE ROUGHENED SURFACES IN PARALLEL AND ACCELERATED FLOWS

by

Nihad Abed-el-Fattah Dukhan

as partial fulfillment of the requirements of
the Doctor of Philosophy Degree in
Engineering Science

Co-advisor K. C. Masiulaniec

Co-advisor K. J. DeWitt

Graduate School

The University of Toledo
December 1996

THE UNIVERSITY OF TOLEDO

COLLEGE OF ENGINEERING

August 23, 1996
Date

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY NIHAD DUKHAN

ENTITLED *Measurements of the Convective Heat Transfer Coefficient from Ice Roughened Surfaces in Parallel and Accelerated Flows*

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN ENGINEERING SCIENCE

THESIS ADVISORS K. C. Masiulaniec and K. J. DeWitt

CHAIRMAN OF DISCIPLINE A. A. Afjeh

Recommendation concurred

Committee

on

Final Examination

An Abstract of

Measurements of the Convective Heat Transfer Coefficient from Ice Roughened Surfaces in Parallel and Accelerated Flows

Nihad Dukhan

Submitted in partial fulfillment of the requirements of
the Doctor of Philosophy Degree in
Engineering Science

The University of Toledo
December 1996

Values for the heat transfer coefficient from different ice roughened surfaces in parallel and accelerated flows were experimentally sought for use in de-icing computer codes. Aluminum castings of different ice accretions in an icing wind tunnel were obtained from which heat transfer models were constructed. Each model was a large composite of heat flux gages to which heat was supplied from the bottom using themofoil heating elements. The heat supplied to each gage was allowed to convect upward from the rough surface to an air stream in a dry wind tunnel. Other heat losses were eliminated and each gage was insulated from surrounding ones. Average values of the heat transfer coefficient were computed from an energy balance for each gage with the known electrical power of the heating elements.

Results were obtained for local Reynolds numbers ranging from $5.3X10^4$ to $1.3X10^6$, and for tilt angles of 0^o, 14^o, 23^o, 32^o, and 41^o. The results were in general qualitative agreement with those of uniform roughness with the different behaviors being more drastic in the case of stochastic roughness. The Stanton

number for random roughness was higher than that for uniform roughness and was directly proportional to both roughness element height and area increase and inversely proportional to spacing. The effect of free-stream velocity diminished at high enough Reynolds number and the Stanton numbers collapsed onto a single curve. Acceleration caused Stanton number to start at lower values close to the leading edge, Stanton numbers then increased as the flow accelerated along each tilted model. In the fully rough region and for parallel and mildly accelerated flows, up to 23^{o}, Stanton number was a function of Reynolds number only and followed a power law. The multiplier and the exponent of Reynolds number in this power law were found to correlate well with the newly defined parameter, Index of Random Roughness, and the roughness height, respectively.

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