Turbulence Modeling in Aircraft Icing

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Workshop on Computational Turbulence Modeling
NASA ICOMP
September 15, 1993

INTRODUCTION

The Icing and Cryogenic Technology Branch develops computational tools which predict ice growth on aircraft surfaces and uses existing CFD technology to evaluate the aerodynamic changes associated with such accretions.

Surface roughness, transition location, and laminar, transition, or turbulent convective heat transfer all influence the ice growth process on aircraft surfaces.

Turbulence modeling is a critical element within the computational tools used both for ice shape prediction and for performance degradation evaluation.

CURRENT CODE DEVELOPMENT

2D CODES

- LEWICE - POTENTIAL FLOW / INTEGRAL BOUNDARY LAYER
- LEWICE/IBL - POTENTIAL FLOW / INTERACTIVE BOUNDARY LAYER
- LEWICE/NS - NAVIER-STOKES, STRUCTURED GRID
- LEWICE/UNS - NAVIER-STOKES, UNSTRUCTURED GRID

3D CODES

- LEWICE3D - PANEL CODE / INTEGRAL BOUNDARY LAYER
- LEWICE3DGR - ANY GRID BASED FLOW SOLUTION

ICE ACCRETION MODELING

CURRENT MODEL USED FOR ICE GROWTH

- MASS AND ENERGY BALANCE IN CONTROL VOLUMES ALONG THE SURFACE
- CONVECTIVE HEAT TRANSFER IS MAJOR FACTOR IN ENERGY BALANCE
- INTEGRAL BOUNDARY LAYER FORMULATION USED TO DETERMINE LAMINAR AND TURBULENT HEAT TRANSFER COEFFICIENTS
- SURFACE ROUGHNESS MODELED AS SAND-GRAIN ROUGHNESS; ACTUAL ICE ROUGHNESS VARIES FROM SMALLER TO LARGER THAN BOUNDARY LAYER THICKNESS

ICE ACCRETION MODELING

CONVECTIVE HEAT TRANSFER MODEL USED FOR ICE GROWTH

SKIN FRICTION COEFFICIENT

$$\frac{c_f}{2} = 0.1681\left[\ln\left(\frac{864.0\theta_t}{k_s} + 2.568\right)\right]^{-2}$$

WHERE

$$\theta_t(s) = \left[\frac{0.0156}{V_e^{4.11}}\int_{s_{tr}}^{s} V_e^{3.86}\,ds\right]^{0.8} + \theta_\iota(s_{tr})$$

ICE ACCRETION MODELING

CONVECTIVE HEAT TRANSFER MODEL USED FOR ICE GROWTH

LAMINAR

$$h_\iota(s) = 0.296\frac{\lambda}{\sqrt{\nu}}\left[V_e^{-2.88}\int_0^s V_e^{1.88}\,ds\right]^{-1/2}$$

TURBULENT

$$h_t(s) = St\rho V_e c_p = \left[\frac{c_f/2}{Pr_t + \sqrt{c_f/2}\,(1/St_k)}\right]\rho V_e c_p$$

ICE ACCRETION MODELING

CONVECTIVE HEAT TRANSFER MODEL USED FOR ICE GROWTH

ROUGHNESS STANTON NUMBER

$$St_k = 1.16 \left(\frac{V_r k_s}{\nu}\right)^{-0.2}$$

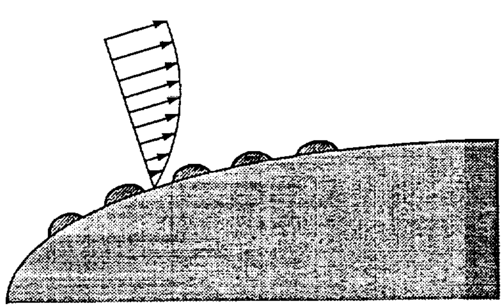
AND

$$V_r = V_e \sqrt{c_f / 2}$$

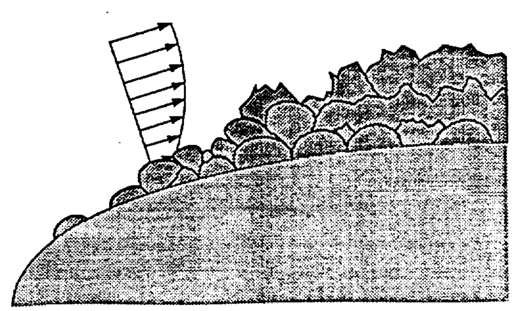
ICE ACCRETION MODELING

ICE ROUGHNESS CHARACTERIZATION

SAND-GRAIN ROUGHNESS



ACTUAL ICE ROUGHNESS



ICE ACCRETION MODELING

PLANS

- EXPERIMENTS TO CHARACTERIZE ICE ROUGHNESS GEOMETRIES AT A VARIETY OF ICING CONDITIONS
- EXPERIMENTS TO CHARACTERIZE VELOCITY FIELD OVER REAL AND ARTIFICIAL ICE ROUGHNESS GEOMETRIES
- EXPERIMENTS TO MEASURE HEAT TRANSFER OVER REAL AND ARTIFICIAL ICE ROUGHNESS GEOMETRIES
- DEVELOPMENT OF MODIFIED COMPUTATIONAL MODEL BASED ON THESE EXPERIMENTS

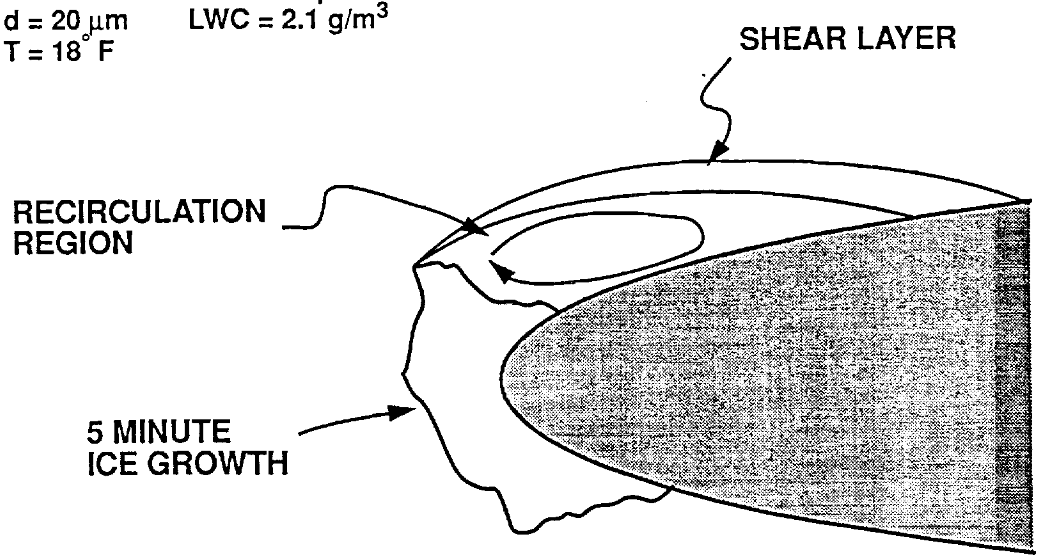
ICED AIRFOIL AERODYNAMICS

NACA 0012 ICING CONDITIONS

$\alpha = 4^\circ$ V = 130 mph

d = 20 μm   LWC = 2.1 g/m^3

T = 18° F



ICED AIRFOIL AERODYNAMICS

BALDWIN-LOMAX TURBULENCE MODEL

Inner Layer

$$\mu_t \sim l^2 \left| (u_y - v_x) \right|$$

l = mixing length

Outer Layer

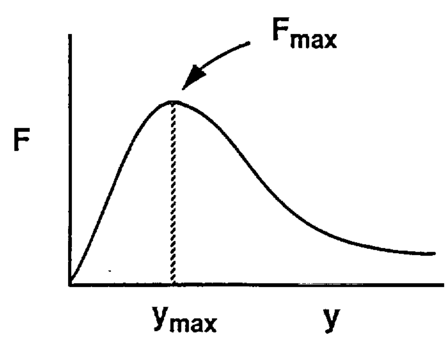
$$\mu_t \sim \mathbf{F}_{max} \mathbf{Y}_{max}$$

$$\mathbf{F}(y) = y|\omega| \left(1 - exp\left((-y^*)/\mathbf{A}\right)\right)$$

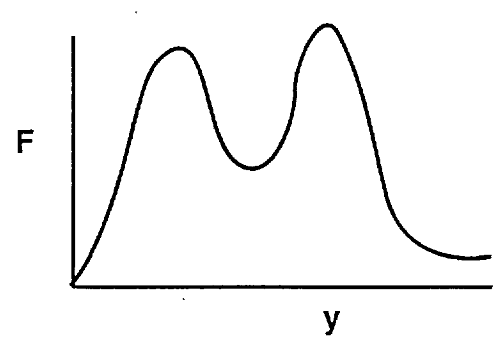
ICED AIRFOIL AERODYNAMICS

BALDWIN-LOMAX TURBULENCE MODEL

NORMAL B.L. F PROFILE



RECIRCULATION REGION
F PROFILE



ICED AIRFOIL AERODYNAMICS

MML TURBULENCE MODEL

$$\mu_t = \rho l^2 \omega$$

WHERE

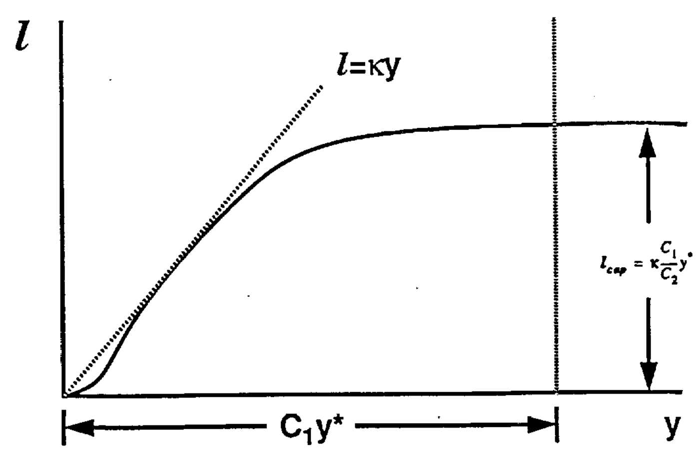
$$\frac{y+\Delta y}{y^*} < C_1 \qquad l(y) = \kappa \frac{C_1}{C_2} y^* \left(1 - \left(1 - \frac{\left(\frac{y+\Delta y}{y^*}\right)}{C_1}\right)^{C_2}\right)\left(1 - e^{-\left(\frac{y+\Delta y}{y^*}/A^+\right)}\right)$$

AND WHERE

$$\frac{y+\Delta y}{y^*} > C_1 \qquad l(y) = \kappa \frac{C_1}{C_2} y^*$$

ICED AIRFOIL AERODYNAMICS

MML TURBULENCE MODEL



$$y^* = \frac{\nu}{u^*} = \frac{\nu}{\sqrt{\tau_w/\rho_w}}$$

ICED AIRFOIL AERODYNAMICS

MML TURBULENCE MODEL

THE CEBECI-CHANG ROUGHNESS MODEL IS ADDED TO THE TURBULENCE MODEL

$$\Delta y^{+} = \begin{cases} 0.9\left[\sqrt{k_s^{+}} - k_s^{+}\exp\left(\dfrac{-k_s^{+}}{6}\right)\right] & 5 < k_s^{+} \le 70 \\ 0.7\,(k_s^{+})^{0.58} & 70 \le k_s^{+} \le 2000 \end{cases}$$

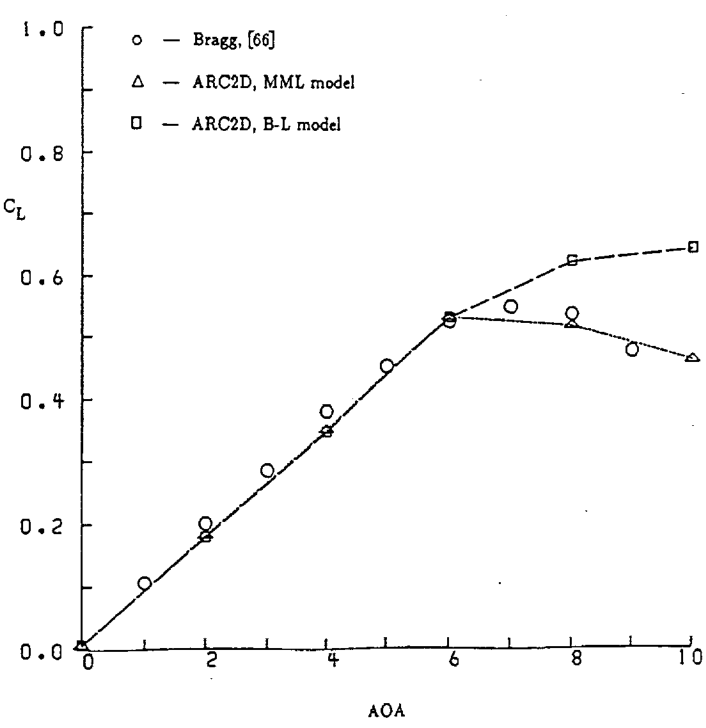
WHERE,

$$\Delta y^{+} = (\Delta y)\,(u_\tau/\nu) \quad \text{and} \quad k_s^{+} = k_s\,(u_\tau/\nu)$$

ICED AIRFOIL AERODYNAMICS

MML TURBULENCE MODEL

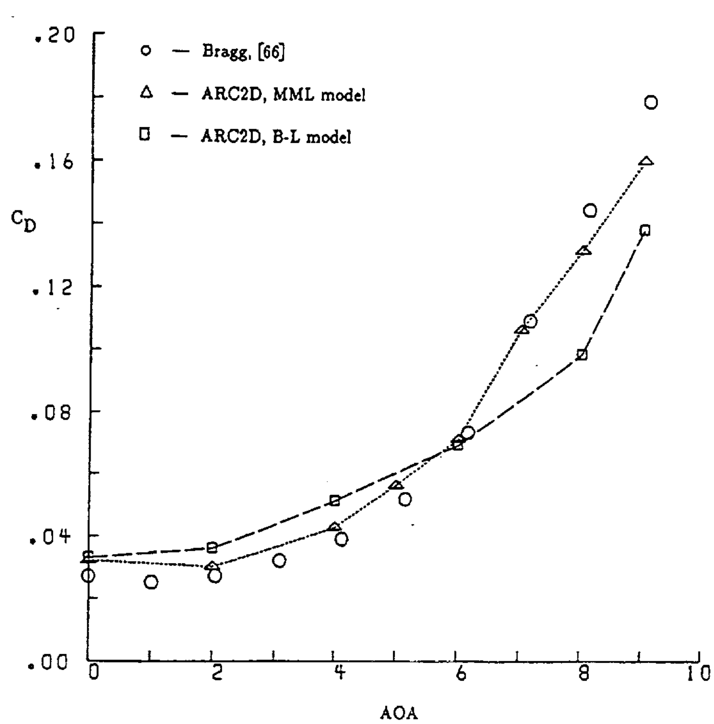
<u>C_L vs. α</u>



ICED AIRFOIL AERODYNAMICS

MML TURBULENCE MODEL

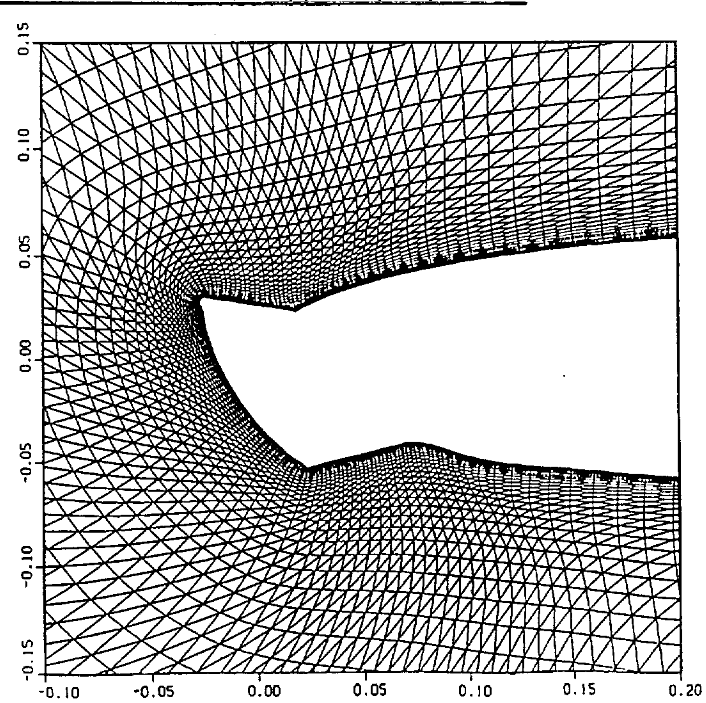
C_D VS. α



ICED AIRFOIL AERODYNAMICS

MML TURBULENCE MODEL

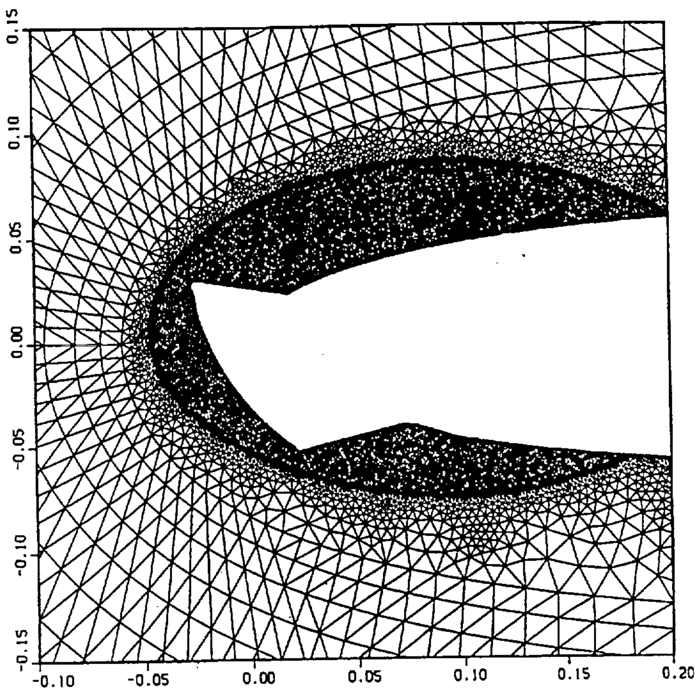
STRUCTURED GRID FOR ARTIFICIAL ICE SHAPE



ICED AIRFOIL AERODYNAMICS

MML TURBULENCE MODEL

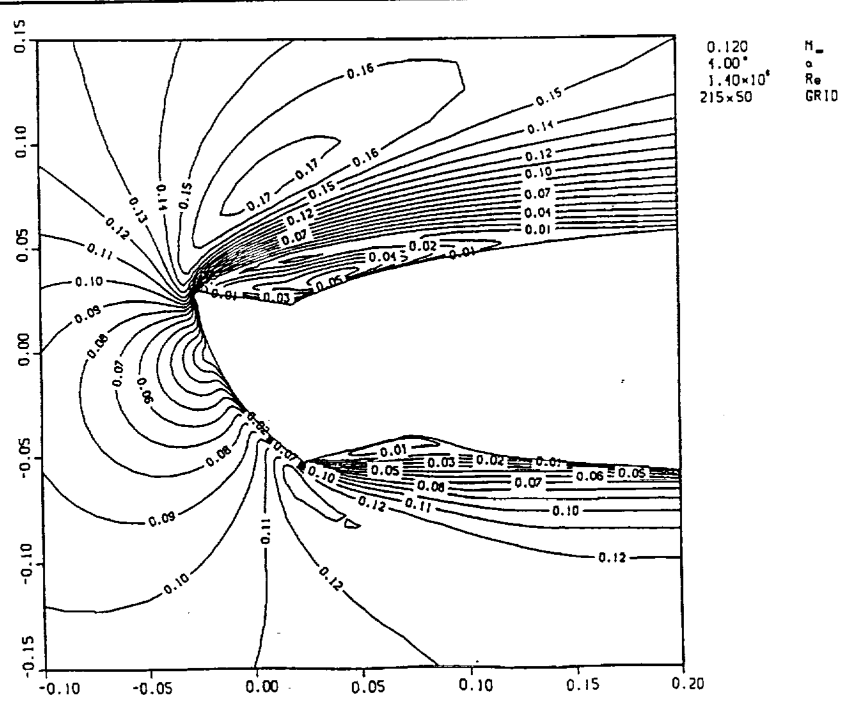
UNSTRUCTURED GRID FOR ARTIFICIAL ICE SHAPE



ICED AIRFOIL AERODYNAMICS

MML TURBULENCE MODEL

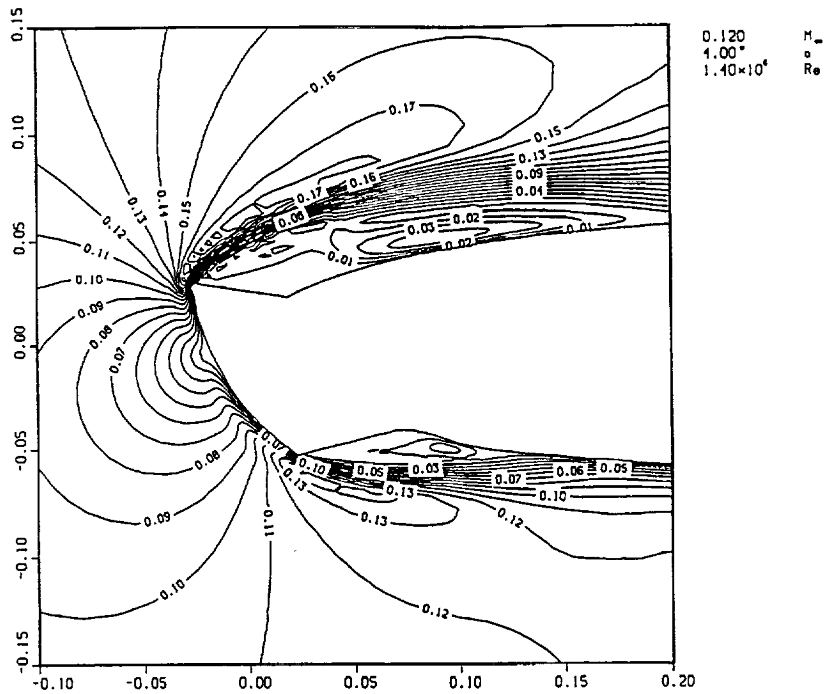
STRUCTURED GRID MACH NUMBER CONTOURS



ICED AIRFOIL AERODYNAMICS

MML TURBULENCE MODEL

UNSTRUCTURED GRID MACH NUMBER CONTOURS



CONCLUDING REMARKS

- TURBULENCE MODELING PLAYS A ROLE IN ICE GROWTH PREDICTION AND IN PERFORMANCE EVALUATION
- NEW MODELING IS REQUIRED FOR THE LARGE ROUGHNESS ELEMENTS OF A TYPICAL ICE ACCRETION
- AN EXPERIMENTAL PROGRAM IS CURRENTLY UNDERWAY TO DEVELOP A DATABASE FOR CREATION OF SUCH A MODEL
- AN ALTERNATE ALGEBRAIC TURBULENCE MODEL HAS BEEN USED TO EVALUATE PERFORMANCE DEGRADATION DUE TO ICING
- THE MML MODEL HAS BEEN USED IN AN UNSTRUCTURED GRID NAVIER-STOKES CODE TO CALCULATE FLOW OVER AN ARTIFICIAL ICE SHAPE