A spongy icing model for aircraft icing

Li Xin, Bai Junqiang, Hua Jun, Wang Kun, Zhang Yang

1. Introduction

Ice accretion is a common and an important feature in flight. The presence of ice accretion can cause a serious safety problem; the most severe penalties encountered deal with increased drag, decreased lift, decreased stall angle, and reduced controllability. On the safety issues, aircraft icing has caused more than 50 accidents in the US in recent 20 years. The ice accretion problems can be studied by the wind tunnel testing and the real flight test, or the engineering and numerical approaches. The real flight test and the wind tunnel testing require extensive analyses, which are expensive and dangerous. The engineering approach employs empirical formulation and experimental data, which is much simpler but lack of precision. Therefore, the numerical method is widely adopted for its economical, efficient, and accurate features.

Conventionally, the simulation of ice accretion is based on the Lagrangian particle-tracking technique for the trajectory calculation and employing Messinger icing model. Bougault et al. developed an Eulerian method for the ice accretion. After that, Eulerian method became popular because of its simplicity and efficiency. However, better numerical methods are needed to track and collect droplets and further studies are needed to understand the key factors on the icing growth. Currently, a number of ice accretion codes have been well developed by some international icing communities, such as ONERA (France), CIRAML (Italy), DRA (United Kingdom), LEWICE (USA), and FENSAP-ICE (Canada). The FENSAP-ICE code employs the Eulerian method, and the others are using the Lagrangian method.

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The ice accretion problem has been studied widely in the last several decades, and many work had been done on prediction of ice shape by many researchers such as Bragg, Shen, and Shin and Bond.

In 1985, Bragg made some improvements on his previous model, and derived a method to solve the droplet trajectories and gave some recommendations for further improvement of the method. LEWICE was developed by the University of Dayton in 1983. Potapczuk and Bidwell extended the original LEWICE based on potential flow analysis to LEWICE/NS which used the solution of 2D Navier–Stokes equations. Besides, it has been implemented to solve the energy equation to obtain the heat-transfer coefficient automatically. Another icing code from DRA has also been developed, especially for the ice protection on airfoils and on rotor blades of a helicopter. Recently, an ALE mesh movement scheme for long-term in-flight ice accretion has been performed by Fossati et al.

The Lagrangian approach provides a good result but there are still some shortages. For example, it is hard to be applied on some complicated geometries, such as 3-D aircraft wing and multi-element airfoils. Bourgault developed an Eulerian approach on ice accretion to overcome the shortages. On modeling the aircraft icing, the classical one was developed by Messinger. Then Myers made some improvements on Messinger model. Also, Bourgault and Ota et al. developed icing model for aircraft respectively. With regard to the existing codes, FENSAP-ICE employs the icing model developed by Bourgault, ICECREMO employs Myers’s lubrication type model, and the icing model of LEWICE is based on Messinger’s work.

The icing model developed in this paper included two physical phenomena that traditional icing model ignores: one is the supercooling of acrating ice surfaces, and the other is the sponginess of ice. Experiments have already confirmed that the accreting surface temperature would fall below the freezing point when ice started to form. Karev et al. investigated the icing growth on a cylinder by the wind tunnel testing, and the surface temperature was found below the freezing point of water. The possibility of liquid entrapment by an ice accretion’s growing matrix has recognized by List. When droplets were entrapped in the ice matrix, this type of icing is named as the spongy icing. To account for the sponginess and the supercooling, Blackmore and Lozowski proposed a theoretical spongy spray icing model with surficial structure in the field of atmospheric icing. The supercooling of the water film and sponginess of ice affect the ice accretion process, and determine the ice growth rate and the ice shape, so the two physical phenomena which are usually ignored by traditional icing models must be considered in aircraft icing. Besides, like many other icing model, the spongy icing model is based on continuity equation and heat balance equation, so it has good successsion.

2. Description of the problem

To verify and validate the Eulerian droplet tracking method and the collection efficiency, a suitable test case must be considered. A comparison between the Eulerian method and LEWICE is presented. In addition, a comparison with experimental impingement data from Papadakis et al. is discussed as well. The impingement data is presented in the form of LWC distribution and water collection efficiency. The experiments were performed with different MVDs for a NACA23012 airfoil and an iced NACA23012 airfoil. The test conditions are shown in Table 1. For the NACA23012 airfoil, the selected MVDs are 20 and 111 μm, while for the iced NACA23012 airfoil, the MVDs are 20, 52, and 111 μm. Moreover, the Eulerian approach and the icing model were validated by simulating icing conditions on a NACA0012 airfoil. The test temperatures are −4.4, −10, −13.3, and −19.4 °C, which cover both dry and wet regimes; details of the test conditions are given in Table 2. The predicted ice shapes were compared to the experimental results under the same conditions in the NASA Lewis Iceing Research Tunnel and the numerical results from LEWICE.

At last, the prediction accuracy of the surface temperature was evaluated through the simulation on the surface of a non-rotating horizontal cylinder, which is 0.038 m in diameter. The computational results were compared with the experimental results in Ref.; the test conditions for cylinder are shown in Table 3. Two duration times of ice accretion are set 15 and 15.4 min. The 15 min computation is used to compare ice shape with experiment, while 15.4 min computation is used to validate the surface temperature with experiment. In tables, AOA, \( V_\infty \), LWC, \( p_\infty \) and MVD are angle of attack, free-stream velocity, liquid water content, free-stream pressure and mean volumetric diameter respectively.

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>AOA (°)</td>
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<tr>
<td>( V_\infty ) (m/s)</td>
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<tr>
<td>LWC (g/m³)</td>
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<td>Chord (m)</td>
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<td>( p_\infty ) (kPa)</td>
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<td>AOA (°)</td>
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<tr>
<td>MVD (μm)</td>
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<td>Chord (m)</td>
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<td>( p_\infty ) (kPa)</td>
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<table>
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<tr>
<td>MVD (μm)</td>
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<td>( p_\infty ) (kPa)</td>
<td>101.3</td>
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3. Formulation and numerical method

Based on the multiphase flow theory, an Eulerian method to numerically simulate ice accretions is presented in this paper. Some assumptions are established as follows:

1. Droplets are spherical and complete without any breakage or deformation.
2. No droplet collision/coalescence.
3. No heat and mass transfer between the air phase and droplet phase.
4. No turbulence effect on droplets.
5. Gravity, air drag, and buoyancy are considered.

3.1. Governing equations for air phase

The flow field for air can be obtained by solving the Reynolds-Averaged Navier-Stokes equations. Numerical approach is based on the finite volume form of the integral equations. In a domain of a volume $\Omega$ with boundary $\Omega_a$, let $\rho$, $u$, $v$, $E$, $H$ and $p$ be the density, Cartesian velocity components, total energy, total enthalpy, and pressure, the equation can be written in the integral form:

$$\frac{\partial}{\partial t} + \int_\Omega \mathbf{Q} \cdot d\mathbf{V} + \int_{\partial \Omega_a} F_e \cdot n dS = \frac{1}{E} \int_{\partial \Omega_a} F_y \cdot n dS$$  \hspace{1cm} (1)

The vector of the conserved variables, the convective flux term, and the viscous flux term are given as follows:

$$\mathbf{Q} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho E \end{bmatrix}, \quad F_e = \begin{bmatrix} \rho u & \rho v \\ \rho u^2 + P & \rho v^2 \\ \rho u v & \rho v^2 + P \\ \rho u H & \rho v H \end{bmatrix},$$

$$F_y = \begin{bmatrix} 0 & 0 \\ \tau_{xx} & \tau_{xy} \\ \tau_{yx} & \tau_{yy} \\ \Pi_x & \Pi_y \end{bmatrix}$$

with

$$\begin{align*}
\tau_{xx} &= \mu \frac{\partial u}{\partial x} + \nu \frac{\partial^2 u}{\partial x^2} - q_x \\
\tau_{xy} &= \mu \frac{\partial u}{\partial y} + \nu \frac{\partial^2 u}{\partial y^2} - q_y \\
\Pi_x &= \mu \frac{\partial \tau_{xx}}{\partial x} + \nu \frac{\partial \tau_{xy}}{\partial y} - q_x \\
\Pi_y &= \mu \frac{\partial \tau_{xy}}{\partial x} + \nu \frac{\partial \tau_{yy}}{\partial y} - q_y
\end{align*}$$

where $\tau_{xx}$, $\tau_{xy}$, $\tau_{yx}$, $\tau_{yy}$, $q_x$, and $q_y$ are the elements of the shear-stress tensor, $q_x$ and $q_y$ the elements of heat-flux vector.

The cell-centered finite volume method is employed to solve the Navier–Stokes. The lower–upper symmetric Gauss–Siedel (LU-SGS) algorithm for time marching and Roe scheme for the spatial discretization of the convective flux were implemented in codes. The treatment of the far field boundary condition is based on the introduction of Riemann invariants for a one-dimensional flow normal to the boundary. Isothermal wall boundary condition is applied. Chi et al. suggested that Spalart–Allmaras was proper for simulating ice accretion in the air. The Navier–Stokes equations were closed by the S–A model with thermally perfect gas and temperature-dependent properties.

3.2. Governing equations for droplets

The droplets distributed in the flow field can be regarded as a kind of pseudo fluid which penetrates in the air flow field. The governing equations for droplets can be written as follows:

$$\frac{\partial q_x}{\partial t} + \nabla \cdot (\rho_d q_x \mathbf{v}_d) = S_x$$  \hspace{1cm} (2)

where $\mathbf{v}_d$ denotes the droplet velocity vector and $S_x$ the source term.

4. Concept and structure of icing model

The following assumptions are considered; further experimental verification is needed to validate these assumptions.

1. Each dendrite has a hemispherical tip and a cylindrical body.
2. Ice accretes like dendrite crystals from the surface (see Fig. 2).
3. The radius of the hemispherical tip of the dendrite is proportional to the height of ice layer.
4. The latent heat of solidification produced by the ice forming layer is rejected to the water film layer.
5. The radius of the dendrite is determined by the ambient temperature and the LWC. However, when the LWC is low, the ambient temperature dominates.
4.1. Modeling of laminar layer film

The continuity equation for each control volume can be expressed as follows:

\[ R_{in} + R_{imp} = R_{wf-ifl} + R_{out} \]  

where \( R_{in} \) is the total mass flux entering the control volume from the previous control volume, \( R_{imp} \) the flux of impinging droplets, and \( R_{out} \) the total mass flux flow out of the control volume. The mass flux of water transferred from the laminar layer to ice forming zone \( R_{wf-ifl} \) equals the ice accretion flux \( R_{wf-ifl} = I_0 + R_0 \). The mass flux entrapped by the ice matrix from the ice forming zone \( R_{ifl-si} \) equals \( R_{wf-ifl} \).

Dukler and Bergelin used the universal velocity distribution equation for turbulent flow of Von Karman in which the non-dimensional film flow rate was expressed by

\[ u^+ = u_f/u_* \]  

where \( u_f \) is the velocity of water films, and \( u_* \) the friction velocity. The non-dimensional coordinate normal to the substrate is

\[ f = \sqrt{\frac{g \rho_w L}{\mu_w}} \]  

where \( \gamma_t \) is the water film thickness.

The Prandtl mixing length hypothesis results in several equations that are used to describe the velocity profile with the non-dimensional variable given in Eq. (5). The laminar layer is expressed by

\[ u^+ = \zeta \quad (0 < \zeta \leq 5) \]  

The total mass flux in the film can be written as

\[ R_t = \mu_w f(\zeta) L_{en}^{-1} \]  

where \( L_{en} \) is the length of the control volume, \( R_t \) the total mass flux in the film

\[ f(\zeta) = 0.5\zeta^2 \quad (0 \leq \zeta \leq 5) \]  

For aircraft icing, \( \zeta < 5 \), which means the water film is laminar. In order to predict the pure ice growth rate and the liquid entrapment within the ice matrix, more details are needed to examine the ice forming layer. The assumptions in this section are applied. Further experimental verifications are needed to validate these assumptions.

4.2. Modeling of ice forming layer

Dendritic growth at the ice surface leads to a spongy ice. In List’s icing model for a growing hailstone, there is a layer of ice lying between the spongy ice matrix and the surficial liquid. Here, we name this as an ice forming layer, which is assumed to contain some ice crystals that are growing with a uniform
tip growth rate. Ice forming layer consists of water and dendritic ice, the thickness of the water film is $y_2 - y_1$ shown in Fig. 3, and all the temperatures are in degrees Celsius.

The conduction and evolution of heat of the ice forming zone are described by a 1D steady-state diffusion equation, known as

$$\frac{d}{dy} \left( k \frac{dT(y)}{dy} \right) + q_e = 0$$

where $y$ is the coordinate normal to the surface with origin $y_0 = 0$ at the interface, $T(y)$ the temperature in the ice forming layer, $k$ the thermal conductivity of the ice forming layer, which is assumed to be independent of $y$, with the boundary condition $T = 0 \, ^\circ C$ and $dT/dy = 0$ when $y = 0$. The solution for Eq. (9) is

$$T_0 - T_1 = q_e (y_1 - y_0)^2 / 2k$$

The volumetric rate of evolution of latent heat in the ice forming layer can be written as

$$q_e = \frac{q_1}{y_1 - y_0}$$

where $q_1$ is the latent heat from the ice forming layer to the laminar layer, which can be expressed by

$$q_1 = L_a L_f - c_w (T_0 - T_1) (I_0 + R_0)$$

where $c_w$ is the specific heat capacity of pure water at $0 \, ^\circ C (4.2 \times 10^3 \, J \cdot kg^{-1} \cdot K^{-1})$, and $L_f$ is the specific latent heat of fusion of pure water at $0 \, ^\circ C (3.34 \times 10^5 \, J \cdot kg^{-1})$.

The crystal growth theory pointed out that the growth rate at the tips of dendrites is a function of the temperature difference of the bulk liquid into which the dendrite is growing; the growth rate can be expressed as

$$V_c = a \Delta T^b$$

where $a$ and $b$ are empirical coefficients and $\Delta T$ is the temperature difference, $\Delta T = T_0 - T_1$. Like List, we assume that the growth rate of the icing surface is a function of the temperature drop across the ice forming layer, Tirmizi recommended values $a$ and $b$ of $1.87 \times 10^{-4}$ and 2.09. However, in order to consider the influence of the ambient temperature and to apply this model to aircraft icing field successfully, after calibration work, we recommend $b$ as of $-3.79 \times 10^{-4} T_0^2 - 1.843 \times 10^{-2} T_0^2 + 0.15406 T_0 + 1.6569$, where $T_0$ is the temperature of air flow and $b$ a sensitive function of the temperature, which has a decisive effect on the speed of the icing interface, and also plays an important role in dividing the type of ice accretion.

Assume $V_c$ to be the rate of advance of liquid across the icing interface, which means

$$V_c = V_1 = \frac{I_0 + R_0}{\rho_w}$$

To determine the thickness of the ice forming layer is very important for modeling the ice forming layer. Tirmizi assumed that there is a continuous linear relationship between temperature drop and the radius of curvature of the tip of a growing ice dendrite, such as

$$r_c = c + d / \Delta T$$

Tirmizi recommended applying $c = 6.16 \times 10^{-5}$ and $d = 2.024 \times 10^{-5}$ for dendritic ice, but for aircraft icing we recommended applying $c = 4.36 \times 10^{-5}$ and $d = 2.864 \times 10^{-5}$. The main function of the two parameters is to make sure that the iterative solution of the spongy icing model is convergent.

The thickness of ice forming layer is proportional to the radius of freely-growing ice dendrite tips

$$y_1 - y_0 = k_y r_c$$

where $k_y$ is the factor of proportionality; for aircraft icing, recommend $k_y = 1.32$. The main function of $k_y$ is not only to guarantee iterative solution of the spongy icing model is convergent but also making sure the predicted ice shapes have physical significance. $k_y$ is dependent of velocity and liquid water content. In recent years, a wide variety of tests have been performed in the NASA Lewis icing research tunnel (IRT). These data facilitates a systematic calibration of the parameters mentioned above, and the parameters are calibrated by experimental data of different temperatures, liquid water contents, MVD, and different speeds. After the calibration work, $c$ and $d$ are constant, no matter for the rime, the glaze or the spongy regime, but $b$ depends on ambient temperature, for $b$ is a function of temperature. From Eqs. (15) and (16) we can conclude that fine ice crystals are (grow at high film supercoolings) with tips of smaller radius of curvature than coarser ice crystals (grow at lower supercoolings). Experiments have proved that high temperature (low film supercoolings) produced coarse ice columnar crystals and vice versa.

4.3. Heat balance of laminar layer film

The heat balance for the laminar layer is

$$H_{in} + H_{hi} + H_{a} + H_{out} = 0$$

where $H_{in}$ is the sensible heat flux in the laminar layer which is used to heat the inflowing liquid, and $H_{hi}$ the bulk heat flux from the ice forming layer to the laminar layer, the initial value of $H_{out}$ is zero, and the value will be updated during iteration.
process. \( H_{\text{af-a}} \) is the heat flux from the laminar layer to the air flow.

The expression for the \( H_{in} \) is

\[
H_{in} = C_w R_{in} \left( T_{in} - \frac{T_1 + T_2}{2} \right)
\]

(18)

where \( T_{in} \) is the mean temperature of the mass flux into the control volume, \((T_1 + T_2)/2\) the mean temperature of the control volume under consideration, and \( C_w \) the specific heat of pure water at 0 °C.

The heat flux exported from the ice forming layer into the laminar layer is

\[
H_{in-af} = I_0 L_d + C_w R_{af-di} \left( \frac{T_1 + T_2}{2} - T_0 \right)
\]

(19)

The bulk heat flux between the laminar and airstream is

\[
H_{af-a} = -k_w \left( \frac{T_1 - T_2}{y_2 - y_1} - C_w R_{af-di} \left( \frac{T_1 + T_2}{2} - T_2 \right) \right)
\]

(20)

where \( k_w \) is the thermal conductivity of water (0.58 W · m⁻¹ · K⁻¹).

The energy balance for the outer surface of the laminar film is

\[
H_c + H_s = 0
\]

(21)

where \( H_c \) is the heat flux on the outer surface of the laminar film, and \( H_s \) the conductive heat flux directed through the laminar layer into airstream from the ice forming layer, which is a component of \( H_{af-a} \).

The conductive heat flux is

\[
H_c = k_w \left( \frac{T_1 - T_2}{y_2 - y_1} \right)
\]

(22)

\( H_s \) can be expressed as follows (more details can be found in Ref. 23):

\[
H_s = -k_c (T_2 - T_3) - \frac{v h_b L_v}{c_p \rho_a} \left( \frac{P_r}{\rho_c} \right)^{0.63} (e_3 - R H e_3)
- \sigma (T_2 - T_3) - c_w R_{imp}(T_2 - T_{imp})
\]

(23)

where \( k_c \) and \( L_v \) (2.26 × 10⁶ J · kg⁻¹) are convective heat transfer coefficient and the specific latent heat of vaporization respectively, \( e_3 \) and \( e_a \) represent the saturation vapor pressures at temperatures \( T_a \) and \( T_3 \) respectively; \( \sigma \) is the Stefan–Boltzmann constant (5.67 × 10⁻⁸), \( c \) the ratio of the molecular weights of water and dry air (0.622), and \( e_a \) linearization constant for thermal radiation (8.1 × 10⁻³). \( R \) is the relative humidity of the air, \( S_c \) is Schmidt number (0.7), and \( P_r \) is Prandtl number.

The definition of ice fraction can be written as

\[
f = \frac{I_0}{I_0 + R_0}
\]

(24)

\( k \) is the function of \( k_w \) and \( k_i \):

\[
k = k f + k_i (1 - f)
\]

(25)

where \( k_i \) is the thermal conductivity of ice (2.25 W · m⁻¹ · K⁻¹).

5. Icing regimes

Once the thermal profile of surficial layers is known, the growth regime can be determined. Conventionally, ice shapes are generally classified as glaze, mixed and rime accretions. As air temperature rises, the spongy icing model identifies icing conditions that include the rime accretion, the spongy without water film, the spongy with water film, and the glaze accretion. The outer surface temperature of the laminar layer, \( T_2 \) is determined by the heat balance equation for the outer surface of the laminar layer. If the calculated flux of entrapped liquid satisfies the condition, \( R_0 = 0 \), then the glaze icing regime will occur, i.e. both \( f \) and \( R_0 \) are equal to zero. The spongy with water film regime is predicted if the impinging mass flux of water is large enough to form both a water film of excess liquid and a spongy accretion, i.e. \( R_{out} > 0 \). As the temperature drops, the formation rate of pure ice becomes larger (Eq. (13)). If the impinging flux, \( R_{imp} \) is large enough to form a spongy accretion with no excess liquid (\( R_{out} = 0 \)), and the formation rate of pure ice is less than the impinging flux (i.e. \( I_0 < R_{imp} \) but \( I_0 + R_0 > R_{imp} \)), in this case the spongy without water film regime occurs. If \( T_2 \) is below 0 °C and the formation rate of pure ice is more than the flux of impinging droplets, no liquid will be entrapped and the ice growth rate can be determined by the flux of impinging droplets, and rime regime occurs.

6. Further study of spongy icing model

In Messinger icing model, one assumption is that the temperature of interface between the liquid and the ice is 0 °C, and the interface is infinitely small. Messinger model can predict rime ice, mixed ice and glaze ice, when glaze ice occurs, the surface temperature equals 0 °C. But in the present model the spongy ice layer, the icing interface and the water film must be supercooled in order to drive the conductive heat away from the icing interface towards the airstream, which has been concluded in experiments. 13 When there is no water entrapped in the spongy ice layer, the ice fraction equals 1. In rime and glaze cases, the ice fraction equals 1. For the present model, the growth rate of the ice matrix will not be less than the rate of the supercooled liquid through the icing interface:

\[
V_0 = \frac{I_0}{\rho_l} \left( \frac{R_0}{\rho_w} \right) \geq V_c = a(\Delta T)^{b} = \frac{I_0 + R_0}{\rho_w}
\]

(26)

In both rime or glaze ice cases, \( R_0 = 0 \) and we can substitute Eq. (11) into Eq. (10):

\[
T_0 - T_i = \frac{q_i(y_1 - y_o)}{2k} = \left( \frac{I_0 L_d - C_w h_0 \Delta T (y_1 - y_o)}{2k} \right)
\]

(27)

Substituting Eqs. (15) and (16) into Eq. (27):

\[
I_0 = \frac{2k \Delta T}{k_c (c + d) \Delta T (L_d - C_w \Delta T)}
\]

(28)

Substituting Eq. (28) into Eq. (26), we have the following equation:

\[
-C_w \Delta T^b + (L_c - C_w d) \Delta T^{b-1} + L_d \Delta T^{b-2} - \frac{2k}{ak_c \rho_l} \leq 0
\]

(29)
Then, we can solve the above equation. For example, when $t_o = -4.4 \, ^\circ C$, it can be solved as $\Delta T \leq 0.743 \, ^\circ C$, which means when $t_o = -4.4 \, ^\circ C$, glaze regime occurs, and the icing interface temperature will be hold in this range $0 > T_i \geq -0.743 \, ^\circ C$.

7. Results

In Figs. 4 and 5, the water collection efficiency $\beta$ is plotted vs surface distance $s$ in mm. The surface distance is measured from the nose (a reference point where $s = 0$ mm) corresponding to the location where $\gamma$ equals zero. For the clean airfoil, the nose is at the leading edge; for the iced airfoils, the nose is located between the ice horns. Note that negative surface distance corresponds to the upper surface of the airfoil.

Analysis of small and large droplets impingement data for all geometries tested are presented in this section. The analysis impingement data are obtained with present code and LEWICE. Figs. 4–6 show the analysis data for the clean NACA23012 airfoil and the 22.5 min iced NACA23012 airfoil.

**Fig. 4** Numerical and experimental results for the clean NACA23012 airfoil.
at 2.5° of AOA. Also shown are the experimentally measured values reported in Ref. 16.

7.1. Impingement on clean NACA23012 airfoil

A Lagrangian particle tracking code usually computes droplets trajectories and uses them to calculate the water collection efficiency. However, for the Eulerian approach, the trajectories are not required for the computation of the collection efficiency. However, from the trajectories, one can tell the impingement limits easily. Fig. 4(a) and (b) demonstrate the streamlines and droplet trajectories for the clean NACA23012 airfoil with MVD = 20 μm. From the streamlines and the trajectories, it can be seen that droplets hit the leading edge due to the inertia, while the flow streamlines have the tendency to avoid the droplets hitting on the airfoil. For the case of MVD = 20 μm, the agreement between the experimental and CFD results is good. For the case of larger MVD = 111 μm, however, both the present code and the LEWICE code predict greater impingement limits and higher water collection efficiency compared to the experimental data. The possible reason is that the present code and the LEWICE code do not account for the splashing effect, which is very common especially when the MVD is greater than 40 μm. It should be noted that the collection efficiency solved by the Eulerian method is lower than the collection efficiency solved by the Lagrangian method, especially around the nose of the airfoil (s = 0).

7.2. Impingement on NACA23012 with 22.5 min glaze ice shape

For the case of the 22.5 min ice shape and the large MVDs (52 and 111 μm), the LEWICE results in the downstream region of the horns (Region A, Figs. 5(d) and (f)) show a gradual decrease in β (collection efficiencies) compared to a sharp drop in the experimental and the present study results. The reason for this is due to the interpolation scheme used in the Lagrangian method. Generally, the interpolation scheme is fine; however, it has difficulties for geometries with multiple impingement regions which can occur on multi-element wings, highly cambered wings, and complex ice shapes. For example, one trajectory tangent with the aft impingement limit of a forward impingement region (Point Q, Fig. 6(d)) and another trajectory represents the forward limit of the aft impingement region (Point N, Fig. 6(d)); the collection efficiency between the two regions should be zero. However, for the Lagrangian method, it is not zero because of the interpolation scheme.

From Figs. 4 and 5, the results from the present study and the LEWICE code indicate higher local collection efficiency and greater impingement limits than the experimental results. There are three reasons for this. First, there is difference...
between the actual and the computed flow field, particularly in the region between the horns. Second, the droplet splashing is not simulated in the present code and the LEWICE code. Third, the errors are associated with the experimental investigation.

7.3. Comments on droplet trajectories

The droplet trajectories for an iced airfoil are depicted in Fig. 6 to illustrate the trends of impingement distribution in the present study. The presented droplet trajectories are for the 22.5 min ice shape with the 20, 52, and 111 µm MVD spray clouds. All trajectory computations are performed with the present code. The droplet trajectories shown in Fig. 6(b) for the 20 µm case demonstrate considerable deflection in the vicinity of the ice shape. As MVD becomes larger, the deflection of trajectories becomes progressively smaller (as shown in Fig. 6(c)); when MVD comes to 111 µm, the trajectories are practically straight (Fig. 6(d)). The reason for this is when MVD becomes larger, the inertia of the droplets becomes bigger too, so it is hard for streamlines to avoid the droplets hitting on the airfoil. Multiple local impingement peaks were observed between the ice horns. Fig. 6(d) can be used to explain how these peaks form. For example, the collection efficiency will be relatively high near Point D on the lower ice horn, for the surface is nearly normal to the incoming droplets; when the droplets hit the surface between Points D and E, the efficiency decreases due to the local slope of the surface. The reason of the peaks in the experimental results is the same as that of the peaks in the numerical results. However, the water re-impingement due to the droplet splashing may be the other reason.

Fig. 6 Streamlines and droplet trajectories for iced NACA23012.

Fig. 7 Comparison of numerical and experimental data at −19.4 °C.
7.4 Ice accretion on NACA0012

The computation is performed at four different temperatures. Figs. 7–10 show the ice shapes after six minutes of simulation from the LEWICE and the present code, which are compared to the experimental data provided by Shin and Bond.\(^4\) Fig. 7 shows the predicted ice shape at \(-19.4\) °C, the ice fraction, and the mass flux of the control volume. There is no water film on the surface, and no droplet is entrapped. This is a typical rime ice. The predicted ice shape agrees well with the measured ice shape. Since it is rime and it is combined with the same Eulerian code, the spongy icing model and Messinger Model predict the same shape. Fig. 8 shows the other type of dry regime, called spongy without water film. The ice fraction holds in \((0,1)\), and there is no mass flux flow out of the control volume. For the temperature is relatively low, the Messinger model and spongy icing model do not have much difference, but the LEWICE predicts greater volume than the present code does. For the case of \(-10.0\) °C (Fig. 9), this is a kind of wet ice accretion regime, named spongy with water film. The ice fraction holds in \((0,1)\) too, which means the liquid is entrapped in the spongy ice. The ice shape predicted by the present code with spongy icing model agrees well at suction side of the airfoil but slightly over-predicted at pressure side; while for the Messinger model, the ice shape fits not so well. There are some differences in predicted ice shapes calculated with spongy icing model and Messinger model, which is mainly due to the difference of predicted convective heat transfer coefficient. When it comes to \(-4.4\) °C (Fig. 10), the predicted ice shape is a typical wet regime, glaze ice. The spongy icing model predicts a horn on the upper surface, which is the same as the LEWICE code does.

During the ice accretion process, it has been shown that the surface temperature is below the freezing point of water,\(^{13}\) while it has been assumed that the temperature of the interface of ice and water film is at freezing point in Messinger model. Fig. 10(b) shows the surface temperature predicted at \(-4.4\) °C by both models. The surface temperature predicted by Messinger model equals 0 °C while predicted by spongy icing model is below 0 °C; the temperature difference is up to 0.757 °C.

As noted above, for temperatures equal to \(-19.4\) and \(-4.4\) °C, corresponding to rime and glaze regime respectively. But for the other two cases (\(-13.3\) and \(-10.0\) °C), one is spongy without water film, another is spongy with water film.

7.5 Prediction of ice accretion and surface temperature on a cylinder

The experimental results of Ref.\(^{14}\) are chosen to validate the capability of the surface temperature prediction. During his
experiment, in order to measure the surface temperature of a cylinder, a non-destructive remote sensing technique was employed. Test conditions are listed in Table 3. The ice shape predicted by the present code is similar to the measured shape (Fig. 11(a)). However, the thickness near the impingement limits is under-predicted and the ice thickness at stagnation point is over-predicted.

For the surface temperature shown in Fig. 11(b), both predicted and experimental results are below 0 °C. The predicted temperature is slightly higher than the experimental data, but the trend of the surface temperature is consistent.

8. Conclusion

A new spongy icing model based on Eulerian approach has been developed to describe glaze, spongy with water film, spongy without water film, and rime ice. A variety of experiments with different test conditions have been carried on in the NASA Lewis Icing Research Tunnel; the key parameters of the icing model are calibrated by these experimental data. The spongy icing model can be applied to aircraft icing condition, and it has a wide scope of application. The LWC range is 0–3.0 g/m³, the MVD range is 8.0–156.0 μm, the velocity range is 0–200.0 m/s, the pressure range is 47.217–101.325 kPa and the temperature range is −30.0–0 °C.

To avoid numerical oscillations, a permeable wall condition is employed. Because of the numerical artifact caused by the interpolation scheme, the Eulerian approach is more feasible and accurate than the Lagrangian approach.

There are three differences between traditional models and the present icing model. The first one is the definition of the surface temperature. It has been assumed that the temperature of the interface between ice and water film is at the freezing point in traditional models, while in spongy icing model, the temperature of the interface is supercooled (e.g. when test temperature is −4.4 °C, the temperature difference is up to 0.757 °C, as shown in Fig. 10(b)). The second one is the capability of describing icing regimes. The present model can describe four different regimes while traditional models can only describe three at best. The last one is the capability of describing the sponginess of ice accretion which is observed by Fraser. The computational results are in good agreement with the experimental data. The results also point out the necessary of incorporating a droplet splash model into the present code.

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