Aircraft Icing
Parallel Computation of Droplet Trajectories

Prof. Dr. Serkan ÖZGEN
Dept. Aerospace Engineering, METU
November 2019
Outline

• Introduction
• Methodology
  o Flow field
  o Droplet trajectories
  o Convective heat transfer coefficients
  o Ice accretion rates, Extended Messinger Model
  o Parallel Processing
• Results and discussion
Introduction

• Accurate representation of droplet physics (trajectories, deformation, breakup and splash) is of great importance for reliable ice accretion calculations.

• Computation of droplet trajectories is the most time-consuming step in the Langrangian approach.

• Reducing computational time is important for parametric studies.
Introduction

• Wing is divided into 2, 4, 8, 16, 24 or 32 spanwise segments.
• Emphasis is on reduction of computational time.
• Dependence of the results on number of spanwise segments is also addressed to.
• Comparisons with numerical and experimental data are done to validate the results.
Geometry (GLC-305 airfoil)
Methodology – flow field

• 3-D panel method is employed for:
  o Constructing a velocity potential at any point in the domain so that flow velocity components can be obtained for droplet trajectory calculations.
  o Boundary-layer calculations in order to compute the convective heat transfer coefficient distribution.
Methodology – droplet trajectories

• Assumptions:
  o Presence of the droplets do not affect the flow field.
  o Gravity and aerodynamic drag are the only forces acting on the droplets.
  o Non-spherical droplets are accounted for through an appropriate drag law.
Methodology – droplet trajectories

• Equations of motion

\[ m\ddot{x}_p = -D \cos \gamma_1, \]
\[ m\ddot{y}_p = -D \cos \gamma_2, \]
\[ m\ddot{z}_p = -(D \cos \gamma_3 + mg), \]

with

\[ \gamma_1 = \tan^{-1} \left( \frac{\dot{x}_p - V_x}{V_{rel}} \right), \quad \gamma_2 = \tan^{-1} \left( \frac{\dot{y}_p - V_y}{V_{rel}} \right), \quad \tan^{-1} \left( \frac{\dot{z}_p - V_z}{V_{rel}} \right), \]

\[ D = \frac{1}{2} \rho V_{rel}^2 C_D A_p, \]

\[ V_{rel} = \sqrt{\left(\dot{x}_p - V_x\right)^2 + \left(\dot{y}_p - V_y\right)^2 + \left(\dot{z}_p - V_z\right)^2}. \]

\( V_x, V_y, V_z \): flow velocity components at the droplet location.

\( \gamma_1, \gamma_2, \gamma_3 \): droplet velocity vector angles
Methodology – droplet trajectories
Methodology – boundary-layer calculations

• Boundary-layer calculations are done in order to obtain the convective heat transfer coefficient distribution.
• Wing is divided into segments and 2-D integral boundary-layer equations are solved for each.
• Boundary-layer calculations start at the stagnation point and march downstream for upper and lower surfaces.
• Transition from laminar to turbulent flow is based on the roughness Reynolds number:

\[ \text{Re}_k = \frac{\rho U_k k_s}{\mu} \]
Methodology – ice accretion, Extended Messinger Model

- Phase change problem is governed by four equations:

\[
\frac{\partial T}{\partial t} = \frac{k_i}{\rho_i C_{pi}} \frac{\partial^2 T}{\partial y^2}, \text{ energy equation in the ice layer,}
\]

\[
\frac{\partial \theta}{\partial t} = \frac{k_w}{\rho_w C_{pw}} \frac{\partial^2 \theta}{\partial y^2}, \text{ energy equation in the water layer,}
\]

\[
\rho_i \frac{\partial B}{\partial t} + \rho_w \frac{\partial h}{\partial t} = \rho_a \beta V_\infty + \dot{m}_{in} - \dot{m}_{e,s}, \text{ mass conservation equation,}
\]

\[
\rho_i L_f \frac{\partial B}{\partial t} = k_i \frac{\partial T}{\partial y} - k_w \frac{\partial \theta}{\partial y}, \text{ phase change condition at the ice - water interface.}
\]

\[B, h: \text{ ice and water layer thicknesses,}
\]

\[T, \theta: \text{ ice and water temperatures.}\]
Methodology – ice accretion, Extended Messinger Model

Initial and boundary conditions:

- Ice is in perfect contact with wing surface:
  \( T(0, t) = T_s. \)
  Surface temperature is the recovery temperature:
  \[
  T_s = T_a + \frac{V_\infty^2 - U_e^2}{2C_p} \left( \frac{1 + 0.2rM^2}{1 + 0.2M^2} \right)
  \]
  - Temperature is continuous at the water-ice interface:
    \( T(B, t) = \theta(B, t) = T_f \): freezing temperature.
  - Wing surface is initially clean:
    \( B(0,0) = h(0,0) = 0. \)
Methodology – ice accretion, Extended Messinger Model

• At the air/water (glaze) or air/ice interface (rime), heat flux is determined by convection, radiation, latent heat release, cooling by incoming droplets, heat brought in by runback water, evaporation (or sublimation), aerodynamic heating, kinetic energy of incoming droplets:

Glaze ice: \[-k_w \frac{\partial \theta}{\partial y} = \left( Q_c + Q_e + Q_d + Q_r \right) - \left( Q_a + Q_k + Q_{in} \right) \text{ at } y = B + h,\]

Rime ice: \[-k_i \frac{\partial T}{\partial y} = \left( Q_c + Q_s + Q_d + Q_r \right) - \left( Q_a + Q_k + Q_{in} + Q_l \right) \text{ at } y = B.\]
Methodology – parallel processing

• Only the droplet trajectories are computed in parallel.
• Parallel processing is applied by implementing mpi with mpich libraries.
• The computing environment consists of distributed PCs with Linux operating systems forming a parallel PC cluster.
• The cluster has 64 nodes.
• Each PC is equipped with Intel Core™ 2 Duo processors with 8 Gb RAM.
• Each node is interconnected with Gb switches.
## Results

- Experimental conditions (Papadakis et al, 2003)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha ), angle of attack (°)</td>
<td>4</td>
</tr>
<tr>
<td>( V_\infty ), freestream velocity (mph)</td>
<td>250, 200, 150</td>
</tr>
<tr>
<td>( T_t ), total temperature (°F)</td>
<td>25, 11.7, 25</td>
</tr>
<tr>
<td>( \rho_a ), liquid water content (g/m³)</td>
<td>0.68, 0.51, 0.65</td>
</tr>
<tr>
<td>( t_{\text{exp}} ), exposure time (min)</td>
<td>2, 5, 10</td>
</tr>
<tr>
<td>( d_p ), droplet diameter (μm)</td>
<td>20, 14.5, 20</td>
</tr>
</tbody>
</table>
Results – ice shapes and thickness distribution (CS2)
Results – comparison of parallel and sequential results (midspan CS2)
Results – effect of # of spanwise panels (midspan CS2)
Performance metrics for parallel processing

• Speed-up:

\[ S_p = \frac{T_1}{T_p} \]

• Efficiency:

\[ E_p = \frac{T_1}{pT_p} = \frac{S_p}{p} \]

\( T_1 \): CPU time with one processor,
\( T_p \): CPU time with \( p \) processors,
\( p \): Number of processors.
Results – effect of # of processors on CPU time (CS2)
Results – effect of # of spanwise panels on ice mass (CS2)
Results – speed-up

- Chart showing the relationship between the number of processors and speed-up.

- The x-axis represents the number of processors, ranging from 0 to 24.

- The y-axis represents speed-up (S), ranging from 0 to 12.

- The graph indicates an increasing trend of speed-up with the number of processors.
Results – efficiency

![Graph showing efficiency vs. number of processors]
Results – ice shapes (CS2)
Results – ice shapes (SC5)
Results – ice shapes (IS10)