MODIFICATION OF THE EXTENDED MESSINGER MODEL FOR MIXED
PHASE ICING AND INDUSTRIAL APPLICATIONS WITH TAICE

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OUTLINE

- Introduction
- TAI ice accretion prediction in house developed tool, TAICE
- Brief information about the implemented models
- Modification of the Extended Messinger Model for mixed phase icing
- Validation of the developed tool
- Industrial Applications with TAICE
- Conclusion
Ice crystal ingestion to aircraft engines may cause ice to accrete on internal components,
- leading to flameout,
- mechanical damage,
- rollback, etc.

Numerous in-flight incidents, which have occurred generally in tropical regions and at high altitude convective weather conditions made researchers to investigate ice accretion due to ice crystals.

Within the last years several projects and groups have focused on this topic. High Altitude Ice Crystals (HAIC) project is one of them.

In the framework of HAIC FP7 European Project, the physical mechanisms of ice accretion on surfaces exposed to ice-crystals and mixed-phase conditions are investigated.
Two-layer modeling (Extended Messinger Model) seems a promising alternative to the Messinger Model.

Most of the Messinger Model assumptions and limitations are dropped off as a more accurate treatment of the transient behavior and of the heat transfer across the layers and the substrate are introduced.

Nevertheless, no extension of such models to the mixed phase conditions have been proposed in the literature so far.

A great advantage of the two-layer model lies in the fact that it is much easier to take into account the influence of the water film on particle impingement, heat transfer and phase change phenomena.
• Hess-Smith Panel Method for flow field computations.

• Lagrangian approach for particle trajectory and collection efficiency calculations.

• Integral Boundary Layer Method for convective heat transfer coefficient calculations.

• Extended Messinger Model for computation of ice accretion rates.

• Flow solution coupling of Euler/Navier-Stokes Solver and remeshing capability for 2D multilayer ice accretion.

• Ice accretion prediction capability using parallel computation of particle trajectories in 3D multilayer ice accretion.
Implemented Models

- Holzer&Sommerfeld Drag Force Coefficient Model
- ONERA Models for Heat Transfer & Phase Change and Impingement
- Modified and further calibrated NASA Erosion Model
- Further Extended Messigner Model for Accretion
Further Extended Messinger Model

• Originally Myers (2001) extended the Original Messinger Model.

• A mathematical model has been developed to determine ice and water growth in the presence of incoming droplets only.

• The main advantages of using the current approach are that it provides
  ▪ The temperature profiles in the ice and water separately,
  ▪ Exact formula for the ice thickness at which glaze ice is observed and transition from rime ice to glaze ice is continuous.

• Up to now this approach has not been extended for mixed phase icing cases.

• In our model, Extended Messinger Model is further extended. Thus,
  ▪ Ice and water layers are modeled separately,
  ▪ Ice crystals are taken into account in the current calculations.
Further Extended Messinger Model

energy equation in the ice layer

\[
\frac{\partial T}{\partial t} = \frac{k_i}{\rho_i C_{pi}} \frac{\partial^2 T}{\partial y^2},
\]

energy equation in the water layer

\[
\frac{\partial \theta}{\partial t} = \frac{k_w}{\rho_w C_{pw}} \frac{\partial^2 \theta}{\partial y^2},
\]

mass balance

\[
\rho_i \frac{\partial B}{\partial t} + \rho_w \frac{\partial h}{\partial t} = r_l \rho_l \beta_l V_\infty + r_c \rho_c \beta_c V_\infty + \dot{m}_{in} - \dot{m}_{e,s},
\]

phase change (Stefan) condition

\[
\rho_i L_f \frac{\partial B}{\partial t} = k_i \frac{\partial T}{\partial y} - k_w \frac{\partial \theta}{\partial y}.
\]

Impinging droplet mass flux = \( r_l \rho_l \beta_l V_\infty \)

Impinging crystal mass flux = \( r_c \rho_c \beta_c V_\infty \)
• **Boundary & initial conditions:**
  - Surface is initially clean and the substrate temperature is assumed to have a fixed and known value:
    \[
    T(0, t) = T_{sub}, \quad B = h = 0
    \]
  - The temperature is continuous at the phase change boundary \((y = B)\) and equal to the freezing temperature:
    \[
    T(B, t) = \theta(B, t) = T_f.
    \]
  - In rime ice condition energy transfer is applied at ice-air contact surface:
    \[
    -k_i \frac{\partial T}{\partial y} = E_{in} - E_{out} \text{ at } (y = B)
    \]
  - In glaze ice condition energy transfer is applied at water-air contact surface:
    \[
    -k_w \frac{\partial \theta}{\partial y} = E_{in} - E_{out} \text{ at } (y = B+h)
    \]
Further Extended Messinger Model

- **Rime ice Growth:**
  The temperature profile in the ice layer is assumed to be linear:

  \[ \frac{\partial^2 T}{\partial y^2} = 0 \quad T(y, t) = a_1 \cdot y + T_{subs} \]

  \[ B(t) = \frac{r_l \rho_l \beta_l V_\infty + r_c \rho_c \beta_c V_\infty + \dot{m}_{in} - \dot{m}_{sub}}{\rho_r} \]

  Heat transfer at ice/air interface:

  \[ -k_i \frac{\partial T}{\partial y} = (Q_{con} + Q_{sub} + Q_{cl} + Q_{cc}) - (Q_{aero} + Q_{kl} + Q_{kc} + Q_{lat} + Q_{in}) \]

  - Convection
  - Sublimation
  - Cooling by incoming droplets
  - Cooling by incoming crystals
  - Aerodynamic Heating
  - Kinetic energy of incoming particles (droplets+crystals)
  - Latent heat release
  - Energy brought in by runback water

Air \rightarrow Ice \rightarrow Substrate
Further Extended Messinger Model

• **Scenarios In Glaze Ice Growth:**
  • While calculating ice growth in the *rime ice* condition:
    ▪ Since all upcoming water droplets and liquid parts of the partially melted ice crystals freeze, water layer **does not appear** above the ice surface.
  • However, when the temperature of the ice layer surface reaches to melting point:
    ▪ Glaze icing condition occurs and
    ▪ Water starts to accumulate on the surface.
  • However, the physical phase of ice crystals becomes a **question mark**.

\[ \eta_{melt} = ? \]

• Depending on the energy transfer between ice crystals and accreted ice and water layers, upcoming ice crystals may completely or partially melt or they could stay as solid.
Further Extended Messinger Model

- **Scenarios In Glaze Ice Growth:**
  \[
  \lambda_{net} = \lambda_{in} - \lambda_{out} - \lambda_{h,w} - \lambda_{h,i}
  \]
  Heat transfers due to droplets due to runback water in
  \[
  \lambda_{h,w} = r_l \rho_l \beta_l V_\infty C_{pw} [T_f - T_l] + \dot{m}_{in} C_{pw} [T_f - T_{in}]
  \]
  Heat transfer due to solid part of crystals
  \[
  \lambda_{h,i} = r_c \rho_c \beta_c V_\infty (1 - \eta_{melt}) C_{pi} [T_f - T_c] + r_c \rho_c \beta_c V_\infty \eta_{melt} C_{pw} [T_f - T_c]
  \]
  Kinetic Energy terms:
  \[
  \lambda_{in} = r_l \beta_l V_\infty \frac{V_{imp,l}^2}{2} + r_c \beta_c V_\infty \frac{V_{imp,c}^2}{2}
  \]
  Convection term
  \[
  \lambda_{out} = h_c [T_{rec} - T_f] + \dot{m}_{ev} L_{ev}
  \]
  Heat loss due to evaporation

- Heat loss by melting part of ice crystals unbalances the energy equation and this unbalance must be compensated by additional freezing or melting.
- Melting ratio can be calculated as follows:
  \[
  \alpha_{melt} = \frac{\lambda_{net}}{r_c \rho_c \beta_c V_\infty L_f}
  \]
Further Extended Messinger Model

- Scenarios In Glaze Ice Growth:

  \[ \lambda_{net} = \lambda_{in} - \lambda_{out} - \lambda_{h,w} - \lambda_{h,i} \]
  \[ \alpha_{melt} = \frac{\lambda_{net}}{r_c \rho_c \beta_c V_\infty L_f} \]

  - When \( \lambda_{net} < 0 \) all upcoming ice crystals will stay as solid even after impact. Surface temperature of the water layer will be less than melting temperature.

  - When \( \lambda_{net} > 0 \) and \( \alpha_{melt} < 1 \) some energy is available in the control volume and it will melt some part of the ice crystals. Surface temperature of the water layer will be equal to melting temperature.

  - When \( \lambda_{net} > 0 \) and \( \alpha_{melt} > 1 \) some energy is available in the control volume and all ice crystals will melt. Remaining energy will increase the temperature of the water layer and the surface temperature of the water layer will be greater than melting temperature.
Further Extended Messinger Model

- **Glaze ice Growth:**
  Assume that temperature profile is linear in both water and ice layers:

\[
\frac{\partial^2 T}{\partial y^2} = 0 \quad T(y, t) = a_3 \ast y + a_4 \quad \quad \frac{\partial^2 \theta}{\partial y^2} = 0 \quad \theta(y, t) = a_5 \ast y + a_6
\]

Heat transfer at water/air interface:

\[-k_w \frac{\partial \theta}{\partial y} = (Q_{con} + Q_{ev} + Q_{cl} + Q_{cc}) - (Q_{aero} + Q_{kl} + Q_{kc} + Q_{in})\]

- **Convection**
- **Evaporation**
- **Cooling by incoming droplets**
- **Cooling by incoming crystals**
- **Aerodynamic Heating**
  Kinetic energy of incoming particles (droplets+crystals)
  Energy brought in by runback water

**Diagram:**

- Air
- Water
- Ice
- Substrate
Further Extended Messinger Model

- **Rime to Glaze Transition:**

- Equate ice accretion rates \( \frac{\partial B_l}{\partial t} \) at the water-ice interface \((y=B)\) and set \( h = 0 \).

\[
\frac{\partial B_l}{\partial t} = \frac{r_l \rho_l \beta_l V_\infty + \eta_{melt} r_c \rho_c \beta_c V_\infty + \dot{m}_{in} - \dot{m}_{sub}}{\rho_r} \]

Accretion rate for rime ice

\[
\rho_g L_f \frac{\partial B_l}{\partial t} = k_i \frac{T_f - T_{sub}}{B_l} - k_w a_5
\]

Accretion rate for glaze ice

Ice thickness at which water first appears

\[
B_g = \frac{K_i(T_f - T_{sub})}{(r_l \rho_l \beta_l V_\infty + \eta_{melt} r_c \rho_c \beta_c V_\infty + \dot{m}_{in} - \dot{m}_{sub})L_f + k_w a_5}
\]

Time at which water first appears

\[
T_g = \frac{\rho_r}{r_l \rho_l \beta_l V_\infty + r_c \rho_c \beta_c V_\infty + \dot{m}_{in} - \dot{m}_{sub}} B_g
\]
COX Icing wind tunnel experiments

- COX Icing wind tunnel experiments (Glaze Ice Cases)

<table>
<thead>
<tr>
<th>Run Number</th>
<th>True Airspeed (m/s)</th>
<th>Total Temp. (°C)</th>
<th>Total Pressure (kPa)</th>
<th>IWC (g/m³)</th>
<th>LWC (g/m³)</th>
<th>Crystal MVD (μm)</th>
<th>Droplet MVD (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>53.6</td>
<td>-5.55</td>
<td>100</td>
<td>-</td>
<td>0.7</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>53.6</td>
<td>-5.55</td>
<td>100</td>
<td>0.7</td>
<td>0.7</td>
<td>200</td>
<td>20</td>
</tr>
</tbody>
</table>

Run 9

Run 10
### COX Icing wind tunnel experiments

- COX Icing wind tunnel experiments (Rime Ice Cases)

<table>
<thead>
<tr>
<th>Run Number</th>
<th>True Airspeed (m/s)</th>
<th>Total Temp. (°C)</th>
<th>Total Pressure (kPa)</th>
<th>IWC (g/m³)</th>
<th>LWC (g/m³)</th>
<th>Crystal MVD (μm)</th>
<th>Droplet MVD (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>53.6</td>
<td>-11.1</td>
<td>100</td>
<td>0.7</td>
<td>0.3</td>
<td>150</td>
<td>20</td>
</tr>
<tr>
<td>20</td>
<td>53.6</td>
<td>-11.1</td>
<td>100</td>
<td>0.3</td>
<td>0.7</td>
<td>150</td>
<td>20</td>
</tr>
</tbody>
</table>

#### Diagrams

**Run 19**

![Diagram for Run 19](image)

**Run 20**

![Diagram for Run 20](image)
### NRC / NASA Icing wind tunnel experiments

- NRC / NASA Icing wind tunnel experiments

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Mach Number</th>
<th>Total Temp. (°C)</th>
<th>Total Pressure (kPa)</th>
<th>Relative Humidity (%)</th>
<th>IWC (g/m³)</th>
<th>LWC (g/m³)</th>
<th>Crystal MMD (μm)</th>
<th>Droplet MVD (μm)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.25</td>
<td>13</td>
<td>44.8</td>
<td>8</td>
<td>7</td>
<td>2.9</td>
<td>70</td>
<td>40</td>
</tr>
<tr>
<td>553</td>
<td>0.25</td>
<td>6</td>
<td>44.8</td>
<td>30</td>
<td>7</td>
<td>2.9</td>
<td>70</td>
<td>40</td>
</tr>
</tbody>
</table>

#### Run 543

- Clean
- TAICE With Erosion
- TAICE Without Erosion

#### Run 553

- Clean
- TAICE With Erosion
- TAICE Without Erosion
Engine Inlet Case

Aim of the case (axisymmetric):
- Calculation of the air intake area loss for the following mixed phase icing cases.
- Evaluation of the engine intake model implemented to TAICE.

<table>
<thead>
<tr>
<th>IWC</th>
<th>LWC</th>
<th>(m/\text{s})</th>
<th>Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3</td>
<td>0.7</td>
<td>7.8</td>
</tr>
<tr>
<td>2</td>
<td>0.7</td>
<td>0.3</td>
<td>7.8</td>
</tr>
<tr>
<td>3</td>
<td>0.3</td>
<td>0.7</td>
<td>10.4</td>
</tr>
<tr>
<td>4</td>
<td>0.7</td>
<td>0.3</td>
<td>10.4</td>
</tr>
<tr>
<td>5</td>
<td>0.3</td>
<td>0.7</td>
<td>7.8</td>
</tr>
<tr>
<td>6</td>
<td>0.7</td>
<td>0.3</td>
<td>7.8</td>
</tr>
<tr>
<td>7</td>
<td>0.3</td>
<td>0.7</td>
<td>10.4</td>
</tr>
<tr>
<td>8</td>
<td>0.7</td>
<td>0.3</td>
<td>10.4</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>0.7</td>
<td>7.8</td>
</tr>
<tr>
<td>10</td>
<td>-</td>
<td>0.7</td>
<td>10.4</td>
</tr>
<tr>
<td>11</td>
<td>-</td>
<td>0.7</td>
<td>7.8</td>
</tr>
<tr>
<td>12</td>
<td>-</td>
<td>0.7</td>
<td>10.4</td>
</tr>
</tbody>
</table>

- Crystal Diameter = 100 μm
- Droplet Diameter = 20 μm
- Static Pressure = 95.84 kPa
- Flight Speed = 75 m/s
- Angle of Attack = 0°
Engine Inlet Case

Particle Trajectories Colored with X Velocity Components

D = 20μm Droplets

V = 200 m/s

D = 100μm Crystals

V = 75 m/s

D = 20μm
**Engine Inlet Case**

**-9.3 °C**

- Glaze ice condition
- High erosion effect is seen
- Ice crystals cause to reduce the amount of accreted ice

**IWC=- LWC=0.7 g/m³**

Run 9

**IWC=0.3 g/m³ LWC=0.7 g/m³**

Run 1

**IWC=0.7 g/m³ LWC=0.3 g/m³**

Run 2
Engine Inlet Case

-29.9 °C

- Rime ice condition
- Erosion is not observed
- Ice crystals do not effect the accreted ice shape.

IWC= -  LWC=0.7 g/m³

Run 11

IWC=0.3 g/m³  LWC=0.7 g/m³

Run 5

IWC=0.7 g/m³  LWC=0.3 g/m³

Run 6
Axisymmetric probe has been analyzed

Ice Crystal Trajectories colored with Temperature (K)

Ice Crystal Trajectories colored with X velocity Components (m/s)

<table>
<thead>
<tr>
<th></th>
<th>IWC</th>
<th>LWC</th>
<th>Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3</td>
<td>0.7</td>
<td>-9.3</td>
</tr>
<tr>
<td>2</td>
<td>0.7</td>
<td>0.3</td>
<td>-9.3</td>
</tr>
<tr>
<td>3</td>
<td>0.3</td>
<td>0.7</td>
<td>-29.9</td>
</tr>
<tr>
<td>4</td>
<td>0.7</td>
<td>0.3</td>
<td>-29.9</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>0.7</td>
<td>-9.3</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>0.7</td>
<td>-29.9</td>
</tr>
</tbody>
</table>

- Crystal Diameter = 100 μm
- Droplet Diameter = 50 μm
- Static Pressure = 95.84 kPa
- Flight Speed = 75 m/s
- Angle of Attack = 0°
Probe Case

-9.3 °C

- Mostly rime but glaze ice observed at some panels.
- Erosion effect is low due to the short glaze ice duration.

IWC=-  LWC=0.7 g/m³
Run 5

IWC=0.3 g/m³  LWC=0.7 g/m³
Run 1

IWC=0.7 g/m³  LWC=0.3 g/m³
Run 2
Probe Case

-29.9 °C

- Rime ice condition
- Erosion is not observed.
- Ice crystals do not affect the accreted ice shape.

IWC=- LWC=0.7 g/m³

Run 6

IWC=0.3 g/m³ LWC=0.7 g/m³

Run 3

IWC=0.7 g/m³ LWC=0.3 g/m³

Run 4
Conclusion

- Mixed phase icing prediction capability has been successfully added to TAICE.

- Further extension of the Original Messinger Model and implemented models increased the accuracy of the ice crystal accretion predictions.

- Calibrated erosion model yielded significant improvements on ice shapes for both NRC-NASA and COX validation cases.

- Developed tool can be used for ice crystal accretion prediction studies on different aircraft components.

- More validation cases are required for further calibration of the models and for the validity of the developed computational tool.