ICE ACCRETION DUE TO MIXED PHASE CLOUD PARTICLES
Outline

• **Introduction**
  - Brief Information About Mixed Phase Icing

• **Mixed Phase Icing Related Studies**
  - High Altitude Ice Crystals (HAIC) Project

• **Necessary Models for Mixed Phase Icing Prediction**
  - Trajectory Models: Drag Coefficient, Heat Transfer and Phase Change
  - Impingement and Erosion Models

• **Mixed Phase Icing Prediction - (Accretion Part)**
  - Original Messinger Model
  - Further Extension of the Messinger Model

• **Validation of the Methodology with Experimental Data**

• **Industrial Applications with TAICE**
  - Engine Inlet Icing Case
  - Probe Icing Case
Ice crystal ingestion to aircraft engines may cause ice to accrete on internal components,
  - leading to flameout,
  - mechanical damage,
  - rollback, etc.

Being a solid substance, ice crystals may not cause any problem for airframe at low temperatures, since they only **bounce off** when they hit the airframe.

Jain *et al*, *Chemical Engineering Sciences*, 2012
• However, when they face warmer flow conditions, they can change phase and pose a threat to flight safety of the aircraft.

• These warmer flow conditions generally occur around or within the engine, on heated components (i.e. pitot and aoa probes) where local temperatures are significantly higher than the freezing temperature.
Introduction

- Partially melted ice crystals and water droplets can impact a solid surface and can create a water film on the surface.

- As a result, the surface temperature may decrease below the freezing temperature and thus, ice accretion can occur in engine core components.
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 the ice crystals.

Larger droplets begin to freeze spontaneously to ice crystals at around -10°C and as droplets get smaller, colder temperatures are required to freeze them. By -40°C virtually are droplets will have frozen (ice crystals).
In recent years, there have been important enhancements in simulating supercooled large droplets. However, ice accretion due to ice crystals has not yet been studied extensively.

In recognition of this thread, FAA and EASA have specified new rules (FAR/CS-25 Appendix P).

To increase the understanding mechanisms of ice crystal accretion and to optimize aircraft safety in glaciated icing conditions, several projects and working groups focus on ice crystal icing research.

- High Altitude Ice Crystals (HAIC) project
- High Ice Water Content (HIWC) project
- Ice Crystal Icing Consortium (ICC)
- Engine Icing Working Group (EIWG)
High Altitude Ice Crystals (HAIC) Project

- High Altitude Ice Crystals- HAIC European Union 7th frame Project.

- 39 Companies including industrial partners, universities and institutes. Project manager is AIRBUS. TA contributed to WP6.
One of the purpose of this project is to develop and validate a computational tool for ice accretion prediction including both liquid and solid phase cloud particles. Some ice accretion prediction tools exist in literature. However, none of them is totally validated for such mixed and glaciated conditions.
Mixed Phase Ice Accretion Prediction

- Ganser
- Heider
- Levenspiel
- Holzer
- Sommerfeld
- Extension of Frössling correlation
- Extension of Mason's model
- NASA Erosion Model is modified and calibrated
- Further Extended Messinger Model
- Onera Impinging Model
- Model is further modified and calibrated
• Ice crystals might be non-spherical and may be partially solid.

A picture from Lawson et al, 2008
Ice Crystal Particle Geometric Properties

• Sphericity, crosswise sphericity, and volume equivalent diameter terms are used to model ice crystals.

\[ \Phi = \frac{\pi d_p^2}{A} \]
\[ d_p = \sqrt[3]{\frac{6v_p}{\pi}} \]

- \( A \) denotes the surface area of the particle, \( d_p \) refers to the volume equivalent diameter and \( v_p \) is the volume of the particle.

- The orientation of the particle with respect to the flow can be taken into consideration by crosswise sphericity. \( A_\perp \) is the projected area of the particle with respect to the flow.

sphericity \( \Phi = \frac{\pi d_p^2}{A} \)
crosswise sphericity \( \Phi_\perp = \frac{\pi r_p^2}{A_\perp} \)
Drag Force Coefficient Models

• Several models exist for drag coefficient calculation in the literature and some of these models are applicable to non-spherical particles and take orientation change into consideration:

  o **Haider & Levenspiel** suggest a model in terms of $\Phi$ and $Re_p$:

    $$ C_d = \left[ \frac{24}{Re_p} (1 + a(Re_p^b)) \right] + \frac{cRe_p}{Re_p + d} $$

    $$ Re_p = \frac{\rho_a d_p v_{rel}}{\mu} $$

    $$ a = \exp(2.4486\Phi^2 - 6.5481\Phi + 2.3288) $$

    $$ b = (0.5565\Phi + 0.0964) $$

    $$ c = \exp(-10.2599\Phi^3 + 18.4222\Phi^2 - 13.8944\Phi + 4.905) $$

    $$ d = \exp(15.8855\Phi^3 - 20.7322\Phi^2 + 12.2584\Phi + 1.4681) $$

  o **Ganser** model also takes crosswise sphericity into consideration:

    $$ C_d = \left[ \left( \frac{24}{Re_p^*} \right)^{0.6567} \right] + \frac{0.4305 \times Re_p^*}{Re_p^* + 3305} \times 10^{1.8148[- \log(\Phi)]^{0.5743}} $$

    $$ Re_p^* = \frac{Re_p}{\frac{2}{3} \phi^{-\frac{1}{2}} + \frac{1}{3} \phi_\perp^{-\frac{1}{2}}} $$

    $$ 10^{1.8148[- \log(\phi)]^{0.5743}} $$
Drag Force Coefficient Model

- Additional **drag model** is suggested by Hölzer and Sommerfeld. Their model also includes the effect of **orientation** of the particle:

\[
C_d = \frac{8}{Re_p} \frac{1}{\sqrt{\Phi_{\perp}}} + \frac{16}{Re_p} \frac{1}{\sqrt{\Phi}} + \frac{3}{\sqrt{Re_p}} \frac{1}{\Phi^{3/4}} + \frac{0.421}{\Phi_{\perp}} 10^{0.4(-\log(\Phi))^{0.2}}
\]
Heat Transfer and Phase Change Models

• The general form of the heat equation is:

\[ m_p c_p \frac{dT_{p,m}}{dt} = \pi d_p \frac{Nu}{\Phi} k_a (T_a - T_{p,s}) \] and,

\[ Nu = 2\sqrt{\Phi} + 0.55Pr^{1/3} \Phi^{1/4} Re_p^{1/2} \]

Modelling of ice particle melting and evaporation was first considered in the pioneering work of Mason [1956].

The model consists of three steps:

• In the first step when \( T_p < T_f \), mass and the heat transfer equation:

\[ \frac{dm_p}{dt} = -\dot{m}_{sub} = -\pi d_p \frac{Sh}{\Phi} \rho_a D_{v,a} (y_{v,s} - y_{v,a}) \]

\[ m_p c_i \frac{dT_p}{dt} = \pi d_p \frac{Nu}{\Phi} k_a (T_a - T_p) - \dot{m}_{sub} (L_f + L_v) \]
Heat Transfer and Phase Change Models

• In the second step $T_p = T_f$, particle starts to melt at melting temperature and is surrounded by a concentric water layer. Mass exchange may occur at the particle surface by evaporation. This step continues until ice particle is completely melted.
  
  o At the end of this step, particle becomes spherical.
  o Evaporation rate $\dot{m}_{ev}$ can be calculated with the following equation

\[
\dot{m}_{ev} = -\frac{dm_p}{dt} = \pi d_p \frac{Sh}{\Phi} \rho a D_{v,a}(y_{v,s} - y_{v,a})
\]

  o Then the final heat transfer equation is as follows:

\[
\pi d_p \frac{Nu}{\Phi} k_a(T_a - T_f) = \dot{m}_{ev} L_v + \dot{m}_f L_f
\]

• In the third step, when $T_p > T_f$ droplet temperature increases from melting temperature and mass exchange may occur by evaporation.

\[
m_p c_w \frac{dT_p}{dt} = \pi d_p Nu k_a(T_a - T_p) - \dot{m}_{ev} L_v
\]
Impingement Model
Impingement Model

- Ice crystal impact on a surface may result in three scenarios depending on particle and surface properties:
  - **Sticking regime**: the particle totally adheres to the wall.
  - **Bouncing regime**: the particle bounces off the wall upon impact. In this case the size and shape of the particle does not change but its velocity is altered.
  - **Shattering regime**: The particle breaks down into smaller fragments. Depending on the presence of a liquid film on the wall or water inside the impinging particle, some fragments may be re-emitted into the flow, while others may adhere to the surface.
Impingement Model

• The current model takes three possible scenarios into account. Accordingly:
  o Case $L \leq 0.5$ : quasi-elastic bouncing & no fracturing,
  o Case $0.5 \leq L \leq 90$ : inelastic bouncing & particle fragmentation
  o Case $L \geq 90$ : highly inelastic impact & high particle fragmentation

• The threshold between bouncing and shattering regimes depends on the particle kinetic energy before impact. A dimensionless number $L$, which is the ratio of the normal kinetic energy to the surface energy is defined:

$$L = \frac{\pi \rho_p d_p^3 (v_{pn})^2}{12 \pi e_\sigma T_p d_p^2} = \frac{1}{12} \frac{\rho_p d_p v_{pn}^2}{e_\sigma T_p}$$

$v_{pn}$ is the perpendicular component of the impact velocity vector and $e_\sigma$ is the surface energy per unit area.
Erosion Model

- Reduction in the amount of accreted ice due to the upcoming ice crystal particles is observed during experiments in mixed phase icing conditions. Generally, it is more noticeable in glaze icing.

- A model has been proposed by William et al (2012). The model has been slightly changed and calibrated with the recently performed experimental results.

\[
\varepsilon_{er} = \varepsilon_{ct} \left( \frac{d}{d_{ref}} \right)^2 \left( \frac{\nu_{tang}}{\nu_{tang,ref}} \right)^2 \left( \frac{IWC}{IWC_{ref}} \right)^{1/3} \left( \frac{\exp \left( 14 - \frac{Q}{RT_{surf}} \right)}{\exp \left( 14 - \frac{Q}{RT_{ref}} \right)} \right)^2
\]

\[
\dot{m}_{er} = \varepsilon_{er} \dot{m}_{imp,c}
\]

\[
\dot{m}_{er} = \dot{m}_{er,i} + \dot{m}_{er,w}
\]

\[
\dot{m}_{er,i} = \dot{m}_{er} \frac{\dot{m}_i}{\dot{m}_i + \dot{m}_w}
\]

\[
\dot{m}_{er,w} = \dot{m}_{er} \frac{\dot{m}_w}{\dot{m}_i + \dot{m}_w}
\]

\[
\dot{m}_{i,upd} = \dot{m}_i - \dot{m}_{er,i}
\]

\[
\dot{m}_{w,upd} = \dot{m}_w - \dot{m}_{er,w}
\]
For mixed phase ice accretion part two different approaches are utilized.

- Modifications on original Messinger Model
- Modifications on two-layer model (Extended Messinger Model)

Two-layer model (Extended Messinger Model) seems a promising alternative to the Original Messinger Model.

Ayan and Özgen (2017) further extended the two-layers model for the mixed phase icing conditions.

Taking into account the influence of the water film on particle impingement, heat transfer and phase change phenomena with the two-layer model is much easier.
In its original form,
• The model represents a one-dimensional, equilibrium energy balance to evaluate the equilibrium temperature onto an unheated, insulated surface exposed to icing.
• In practice, it is evaluated at discrete positions around the leading edge of the body under investigation by using a control volume approach.

Aim is to find equilibrium temperature!
• 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, i.e. smooth transition from rime to glaze ice.

• In the further extended version:
  • Ice and water layers are separately modeled,
  • Ice crystals are taken into consideration as well.
Further Extended Messinger Model

Implemented impact model suggests:

- Sticking probability of the ice crystals depends on the water film thickness on ice crystal and wall surfaces.
- Solid ice crystals just bounce off from the wall when they hit to the surface.
- They may adhere to the wall when they are partially melted or when a water film covers the wall.
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 = \[ r_l \rho_l \beta_l V_\infty \]

Impinging crystal mass = \[ r_c \rho_c \beta_c V_\infty \]
Further Extended Messinger Model

- **Rime ice Growth:**
  The temperature profile in the ice layer is assumed to be linear (Myers, 2001).

\[
\frac{\partial^2 T}{\partial y^2} = 0 \quad T(y, t) = a_1 \cdot y + T_{subs} \quad B(t) = \frac{r_l \rho_l \beta_l V_{\infty} + r_c \rho_c \beta_c V_{\infty} + \dot{m}_{in} - \dot{m}_{sub}}{\rho_r} t
\]

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
  - Latent heat release
  - Energy brought in by runback water
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 needs more attention.

\[ \eta_{melt} = ? \]

- Depending on the energy transfer between ice crystals and accreted ice and water layers, upcoming ice crystals may completely / partially melt or they could remain solid after impact.
Further Extended Messinger Model

- **Scenarios In Glaze Ice Growth:**
  \[ \lambda_{net} = \lambda_{in} - \lambda_{out} - \lambda_{h,w} - \lambda_{h,i} \]

  Heat transfer 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:

  \[ \lambda_{in} = r_l \beta_l V_\infty \frac{V_{imp,l}^2}{2} + r_c \beta_c V_\infty \frac{V_{imp,c}^2}{2} \]

  Convective term

  \[ \lambda_{out} = h_c [T_{rec} - T_f] + \dot{m}_{ev} L_{ev} \]

  Evaporative term

- 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 remain 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:

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

  Heat transfer at water/air interface:

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

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

\[
\frac{\partial B_l}{\partial t} = \frac{r_l \rho_l \beta_l V_\infty + \eta_{melt} r_c \rho_c \beta_c V_\infty + \dot{m}_{in} - \dot{m}_{sub}}{\rho_r} \tag{1}
\]

Accretion rate for rime ice

\[
\rho_g L_f \frac{\partial B_l}{\partial t} = \frac{k_i (T_f - T_{subs})}{B_l} - k_w a_5 \tag{2}
\]

Accretion rate for glaze ice

Ice thickness at which water first appears

\[
B_g = \frac{K_i (T_f - T_{subs})}{(r_l \rho_l \beta_l V_\infty + \eta_{melt} r_c \rho_c \beta_c V_\infty + \dot{m}_{in} - \dot{m}_{sub}) L_f + k_w a_5} \tag{3}
\]

Time at which water first appears

\[
t_g = \frac{\rho_r}{r_l \rho_l \beta_l V_\infty + r_c \rho_c \beta_c V_\infty + \dot{m}_{in} - \dot{m}_{sub}} B_g \tag{4}
\]
TUBS Icing Wind Tunnel experiments (0°C)

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<thead>
<tr>
<th>Run Number</th>
<th>Air Velocity (m/s)</th>
<th>Static Temp. (°C)</th>
<th>Static Pressure (Pa)</th>
<th>Relative Humidity (%)</th>
<th>IWC (g/m³)</th>
<th>LWC (g/m³)</th>
<th>Crystal MVD (μm)</th>
<th>Droplet MVD (μm)</th>
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# TUBS Icing Wind Tunnel experiments (-5°C)

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**Diagram:**

- **Run 8**
- **Run 10**
- **Run 12**
### COX Icing Wind Tunnel Exp. (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>
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**Graphs:**
- **Run 9:**
  - TAICE Orig. Messinger
  - TAICE Further Ext. Messinger
  - Clean Airfoil
  - Experimental

- **Run 10:**
  - Clean Airfoil
  - Experimental
  - TAICE
  - Twente Uni.
## COX Icing Wind Tunnel Exp. (Rime Ice Cases)

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### Diagrams

- **Run 19**
- **Run 20**
### NRC / NASA Icing wind tunnel experiments

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**Graphs:**
- **Run 543:**
  - Clean
  - TAICE With Erosion
  - TAICE Without Erosion
- **Run 553:**
  - Clean
  - TAICE With Erosion
  - TAICE Without Erosion
Engine Inlet Case

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<th>LWC</th>
<th>( m ) (kg/s)</th>
<th>Temp. (°C)</th>
</tr>
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<tbody>
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<td>6</td>
<td>0.7</td>
<td>0.3</td>
<td>7.8</td>
</tr>
<tr>
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<td>0.3</td>
<td>0.7</td>
<td>10.4</td>
</tr>
<tr>
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<td>0.7</td>
<td>0.3</td>
<td>10.4</td>
</tr>
<tr>
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<td>-</td>
<td>0.7</td>
<td>7.8</td>
</tr>
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<td>-</td>
<td>0.7</td>
<td>10.4</td>
</tr>
<tr>
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<td>-</td>
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</tr>
<tr>
<td>12</td>
<td>-</td>
<td>0.7</td>
<td>10.4</td>
</tr>
</tbody>
</table>

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.

- 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 = 200 m/s

- 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=0.3 g/m³ LWC=0.7 g/m³

Run 1

Run 9

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/m$^3$

Run 11

IWC=0.3 g/m$^3$  LWC=0.7 g/m$^3$

Run 5

IWC=0.7 g/m$^3$  LWC=0.3 g/m$^3$

Run 6
Probe Case

Ice Crystal Trajectories colored with Temperature (K)

<table>
<thead>
<tr>
<th>IWC</th>
<th>LWC</th>
<th>Temp. (°C)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
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<td>0.7</td>
</tr>
<tr>
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<td>0.3</td>
</tr>
<tr>
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<td>4</td>
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<td>0.3</td>
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<tr>
<td>5</td>
<td>-</td>
<td>0.7</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>0.7</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=0.3 g/m³**  **LWC=0.7 g/m³**

Run 1

**IWC=-**  **LWC=0.7 g/m³**

Run 5

**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 3

Run 4

IWC = 0.7 g/m³
LWC = 0.3 g/m³

Run 6

IWC = 0.3 g/m³
LWC = 0.7 g/m³
Conclusion

• Following models are required for prediction of mixed phase icing
  • Drag coefficient model
  • Heat transfer and phase change model
  • Impingement model
  • Erosion model
  • Accretion model

• Further extension of the Extended Messinger Model increased the accuracy of the ice crystal accretion predictions.

• Calibrated erosion and impingement models yielded significant improvements on ice shapes for both NRC-NASA, COX and TUBS validation cases.

• More validation cases are required for further calibration of the models.

• Issues related to film dynamics and runback water mechanism should be more focused on to better model the water film behavior.