Swept Wing Icing Physics Studies at NASA Glenn Research Center 1990-2006

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Outline

- Background
- First Icing Physics Studies
- Study on Mechanisms of Scallop Formation
- Parametric Studies
- FAA/NASA/WSU Study on Aerodynamic Effects
- Modeling of Heat Transfer over Large Roughness Elements
- Development of Roughness Elements into Feathers and Scallop Tips
- Conceptual Steps in Modeling Scallops
- Final Comments

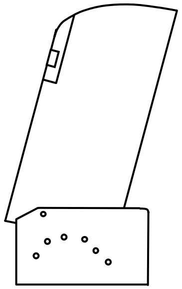
Background

V=150 mph, T_{total}=25°F, LWC=0.75g/m^3, MVD=20μm

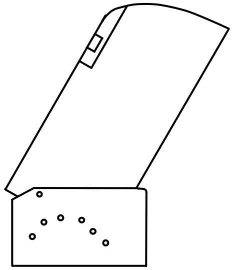
No-scallop

Incomplete Scallops

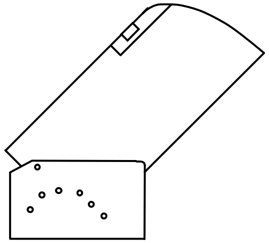
Complete Scallop



Airfoil at 15°



Airfoil at 30°



Airfoil at 45°

Background

Statement of Research Problem

- **Why, under some icing conditions, do ice accretions on swept wings exhibit the icing structures called scallop tips? Why they do not appear on straight wings?**
  - **What are the physical mechanism involved**
  - **What are the main parameters that define the phenomena**
  - **What is important in the physics of formation and what is not**
  - **How the changing icing conditions affect the formation**
  - **Is there an underlying simplicity**
  - **Can we model them? How?**

Background

Approach Taken

Qualitative Observations

- Gain understanding of how phenomena occur
- Find the important parameters and measure them
- Identify what seem to be the dominant physical mechanisms

- Conceptual modeling approach
- Build hypotheses
- Develop theoretical and computational approaches
- Develop quantitative experiments

Develop Model

Background

- Understanding how ice accretions form on swept wings is needed for:
  - Development of ice accretion models that can be implemented into 3D ice accretion codes
  - Development of scaling laws that can be applied to swept airfoils

First Icing Physics Studies

Reehorst (1989-1990)

- Conducted an experiment in the NASA Glenn Research Center's DHC-6 DeHavilland Twin Otter aircraft to obtain swept wing ice accretion data.
  - A NACA 0012 swept wing tip airfoil was extended from the overhead hatch of the aircraft and set at a given sweep angle (0^o, 30^o, or 45^o).
  - At the end of the icing encounter the airfoil was retracted into the cabin of the aircraft and photographic data and ice shape tracings were taken.

- From the icing conditions and the types of ice accretions that he reports, the strong effect of sweep angle and temperature on the formation of the scallops can be inferred.

Study of Mechanisms of Scallop Formation

Vargas and Reshotko (1996)

- A series of experiments were conducted in the Icing Research Tunnel (IRT) to understand the physical mechanisms that lead to the formation of scallops on swept wings.
- Icing runs were performed on a NACA 0012 swept wing tip at 45°, 30°, and 15° sweep angles starting with a baseline case at 45°.
- The time history of scallop formation was studied for the baseline case.
- Direct measurements of scallop height and spacing, castings, video data and close-up microphotography data were obtained.
- Additional icing runs were carried out to study the velocity effect, the temperature effect and the LWC effect on the formation of the scallops
- Measurements of scallop height and spacing versus ice accretion time were performed.
- Measurements of the distance from the attachment line to the point beyond which the roughness elements become glaze ice feathers were taken at several conditions.

Study of Mechanisms of Scallop Formation

Vargas and Reshotko (1996)

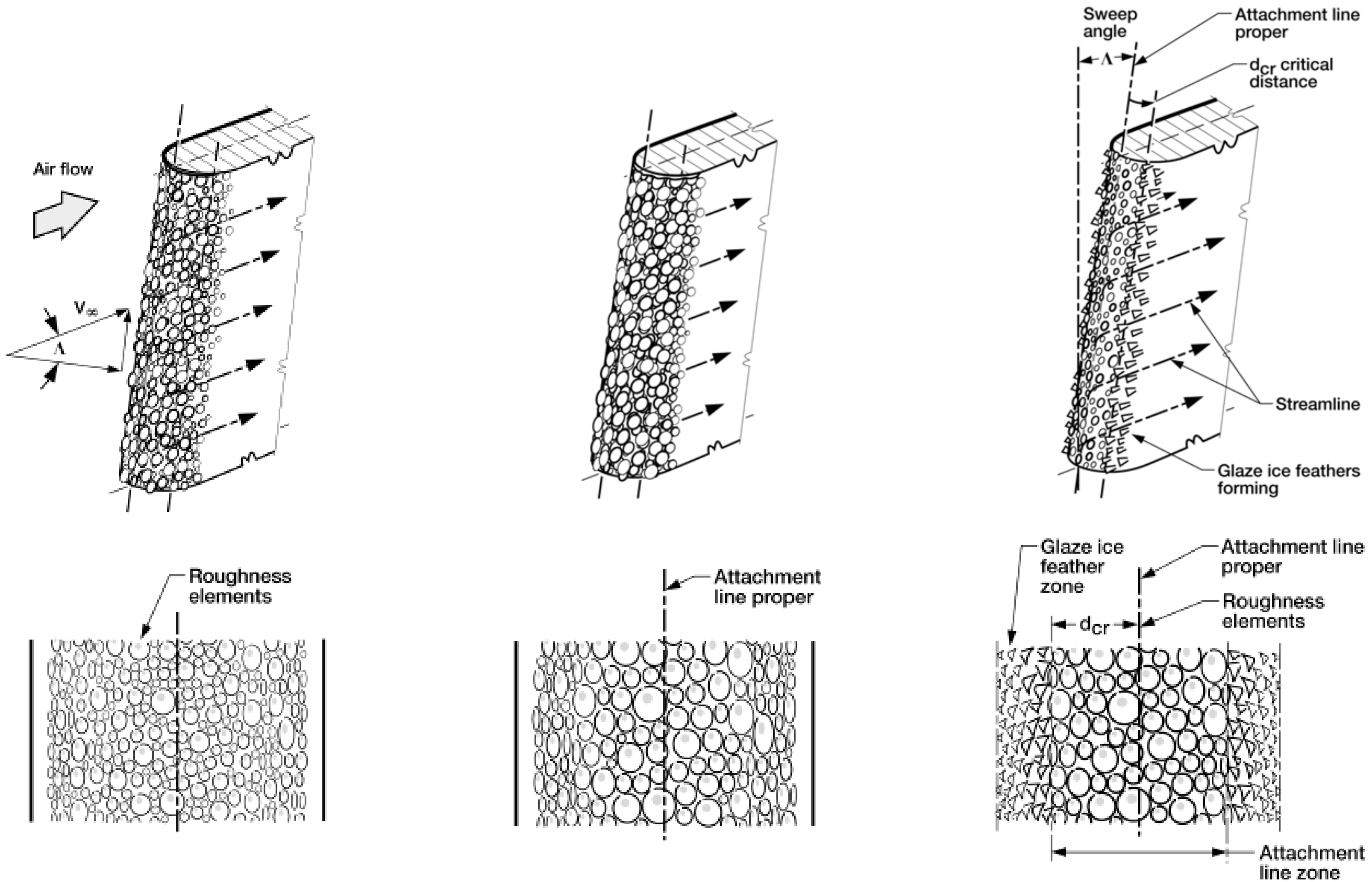
NACA 0012 Swept Wing Tip

Photographic Data

Casting

Study of Mechanisms of Scallop Formation

Vargas and Reshotko (1996)



Roughness elements develop on leading edge

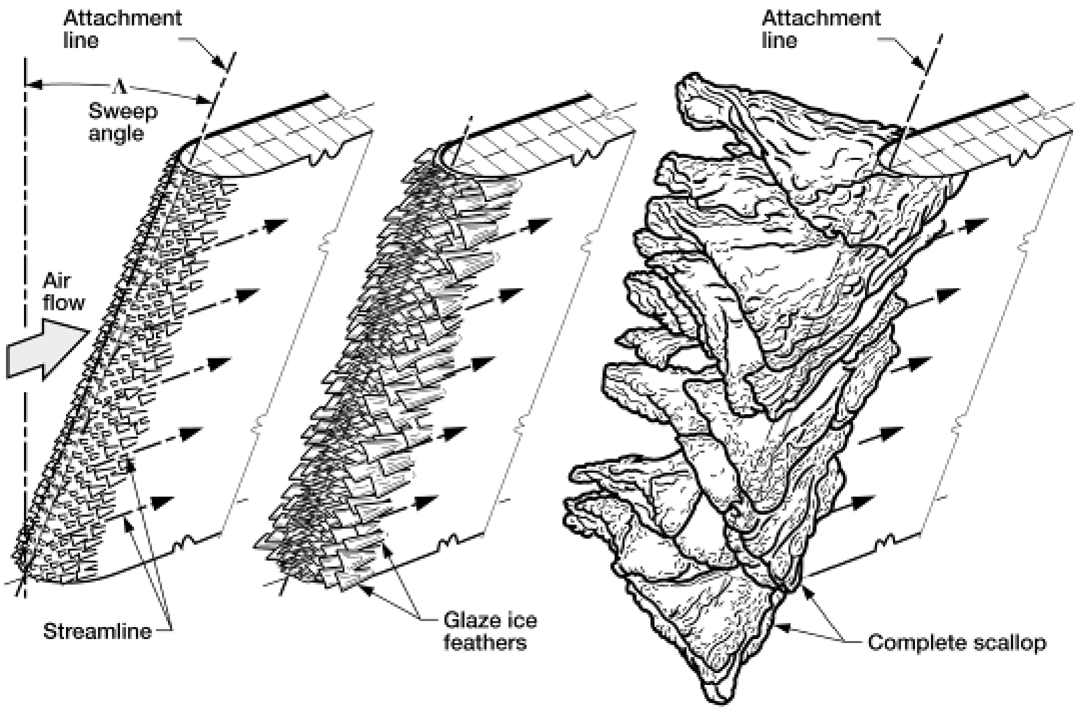
Roughness elements grow

Roughness elements at a given distance from the attachment line develop into glaze ice feathers

Study of Mechanisms of Scallop Formation

Vargas and Reshotko (1996)

COMPLETE SCALLOP CASE, $\Lambda = 45^{o}$, CRITICAL DISTANCE = 0

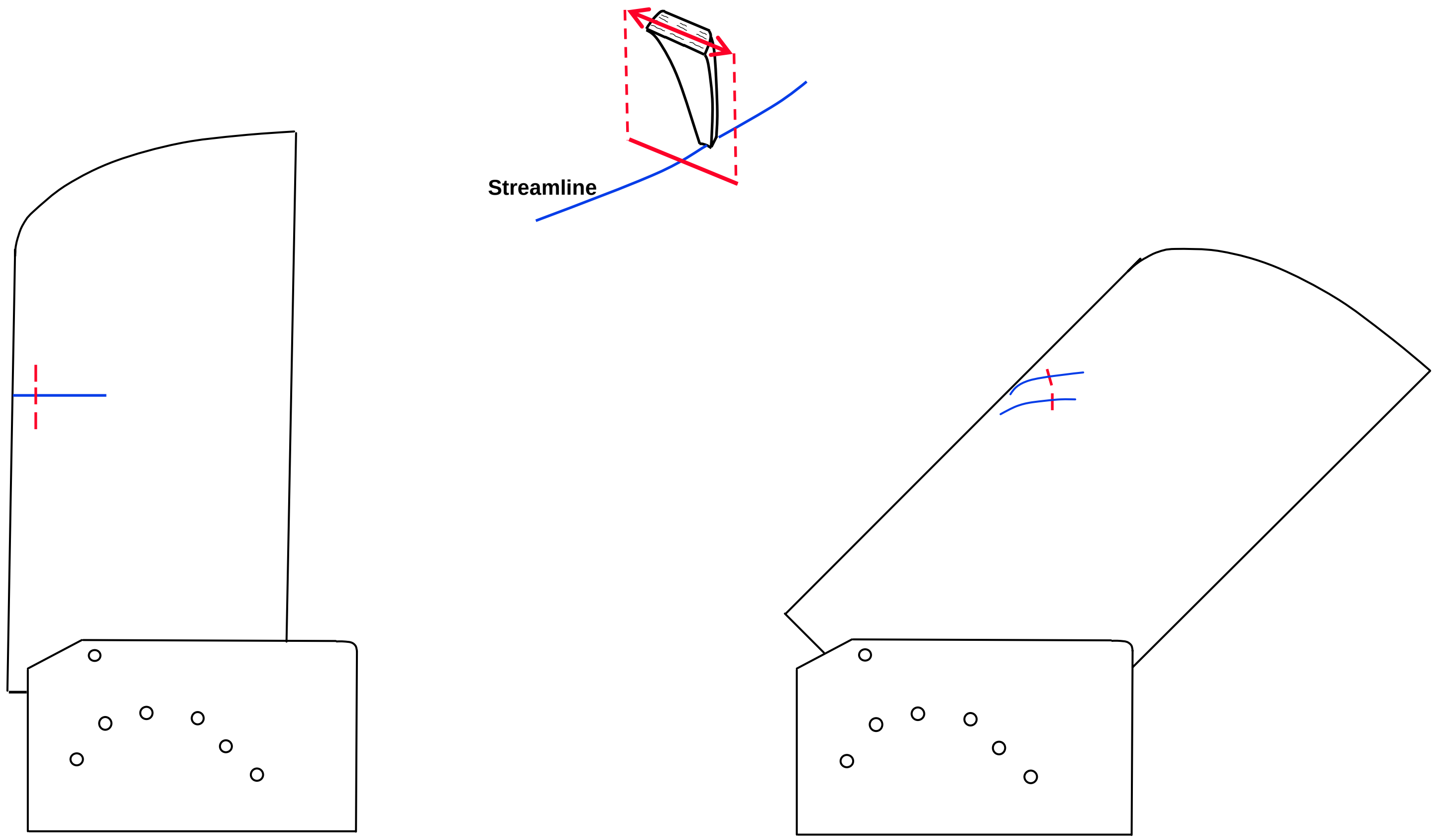


Roughness elements develop into glaze ice feathers

Feathers join along the preferred direction of growth to form ridges

Incipient scallop tips join at their tops to form complete scallops

ROLE OF STREAMLINE SHAPE, PREFERRED DIRECTION OF GROWTH AND CRITICAL DISTANCE IN SCALLOP TIP FORMATION



Study of Mechanisms of Scallop Formation

Vargas and Reshotko (1996)

- Scallop formation is governed by local effects on roughness elements.
- Scallops are made of glaze ice feathers that grow from roughness elements located beyond the critical distance d_{cr}, a critical parameter in the formation of scallops. It determines (together with the shape of the streamlines) if complete scallops, incomplete scallops or no-scallops are going to be formed.
- The critical distance was found to increase as temperature or LWC are increased, and to decrease as the sweep angle is increased.
- Velocity, temperature, and LWC influence the formation of the scallops by affecting the critical distance, the growth of the ice in the attachment line zone, and the growth of the feathers in the glaze ice feathers zone.
- Observations of ice accretions on the end cap of the airfoil showed that for the same tunnel conditions the scallops showed a very strong dependence on local sweep angle.
- Scallop height was found to increase linearly with ice accretion time.
- Scallop spacing, defined as the number of scallops per unit length, was found to decrease with ice accretion time.

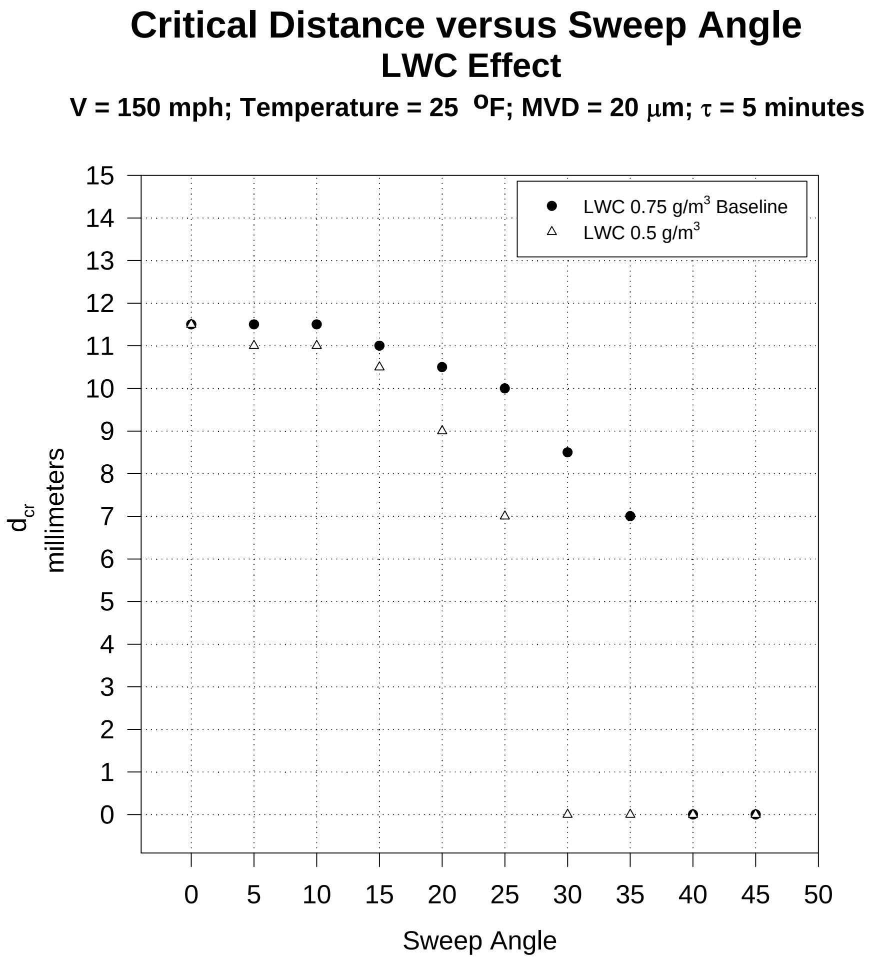
Parametric Studies

Vargas and Reshotko (1998)

- **Parametric studies to measure effect of icing conditions on critical distance**
  - **Effect of Velocity and Sweep Angle on the Critical Distance**
  - **Effect of Temperature and LWC on Critical Distance**

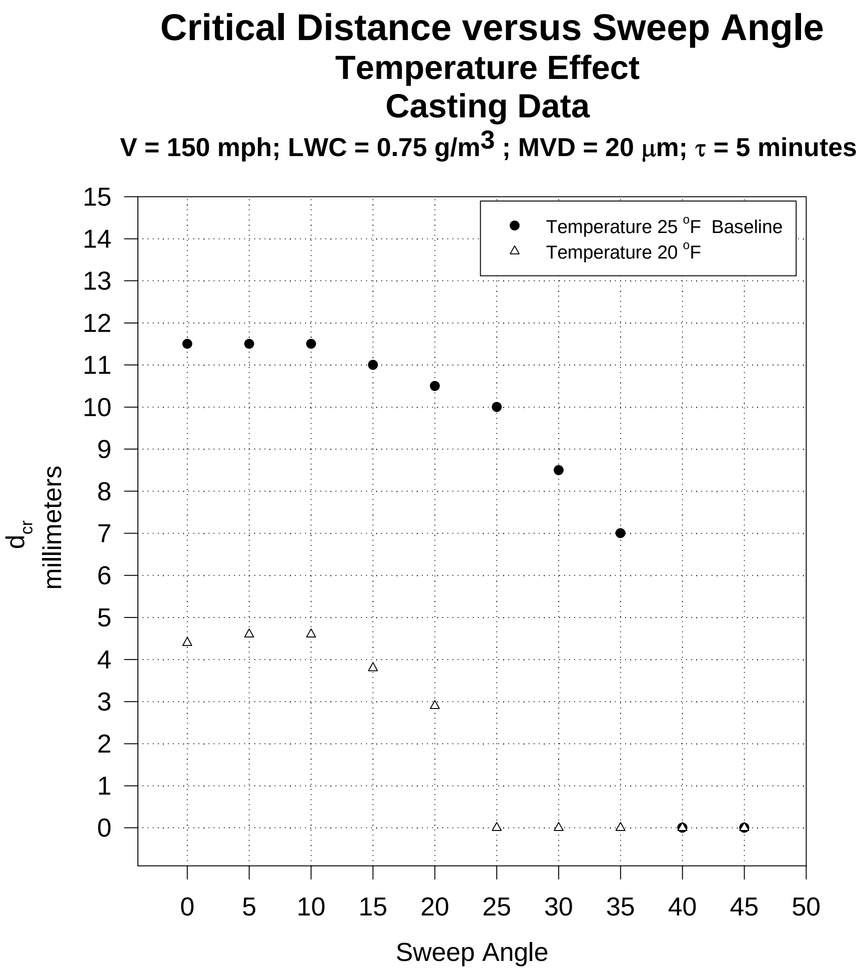
Parametric Studies

Vargas and Reshotko (1998)



Parametric Studies

Vargas and Reshotko (1998)



Study of Scallop Formation in Natural Icing Conditions

Vargas, Giriunas, Ratvasky (2000)

- **Experiment was conducted in the DeHavilland DHC-6 Twin Otter Icing Research Aircraft at NASA Glenn Research Center to study the formation of ice accretions on swept wings in natural icing conditions.**

- **The experiment was designed to obtain ice accretion data to determine if the mechanisms of ice accretion formation observed in the Icing Research Tunnel were present in natural icing conditions.**

- **The experiment in the Twin Otter was conducted using the same NACA 0012 swept wing tip used in the 1996 and 1998 experiments in the IRT. Casting data, ice shape tracings, and close-up photographic data were obtained.**

- **The results showed that the mechanisms of ice accretion formation observed in-flight agree well with the ones observed in the Icing Research Tunnel.**

FAA/NASA/WSU Study of Aerodynamic Effects of 3D Ice Accretions

Vargas et al. (2002), Potapczuk et al. (2003), Papadakis et al. (2003)

- **The objective of the research program was to develop an experimental database of ice accretions effects on the aerodynamic performance of finite swept wings.**
- **Experiments were conducted on a 28^o swept GLC-305 airfoil representative of modern business jet wing section.**
- **An icing test was conducted at the NASA Glenn Icing Research Tunnel facility to generate five glaze ice shapes with complete and incomplete scallop features, and one rime ice shape.**
- **3D simulated ice shapes were generated using NASA Glenn Research Center LEWICE v2.0 for the same icing conditions as in the IRT icing tests, and were fabricated from wood or aluminum.**
- **A second experiment was conducted at the WSU 7-ft x 10-ft wind tunnel facility to generate the aerodynamic data for the clean and iced wing.**

FAA/NASA/WSU Study of Aerodynamic Effects of 3D Ice Accretions

Vargas et al. (2002), Potapczuk et al. (2003), Papadakis et al. (2003)

- **In the course of the aerodynamic testing a limited study was conducted on the effect of gaps between scallop tips using the ice shape casting for the 22 minutes.**
  - **The gaps between the scallops were progressively filled with a modeling compound to produce an ice shape with a "solid" horn.**
- **The aerodynamic data showed that the scallop features and in particular the gaps between the scallops can result in greater loss of lift than ice shapes with solid horns.**
- **It was a limited study, but if the results are confirmed by additional research studies it will have very important consequences for modeling scallops because it will indicate (from the aerodynamic perspective) how much detail has to be included in the actual modeling.**

Modeling of Heat Transfer over Large Roughness Elements

McClain, Vargas, Kreeger,Tsao (2002)

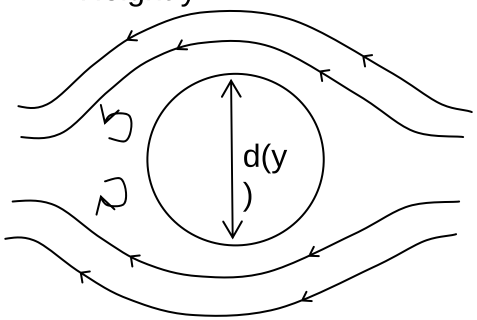
- Developed Extended Surface-Discrete Element Method (ES-DEM) to calculate heat transfer over large roughness elements
- ES-DEM is based on:
  - Fin/extended surface equation
  - Discrete-element local heat transfer correlations
- Examined the importance of thermal boundary layer thickness, the thermal conductivity of the roughness element and the radiation into the element

Modeling of Heat Transfer over Large Roughness Elements

McClain, Vargas, Kreeger, Tsao (2002)

ES-DEM Analysis

Slice of the Element at Height y



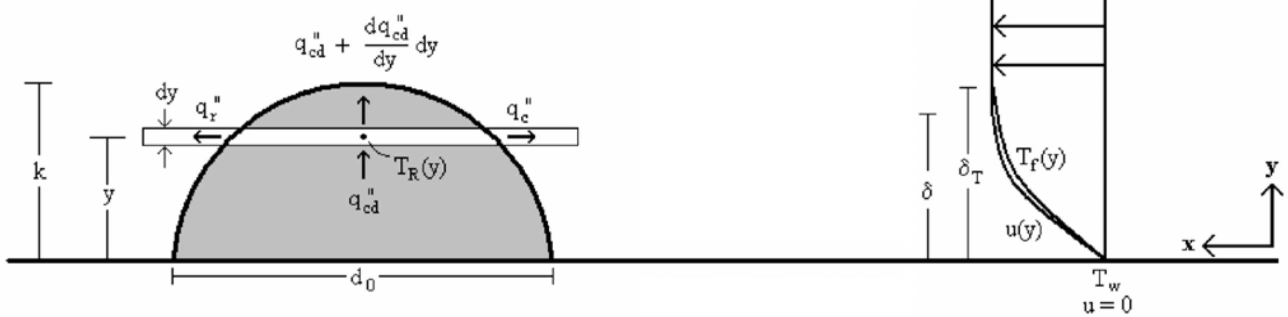
u(y)

$T_f(y)$

$$\begin{cases} \frac{\partial}{\partial x}u + \frac{\partial}{\partial y}v = 0 \\ u\cdot\frac{\partial}{\partial x}u + v\cdot\frac{\partial}{\partial y}u = \left(\frac{\mu}{\rho}\right)\cdot\frac{\partial^2}{\partial y^2}u \\ u\frac{\partial}{\partial x}T_f + v\cdot\frac{\partial}{\partial y}T_f = \alpha\cdot\frac{\partial^2}{\partial y^2}T_f \\ \text{+ Boundary Conditions} \end{cases}$$

$$h_d = \frac{k_f}{d}\mathrm{Nu}_d \qquad \mathrm{Nu}_d = \begin{cases} 1.7\,\mathrm{Re}_d^{0.49}\,\mathrm{Pr}^{0.4} & \text{for } \mathrm{Re}_d \le 13{,}776 \\ 0.0605\,\mathrm{Re}_d^{0.84}\,\mathrm{Pr}^{0.4} & \text{for } \mathrm{Re}_d > 13{,}776 \end{cases}$$

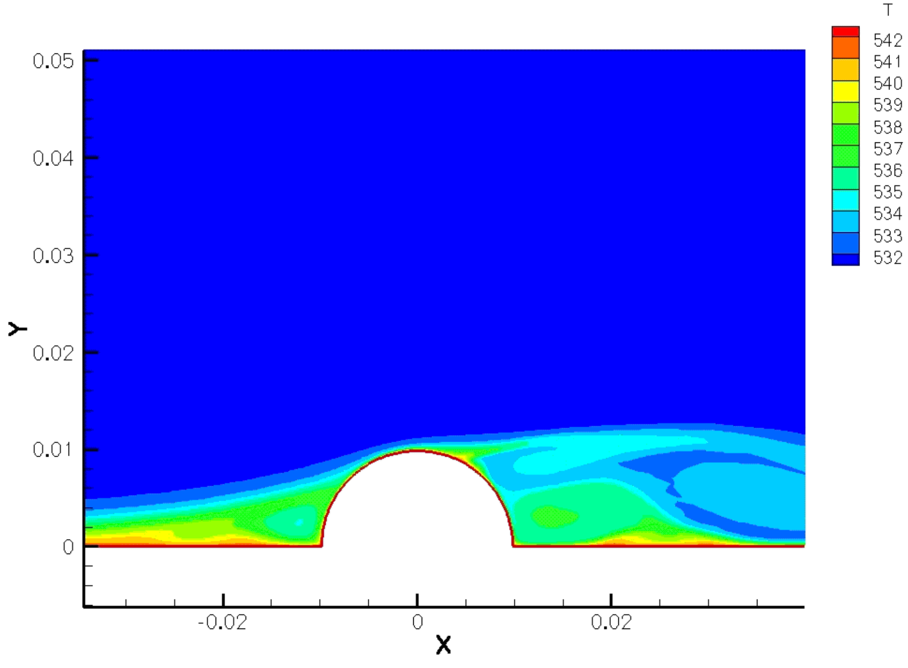
$$\frac{d^2T_R}{dy^2} + \frac{1}{A}\frac{dA}{dy}\frac{dT_R}{dy} - \frac{h_d\left(T_R - T_f\right)}{kA}\frac{dA_s}{dy} - \frac{q_r''}{kA}\frac{dA_s}{dy} = 0$$



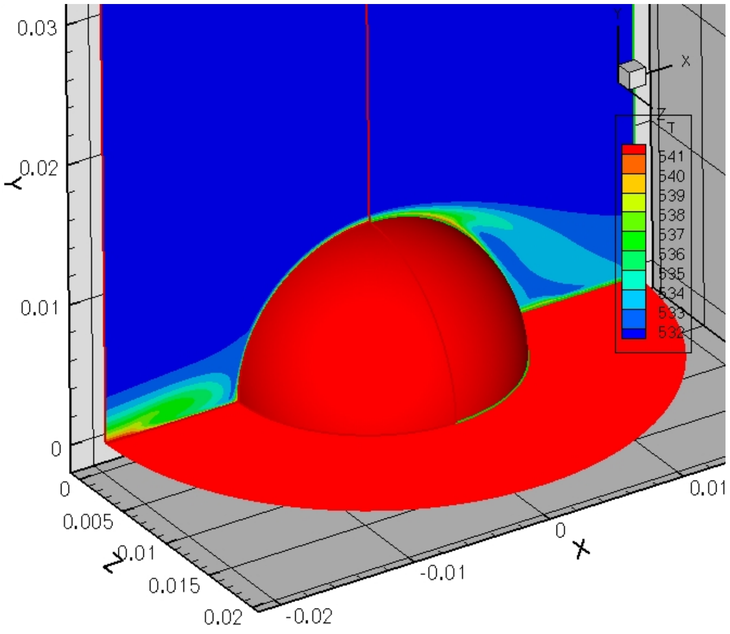
Modeling of Heat Transfer over Large Roughness Elements

Kreeger, Vargas, McClain (2005)

- **Conducted computational studies of the heat enhancement caused by the acceleration of the flow over an isolated 2D roughness elements in laminar flow when the element is located on a flat plate. The problem was extended to a 3D roughness element in turbulent flow.**



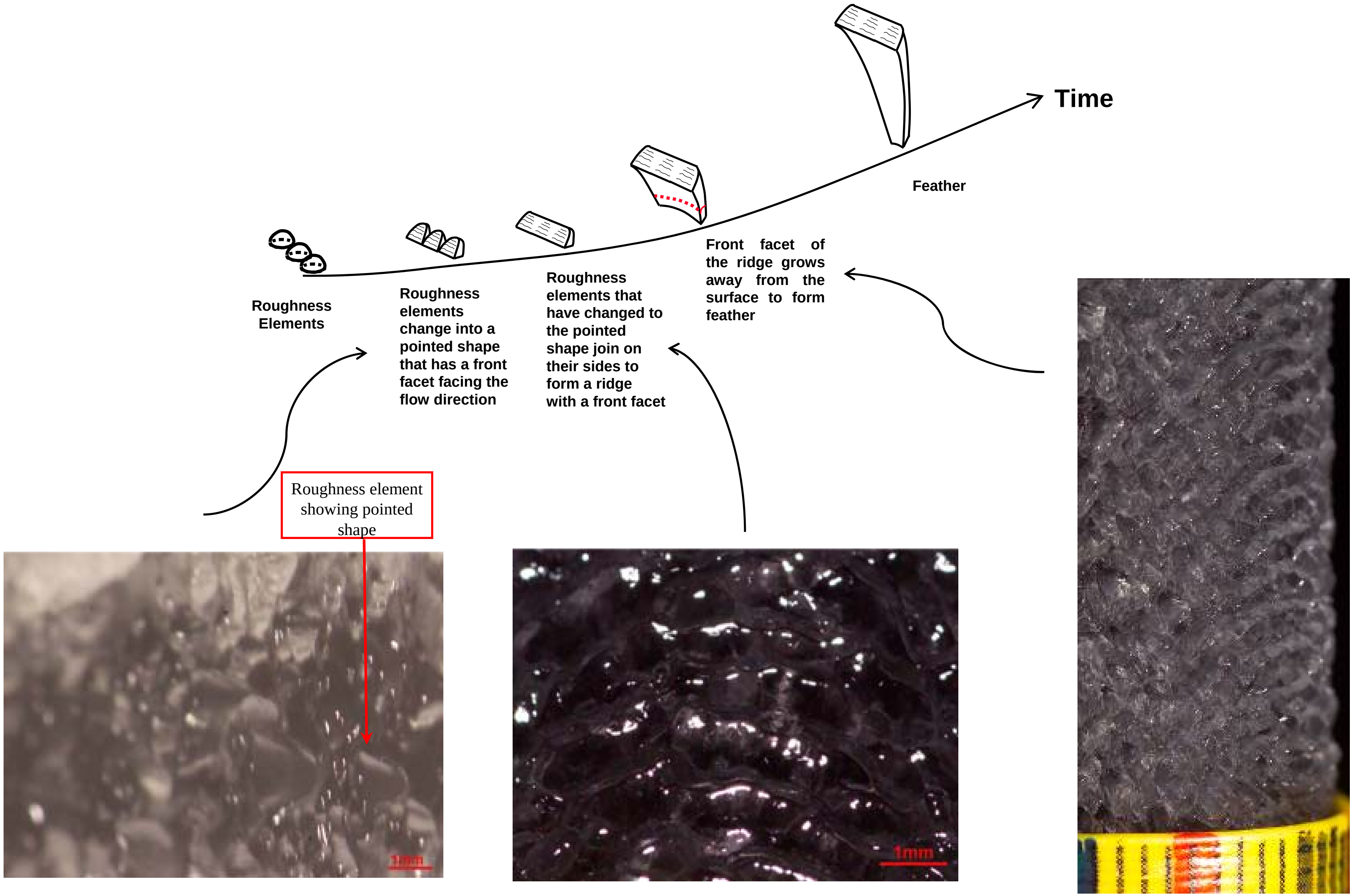
Temperature Profile (Laminar, 2D)



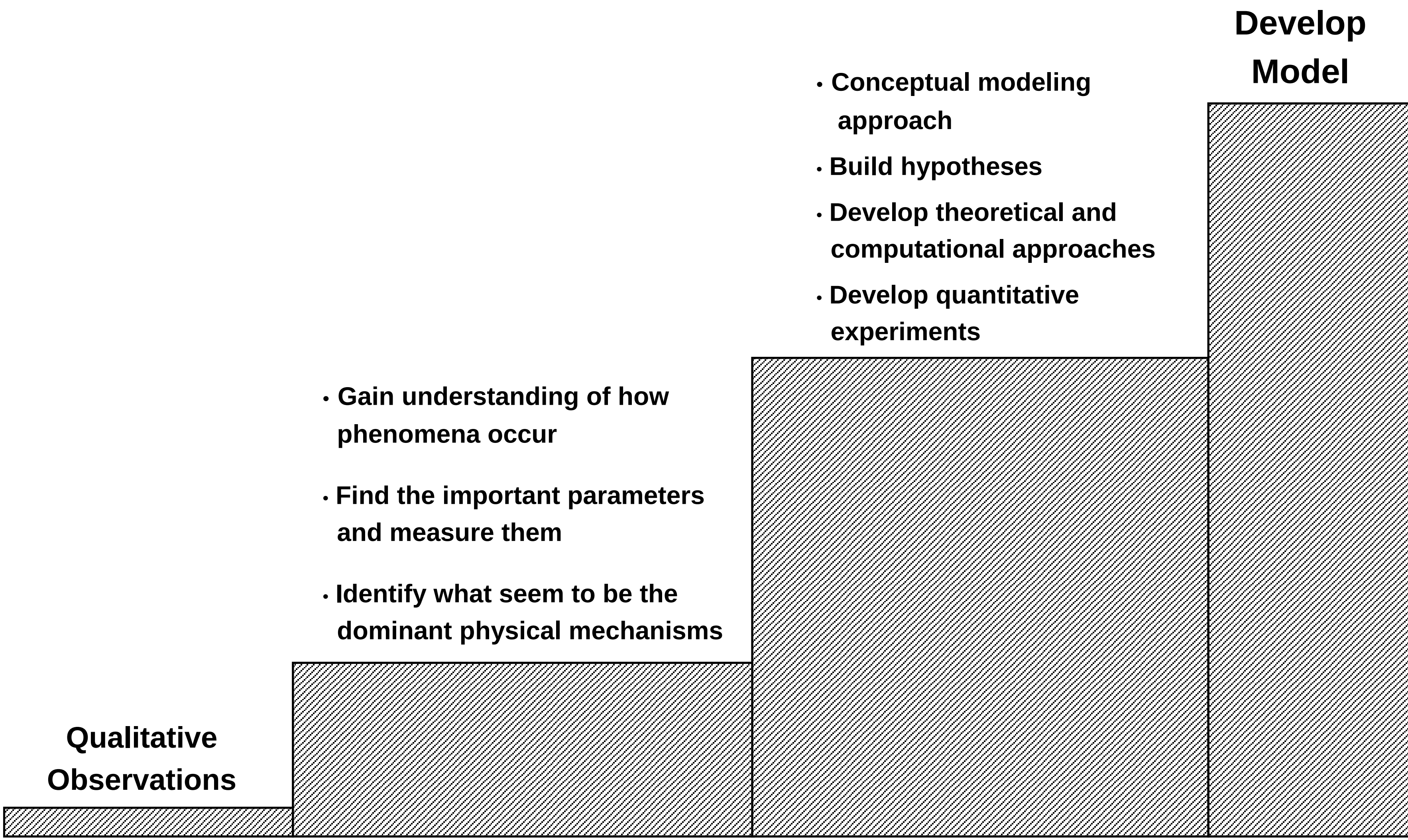
Temperature Profile (Turbulent, 3D)

Development of Roughness Elements into Feathers and Scallop Tips

Vargas, Tsao 2006

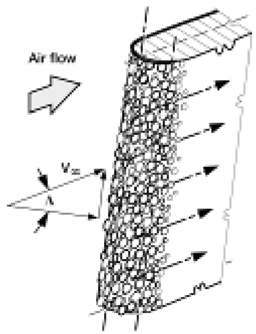


APPROACH TAKEN

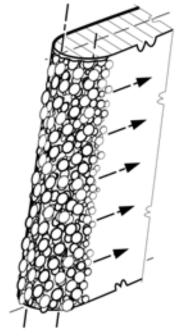


Conceptual Steps in the Modeling of Scallops

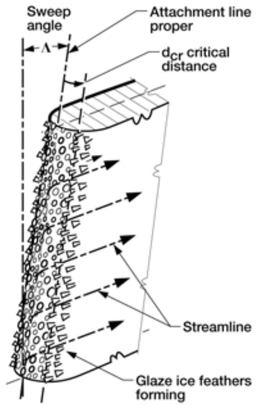
(a) Initiation Step



Roughness elements develop on the leading edge

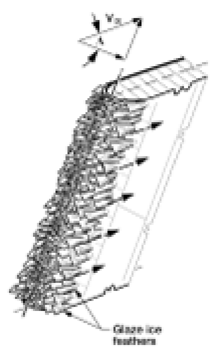


Roughness elements grow in size

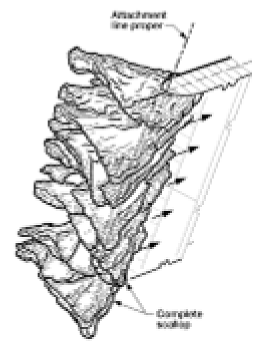


Roughness elements at a given distance from the attachment line develop into glaze ice feathers

(b) Macroscopic Growth Step



As the feathers grow, they develop a preferred direction of growth that is aligned perpendicular to the streamlines direction. The feathers growth is inclined at a given angle with respect to the leading edge surface. The feathers growth is at a given rate



The feathers join along the preferred direction of growth to form ridges. The ridges join to form scallop tips

Conceptual Steps in the Modeling of Scallops

Initiation Step

- **Initiation Step involves modeling the formation and growth of large roughness elements, and their development into glaze or rime ice feathers under a given flow field and icing conditions. By "large roughness elements" we mean that the roughness element at a given location is of a height comparable or larger than the size of the boundary layer at that location.**
  - **An important part of the Initiation Step is to predict when large roughness elements are going to develop into feathers.**
  - **Requires knowing or modeling the roughness characteristics (spacing, shape, time growth and size) under a given flow field and icing conditions,**
  - **Modeling the effect of large roughness effects on flow field and heat transfer.**

Conceptual Steps in the Modeling of Scallops

Macroscopic Growth Step

- **Macroscopic Growth Step involves modeling the growth of the feathers (individually or in groups of multiple feathers) after initiation.**
- **This step requires the ability to model:**
  - **Feather's angle,**
  - **Preferred shape of feathers**
  - **Rate of growth,**
  - **How feathers align with respect to flow direction and streamlines**
  - **How feathers join and form additional structures**
- **All these elements need to be modeled for glaze and rime ice feathers.**

Final Comments

- **A Swept Wing Icing Research Plan (SWIRP) was developed by a team of researchers, *Mario Vargas, Richard Kreeger, Jen-Ching Tsao, Stephen McClain, Colin Bidwell, Alric Rothmayer***

- **The plan includes a Road Map that outlines the basic research needed to develop a model of ice accretion formation on swept wings**

END OF PRESENTATION