Overview of Icing Physics Relevant to Scaling

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Introduction

- **Successful Scaling Requires Ice-Shape Simulation**
  - **Scale and Reference Non-dimensional Shapes Agree**
  - **Correct Relation of Scale Test Conditions to Reference Depends on Correct Description of Physics**
- **Similitude Analysis Needed**
  - **Identify Most Important Physical Phenomena**
  - **Non-Dimensional Parameters**
  - **Equate Scale and Reference Parameters**
- **Bilanin's Buckingham-π Analysis (1988)**
  - **18 Similarity Parameters**
  - **Need only 6 to Define Scale Conditions**

Similarity for Icing Scaling

- Geometric
- Flowfield
- Drop Trajectory
- Water Catch
- Energy Balance
- Surface Phenomena

Geometric Similarity

Scale and Reference Models have Same Non-dimensional Coordinates

Flowfield Similarity

$$Re = \frac{V d \rho_a}{\mu_a}$$

$$M = \frac{V}{\sqrt{\gamma R_a T_{st}}}$$

Drop Trajectory Similarity

Modified Inertia Parameter (Langmuir and Blodgett), K_0

$$K_0 = \frac{1}{8} + \frac{\lambda}{\lambda_{Stokes}}\left(K - \frac{1}{8}\right)$$

Modified Inertia Parameter

$$\frac{\lambda}{\lambda_{Stokes}} = \frac{1}{Re_\delta}\int_0^{Re_\delta} \frac{24}{C_D Re_{rel}}\, dRe_{rel}$$

Range Parameter

$$K = \frac{V\,\delta^2 \rho_w}{18\, d\, \mu_a}$$

Inertia Parameter

Drop Trajectory Similarity

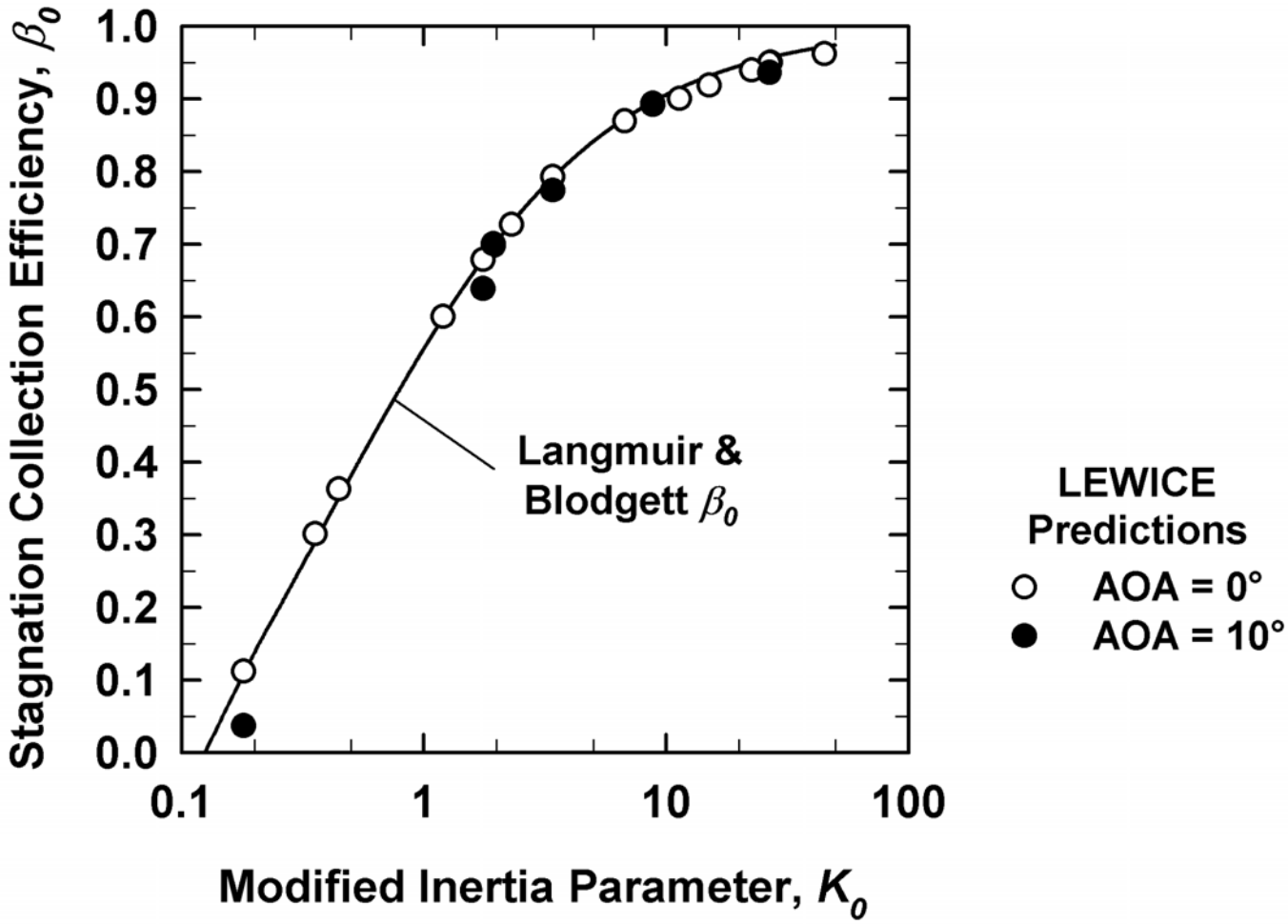
Stagnation Collection Efficiency, β_0

$$\beta_0 = \frac{1.40\left(K_0 - 1/8\right)^{0.84}}{1 + 1.40\left(K_0 - 1/8\right)^{0.84}}$$

Drop Trajectory Similarity

Stagnation Collection Efficiency

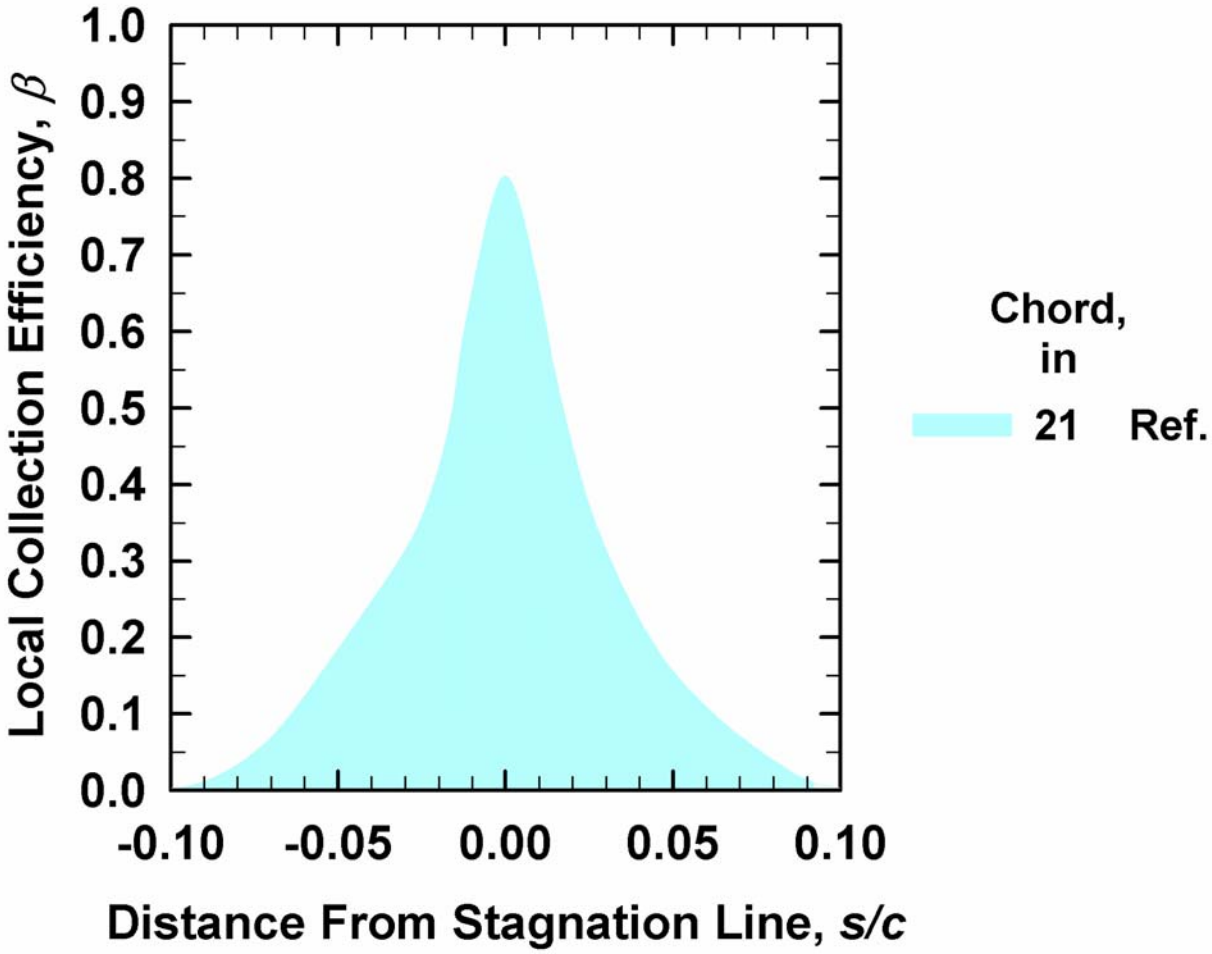
NACA 0012



Drop Trajectory Similarity

LEWICE Collection Efficiency

NACA 0012



Drop Trajectory Similarity

Collection Efficiency for Scaled Test Conditions

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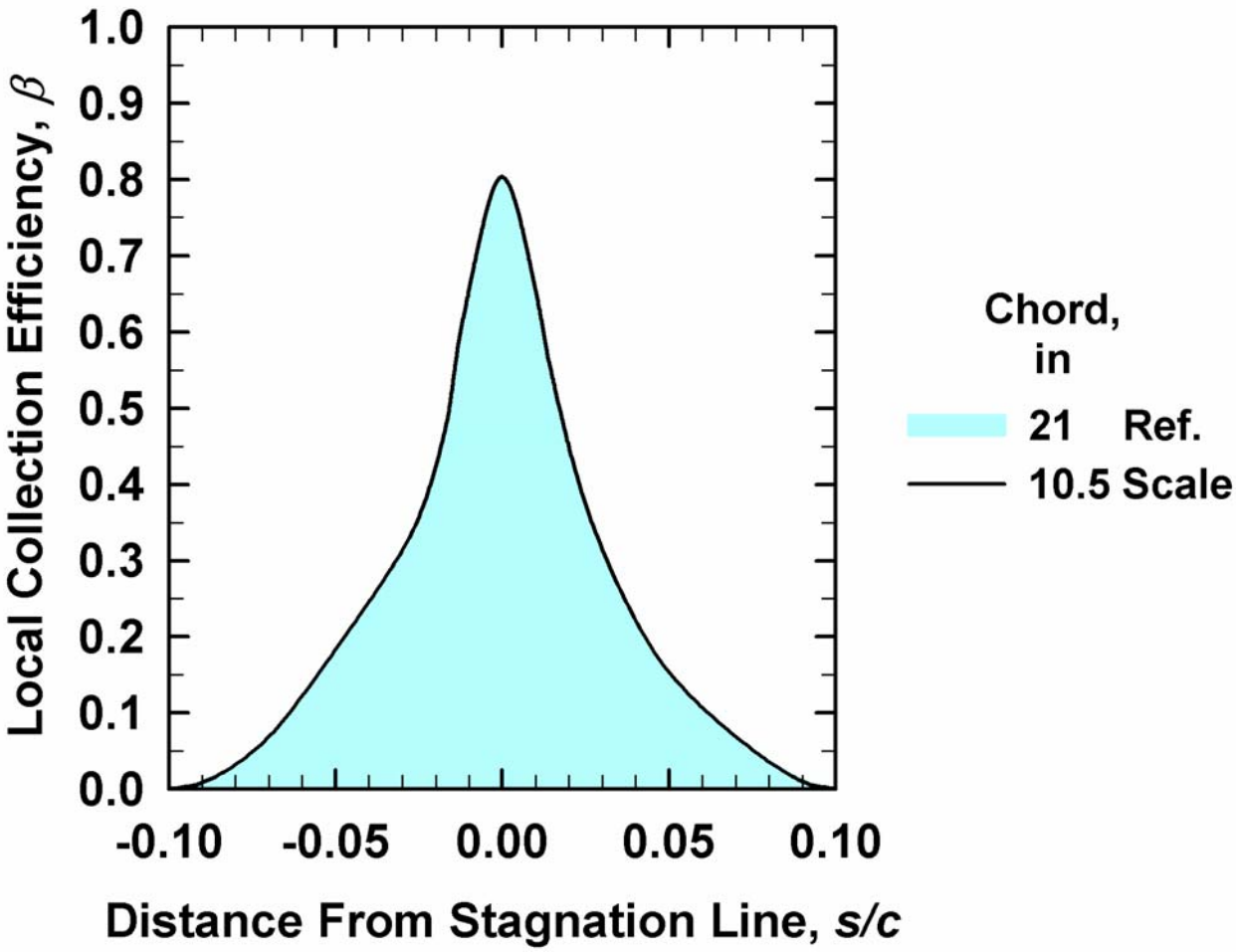
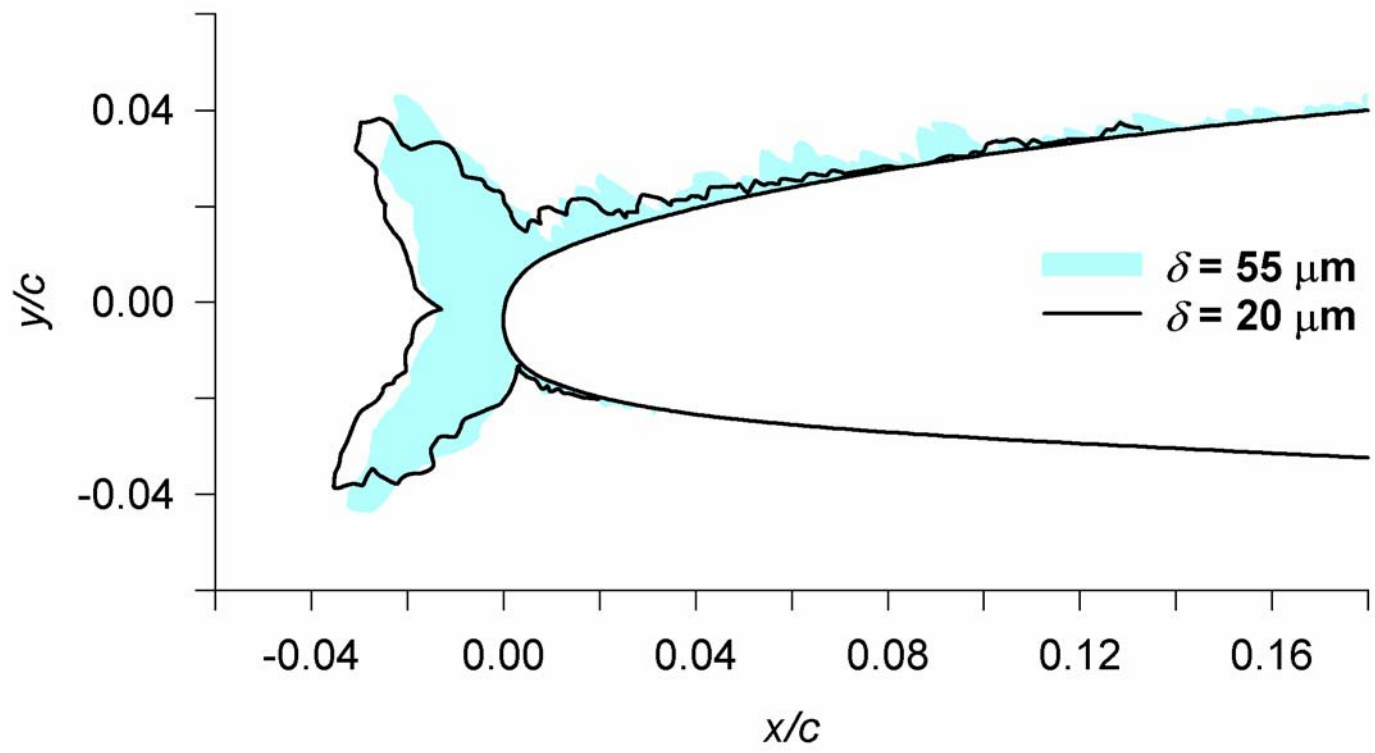


Drop Trajectory Similarity

Effect of Drop Size

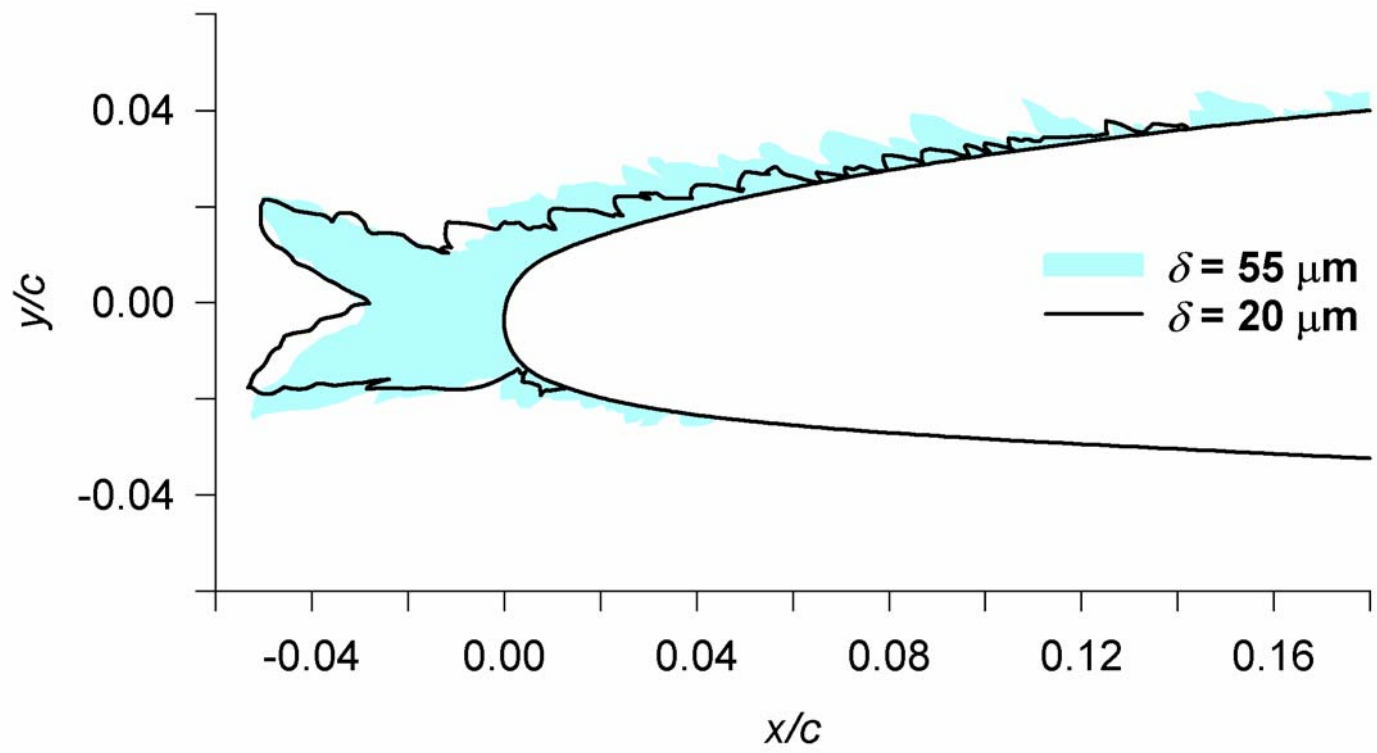
24-in-Chord GLC 305 Airfoil at 0°AOA; n_0 = 0.28



Drop Trajectory Similarity

Effect of Drop Size

24-in-Chord GLC 305 Airfoil at 0°AOA; n_0 = 0.52



Drop Trajectory Similarity
Summary

- **Langmuir and Blodgett β_0 Expression Consistent with LEWICE**
- **If Trajectory Similarity is Achieved at Stagnation, β-Curve will Match Everywhere on the Model**
- **K_0 (or β_0) Appears to Have Little Effect on Main Shape**
- **K_0 (or β_0) Match Needed for Impingement Limits**
- **If Main Ice Shape of Primary Interest, K_0 (or β_0) Does not Have to Match Exactly**

Water-Catch Similarity

$$\Delta = \frac{LWC\ V\ \beta\ \tau}{\rho_i}$$

Water-Catch Similarity

$$\Delta = \frac{LWC\ V\ \beta\ \tau}{\rho_i}$$

$$A_c = \frac{LWC\ V\ \tau}{\rho_i\ d}$$

Water-Catch Similarity

Accumulation Parameter

$$A_c = \frac{LWC\ V\ \tau}{d\ \rho_i}$$

Energy-Balance Similarity

Energy-Balance Similarity

Freezing Fraction

Messinger's Energy Balance Evaluated at Stagnation

$$n_0 = \frac{c_{p,ws}}{\Lambda_f}\left(\varphi + \frac{\theta_0}{b_0}\right)$$

Energy-Balance Similarity

Freezing Fraction

Messinger's Energy Balance Evaluated at Stagnation

$$n_0 = \frac{c_{p,ws}}{\Lambda_f}\left(\varphi + \frac{\theta_0}{b_0}\right)$$ **Freezing Fraction**

$$\varphi = T_f - T_{st} - \frac{V^2}{2c_{p,ws}}$$ **Water-Energy Parameter**

$$\theta_0 = T_s - T_{st} - \frac{V^2}{2c_p} + \frac{h_G}{h_{c,0}}\left(\frac{p_{ww} - p_w}{p_{st}}\right)\Lambda_v$$ **Air-Energy Parameter**

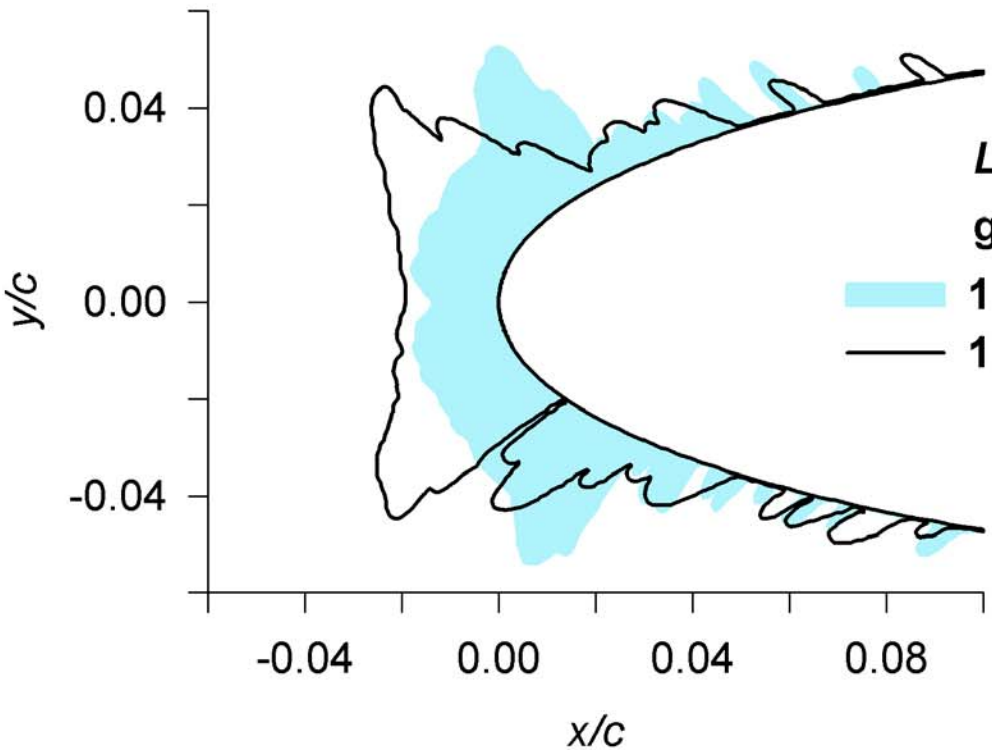
$$b_0 = \frac{LWC\ V\ \beta_0\ c_{p,ws}}{h_{c,0}}$$ **Relative Heat Factor**

Energy-Balance Similarity

Effect of Temperature

NACA 0012

c, 21 in; *V*, 150 mph; δ, 38 μm; β_0, 85%; A_c, 1.88



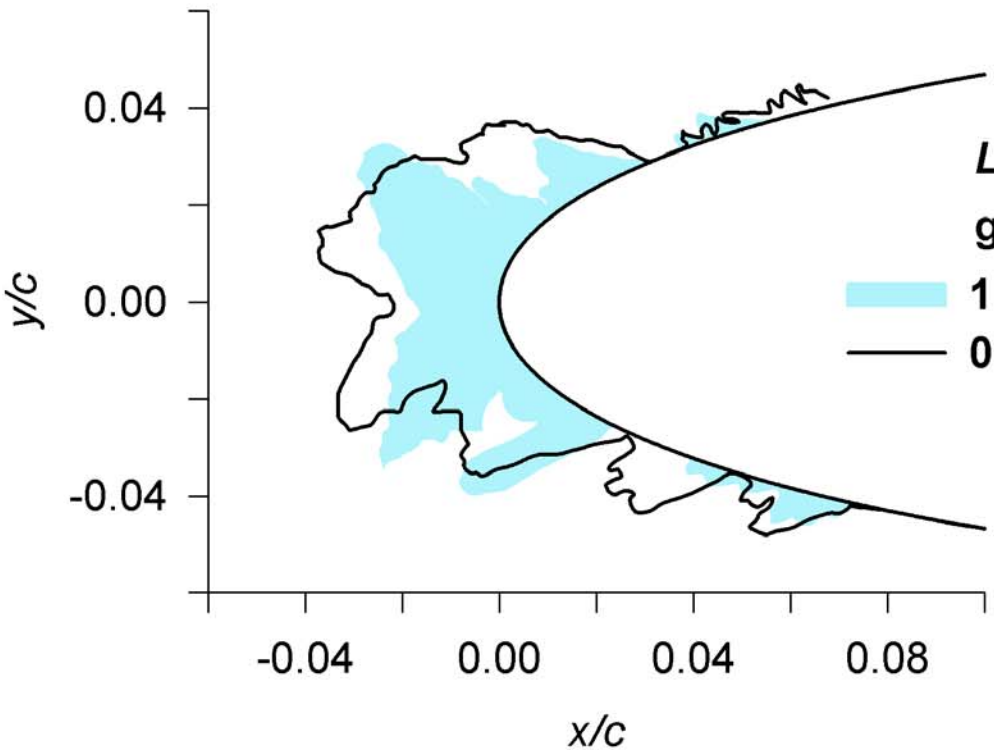
LWC, g/m^3	t_{st}, °F	n_0	b_0	ϕ, °F	θ, °F
1.00	19	0.28	0.58	11.8	16.2
1.00	14	0.40	0.58	16.7	23.2

Energy-Balance Similarity

Effect of *LWC*

NACA 0012

***c*, 21 in; *V*, 150 mph; δ, 30 μm; β_0, 80%; A_c, 1.90**



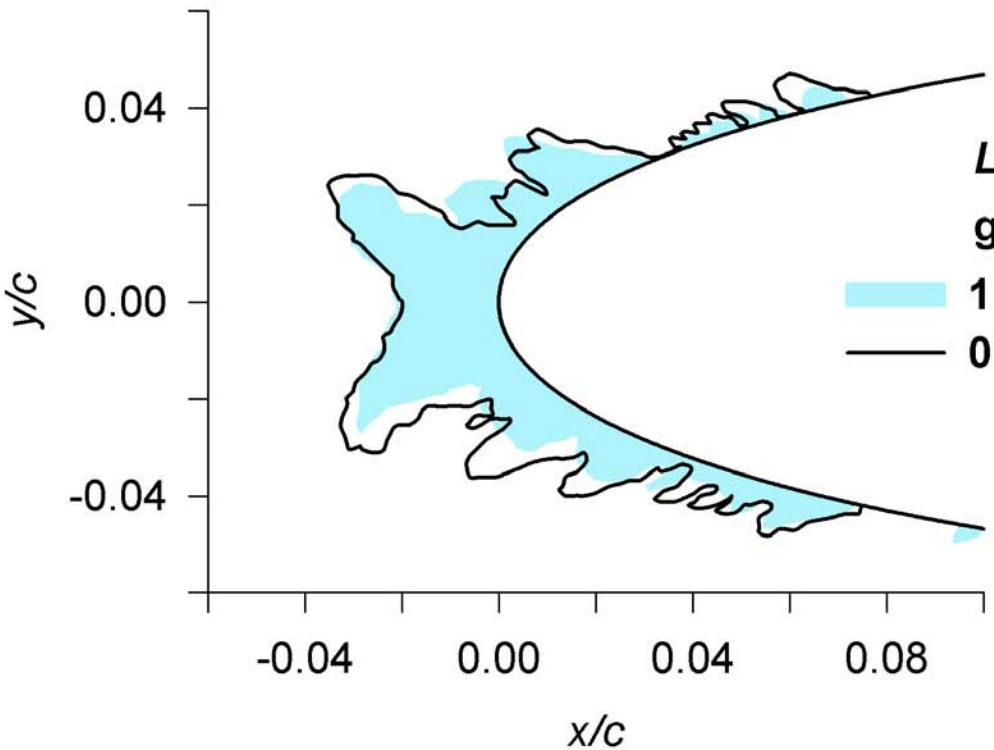
LWC, g/m^3	t_{st}, °F	n_0	b_0	ϕ, °F	θ, °F
1.40	11	0.40	0.77	20.4	28.2
0.80	11	0.59	0.44	20.4	28.2

Energy-Balance Similarity

Effect of *LWC* – Constant n_0

NACA 0012

***c*, 21 in; *V*, 150 mph; δ, 30 μm; β_0, 80%; A_c, 1.90**



LWC, g/m^3	t_{st}, °F	n_0	b_0	ϕ, °F	θ, °F
1.40	4	0.52	0.77	26.6	36.4
0.80	13	0.52	0.44	17.8	24.7

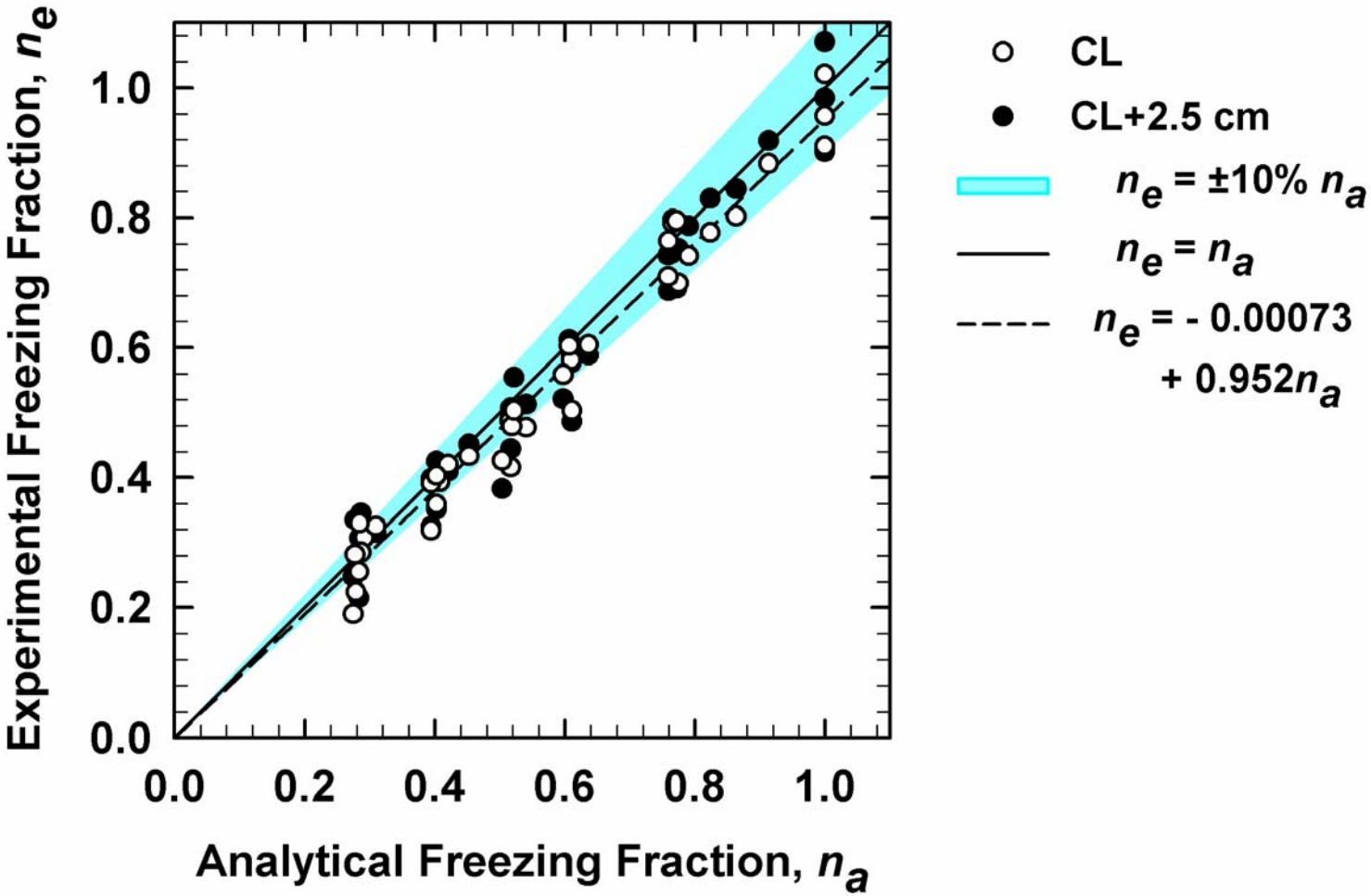
Energy-Balance Similarity

Validation of Messinger Freezing Fraction

$$\frac{\Delta_0}{d} = \beta_0 \, A_c \, n_0$$

Energy-Balance Similarity

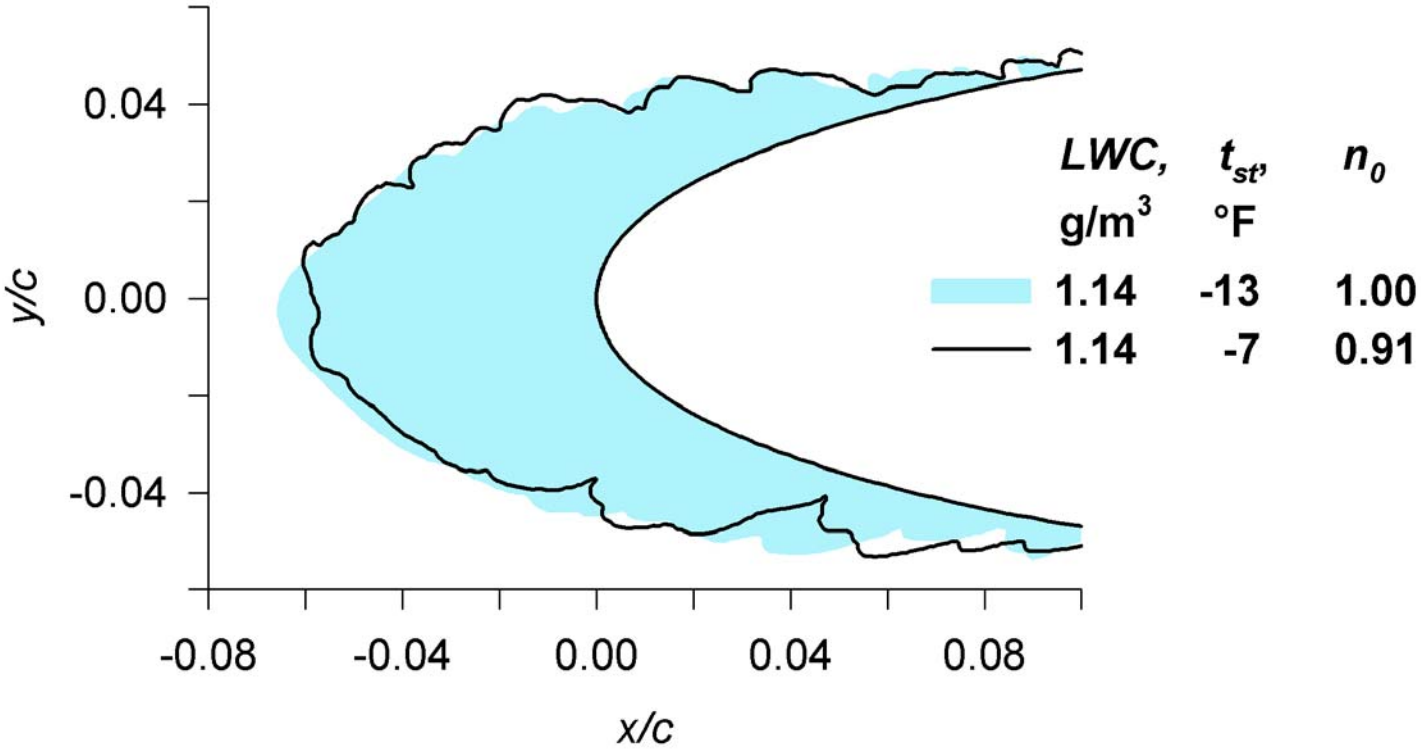
Validation of Messinger Freezing Fraction at Stagnation



Energy-Balance Similarity

Validation of Messinger Freezing Fraction

Rime and Near-Rime Shapes



Energy-Balance Similarity
Summary

- **Ice Shape Sensitive to Value of n_0**
- **b_0, ϕ, and θ_0 Appear to Have Little Effect on Main Shape**
- **Messinger n_0 Expression Consistent with Experimental Ice Shapes**

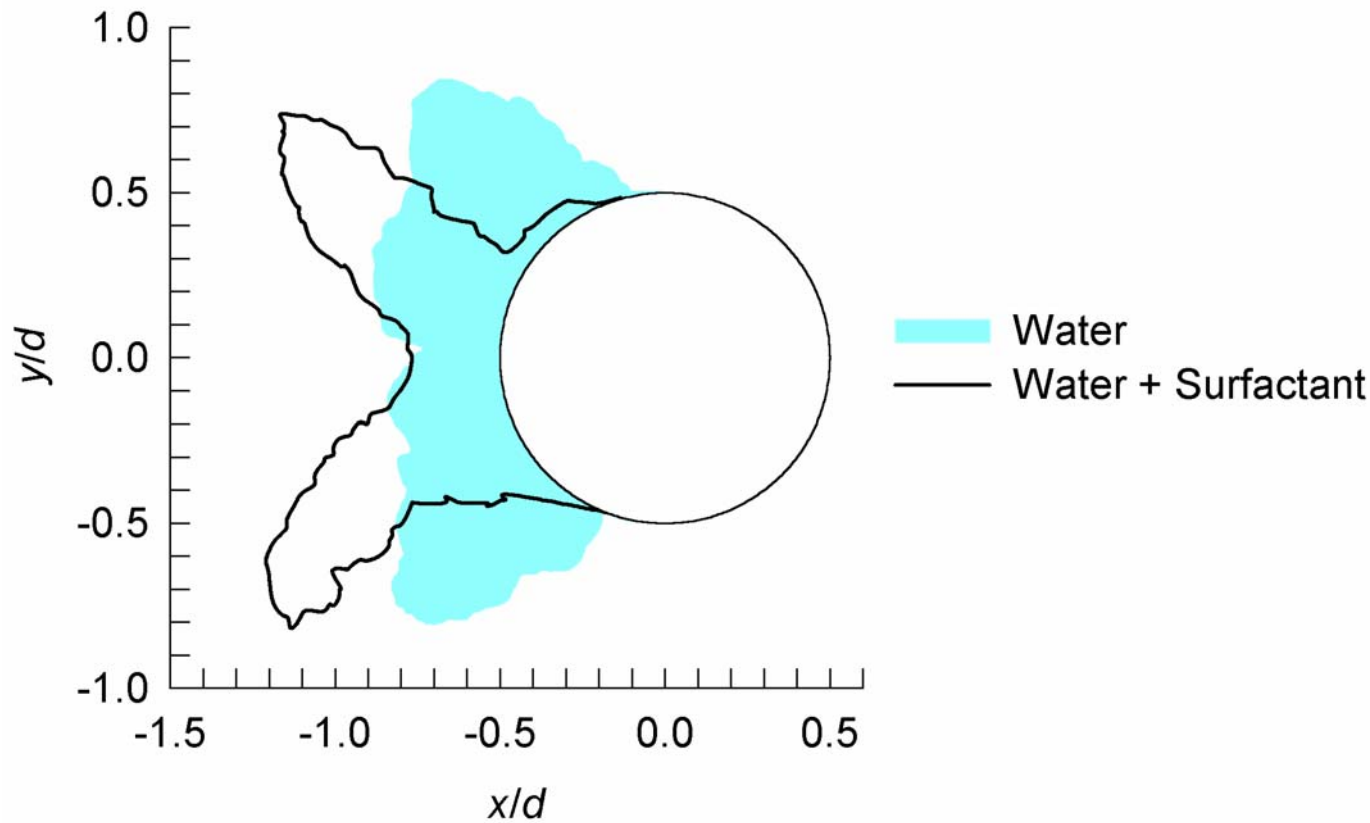
Surface-Water Phenomena Similarity

Surface-Water Similarity

Effect of Surfactant on Ice Shape

2-in-Diam Cylinder

t_{st}, °F	V, mph	MVD, μm	LWC, g/m³	τ, min	β_0, %	A_c	n_0
18	105	40	1.16	7.3	66	1.13	0.28

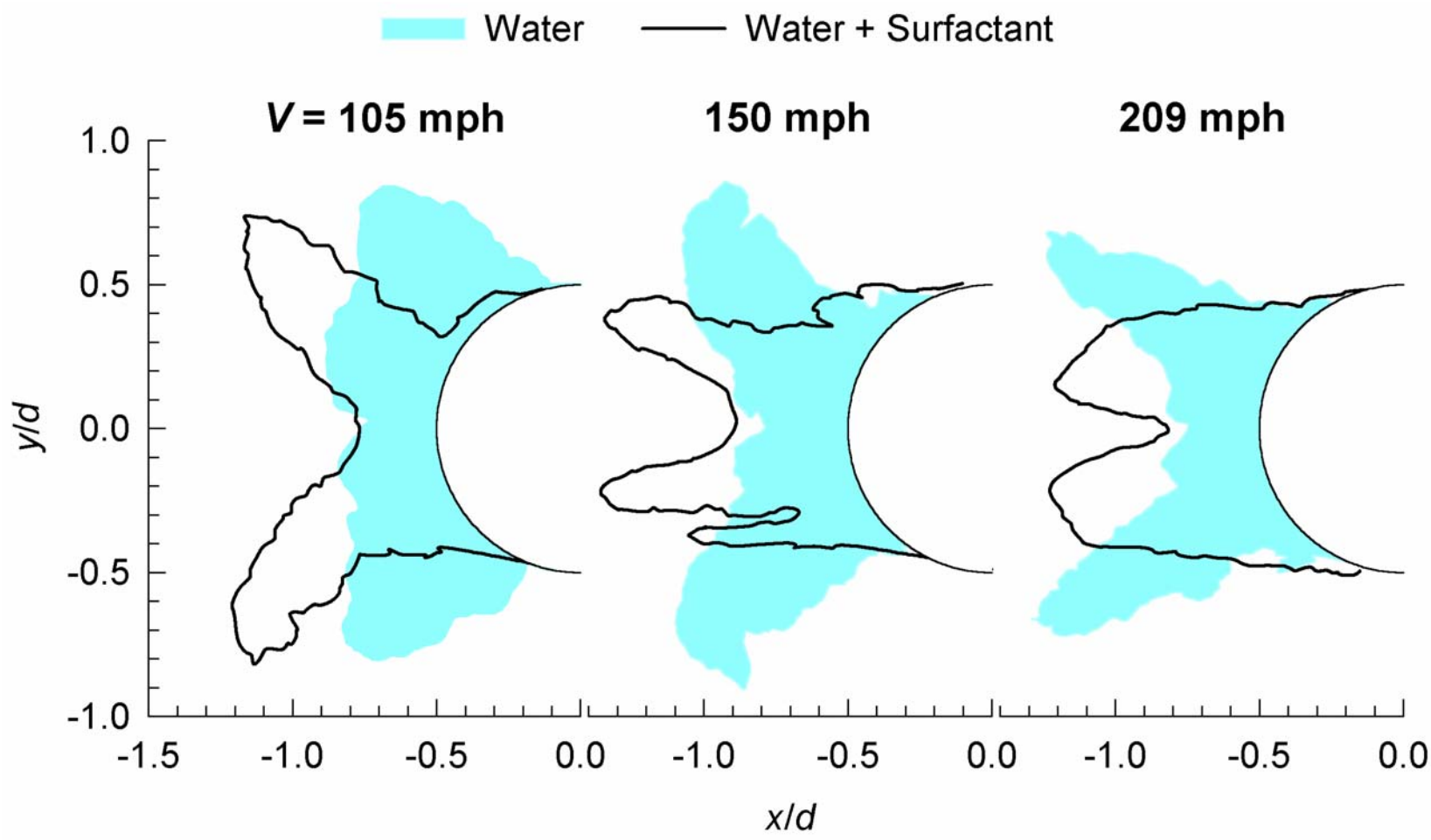


Surface-Water Similarity

Effect of Velocity on Ice Shape

2-in-Diam Cylinder

β_0 = 65 - 66%, A_c = 1.13 – 1.23, n_0 = 0.28 – 0.33



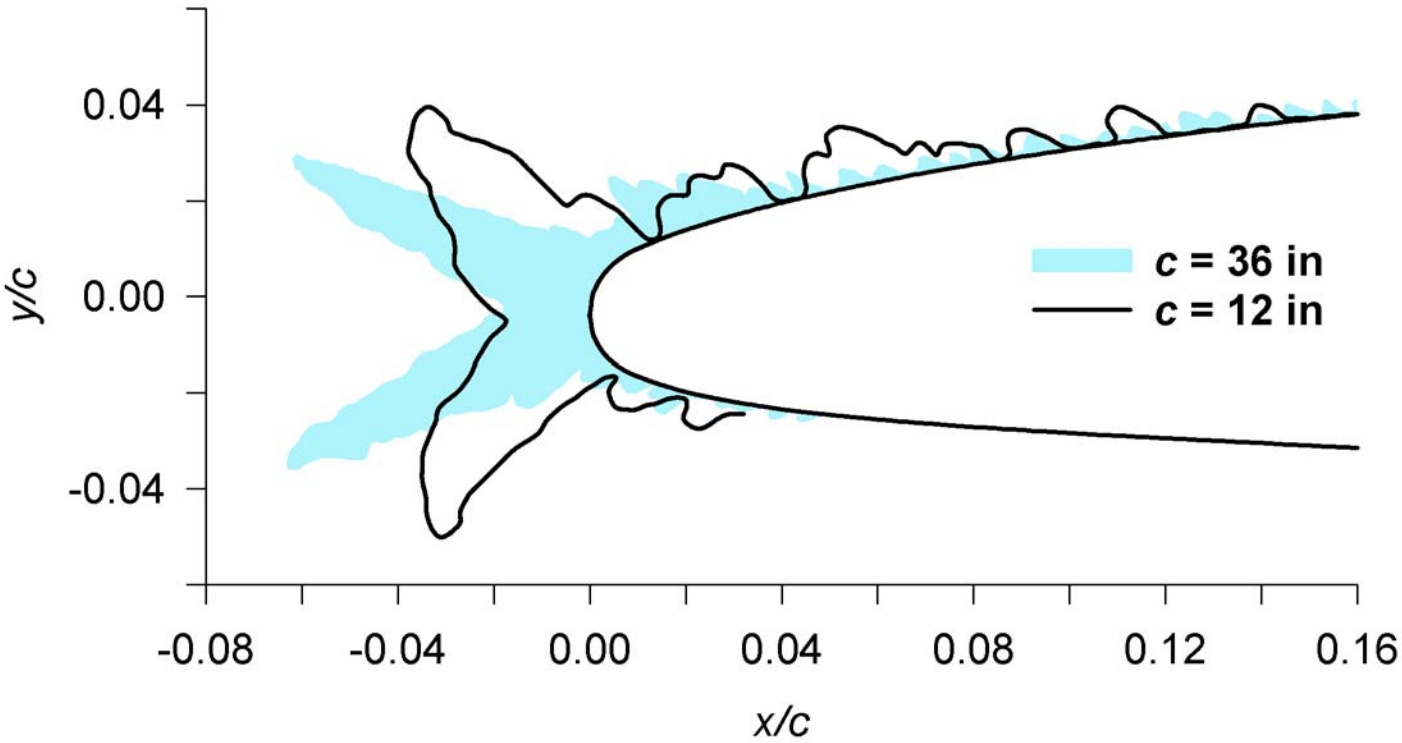
Defining the Surface-Water Similarity Parameter

- Weber Number Includes Effects of
  - Surface Tension (Surfactant)
  - Velocity
- $We = V^2 L \rho / \sigma_{w\,l\,a}$

Surface-Water Similarity

Effect of Model Size

GLC 304 n_0 = 0.4



Surface-Water Similarity

Density Term in *We*

Air or Water?

- **Bartlett (1986, 1988)**
  - **AEDC**
  - **No Effect of Altitude (Pressure) on Ice Shape**
- **Oleskiw, et al (1996)**
  - **NRC**
  - **No Effect of Altitude (Pressure) on Ice Shape**
- **Conclusion**
  - **Air Density, ρ_a, in *We* is Unlikely**
  - **Water Density, ρ_w, is Probable**

Surface-Water Similarity

Weber-Number Similarity Parameter

$$We_L = V^2 L \rho_w / \sigma_{w\,l\,a}$$

Where $L \propto d$

$$We_L = V^2 d \rho_w / \sigma_{w\,l\,a}$$

Summary

- **Geometric Similarity**
  - **Define Scale Model Coordinates**
- **Flowfield Similarity**
  - **Not Used**
- **Droplet Trajectory Similarity**
  - **Match K_0 to Determine Scale Drop Size**
  - **Not as Important as Once Thought for Main Ice Shape**
- **Water-Catch Similarity**
  - **Match A_c to Define Scale Time**

Summary (con't)

- **Energy-Balance Similarity**
  - **Match n_0 to Calculate Scale *LWC* or Temperature**
  - **Messinger n_0 Consistent with Experimental Results**
  - **Parameters b_0, ϕ and θ_0 Appear to be of Little Importance**
- **Surface-Water-Phenomena Similarity**
  - **Match We_L to Find Scale Velocity**
  - **Physics not Fully Understood**