CFD Methods for SLD Simulation Workshop
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SLD Icing Physics

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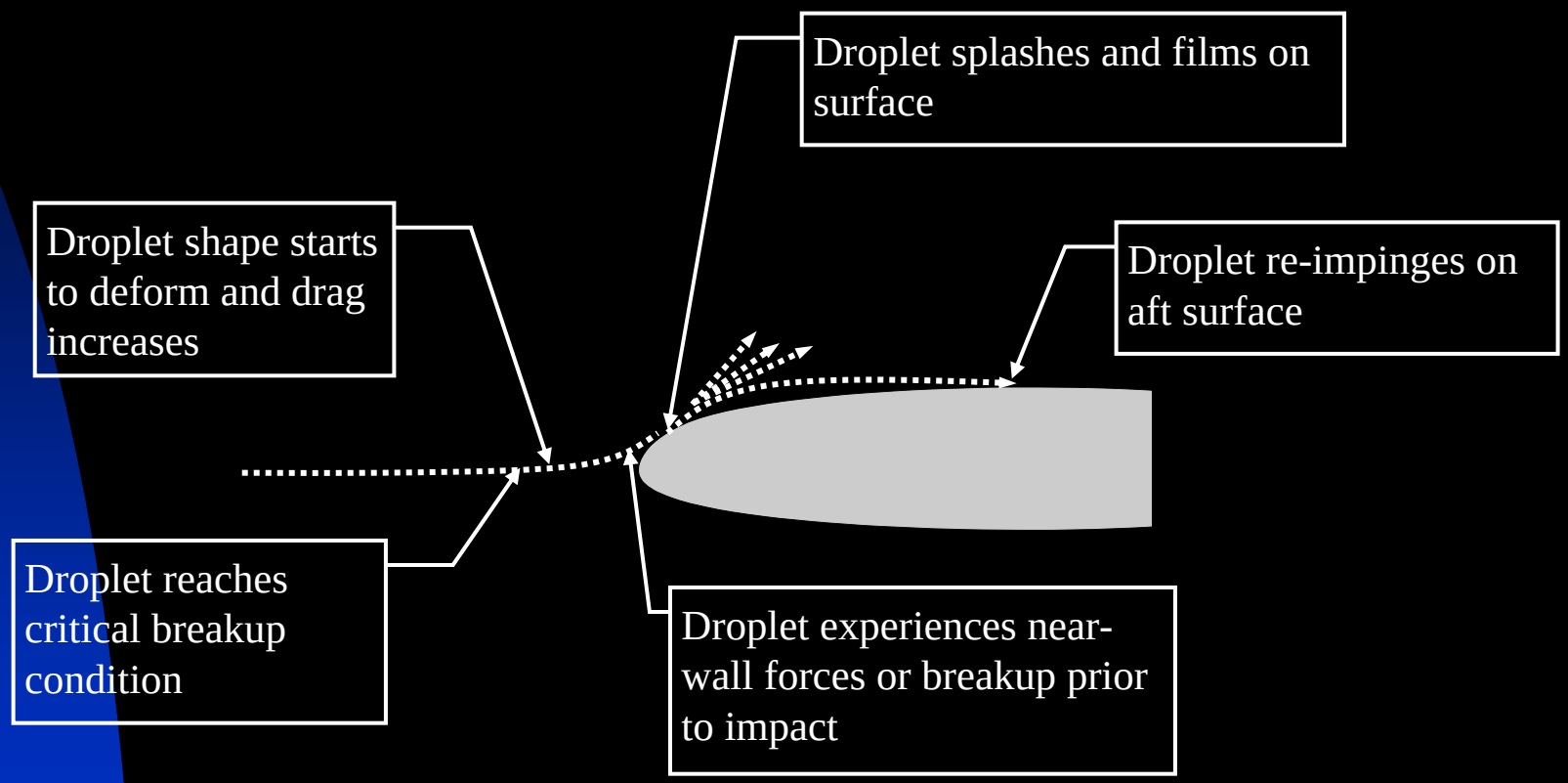
Presentation Topics

- Introduction
- Large Droplet Transition Regimes
- Effects of Droplet Splashing (2004)
  - Development of Droplet Splash Model
- Effects of Droplet Breakup (2005)
  - Development of Droplet Breakup Model
- Effects of Droplet Re-impingement (2006)
  - Development of Droplet Rebound and Re-impingement Model
- Limitations and Assumptions of the LDD Models
- Overall effects of the LDD
- Further work

Introduction

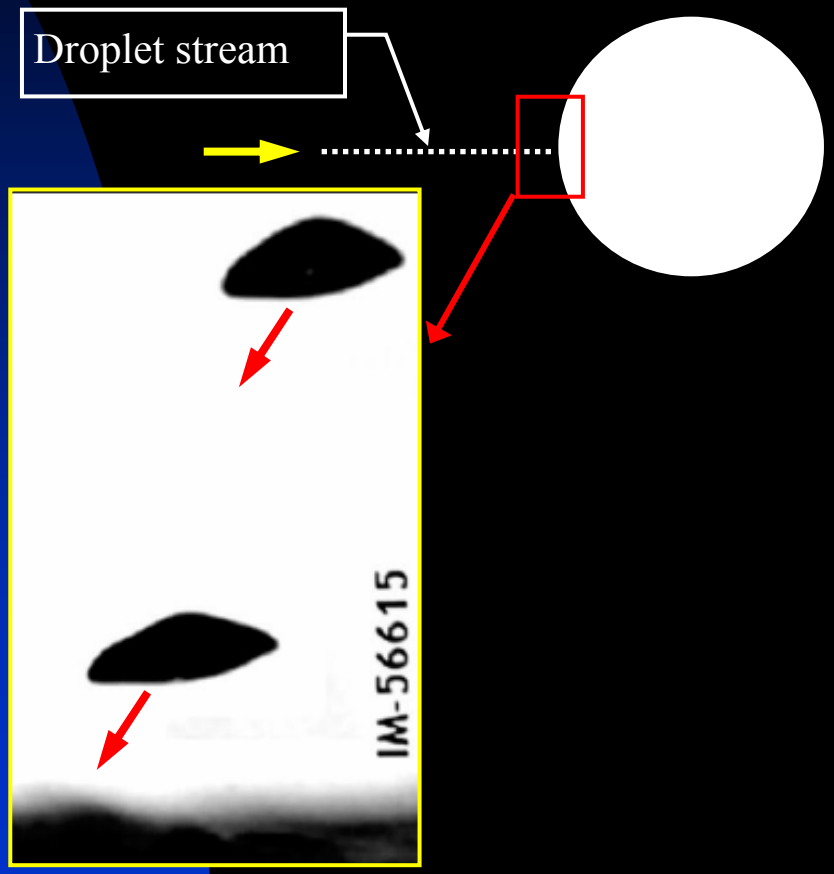
- Ice accretion on lifting surfaces of an aircraft can affect aerodynamic performance and handling qualities.
- Ice protection systems (IPS) are installed to ensure the safe operation of the aircraft in icing conditions.
- Aircraft icing certifications have been performed mainly in Appendix C clouds (MVDs ~ 11 - 40 μm; Droplet sizes ~ several microns to about 100 μm).
- Icing in SLD clouds poses a challenge to the design and installation of IPS because ice can accrete beyond the limits of IPS. MVD > 40 μm. Droplet size ~ 50 to several mm.
- Large droplets have greater inertias, and tend to splash on impact with a surface. The splash 'ejecta' can potentially re-impinge on aft surfaces. Large droplets are also susceptible to breakup when subjected to severe pressure gradient.

Droplet Transition Regimes

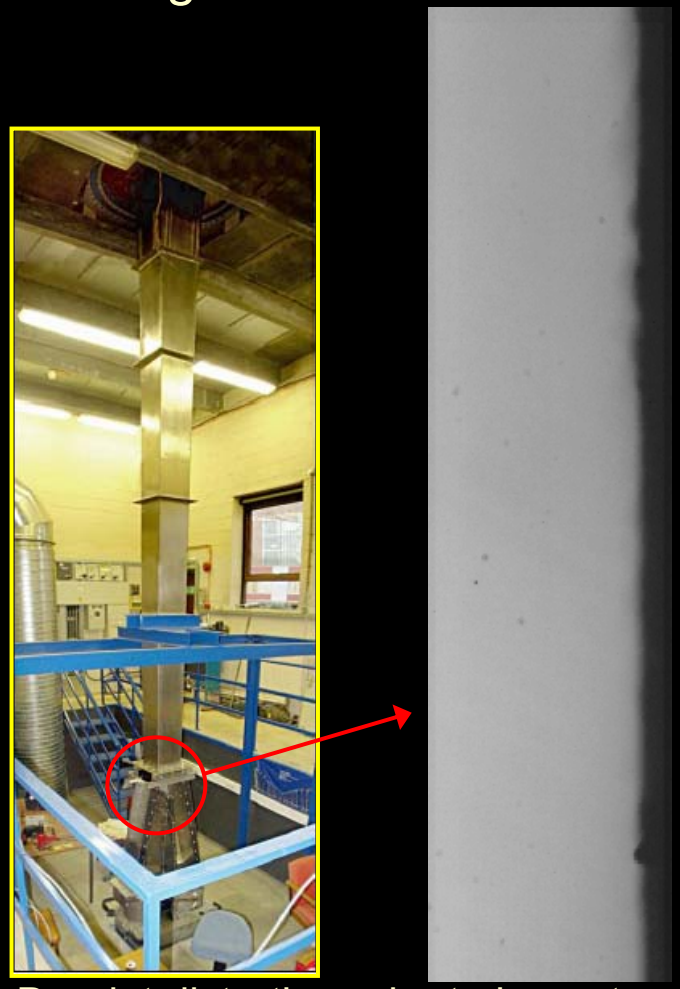


Droplet Distortion

- Large droplet tends to distort prior to impact with a surface.
- Effect is due to the near-wall pressure gradients.



Droplet distortion at the leading edge of a cylinder. (Courtesy of Dr. G. Luxford)

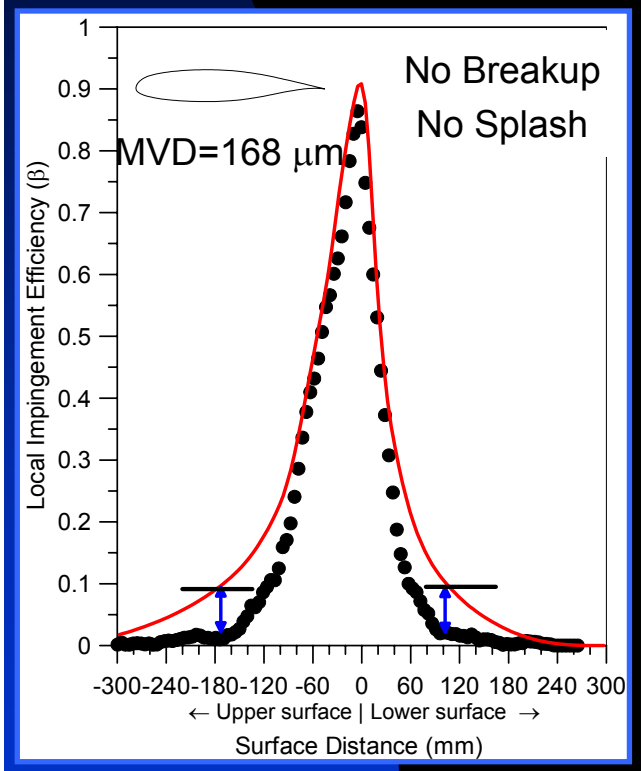


movie

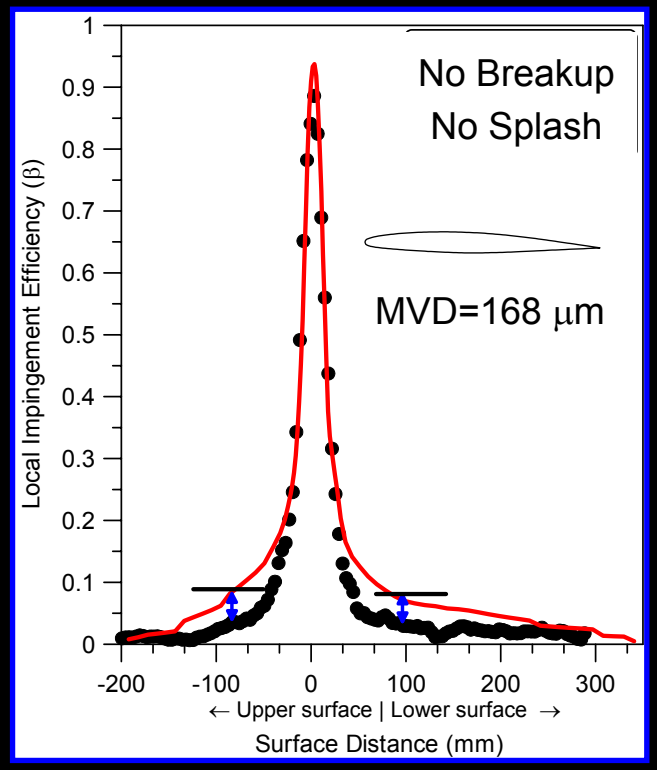
Droplet distortion prior to impact with a dry surface (Courtesy of Cranfield Univ. and NASA Glenn)

Effects of Droplet Splashing on Droplet Impingement Distribution

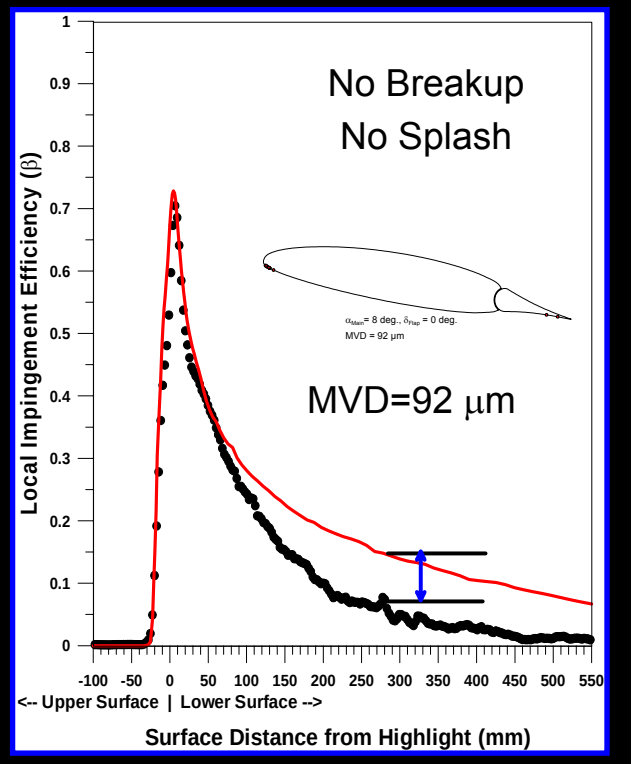
- Significant discrepancies between predicted and experimental droplet impingement distributions were found in SLD clouds.
- It was thought that droplet splashing was the main cause of the discrepancies.



MS317 airfoil
(chord = 36”, α = 0°, V_∞= 176mph)



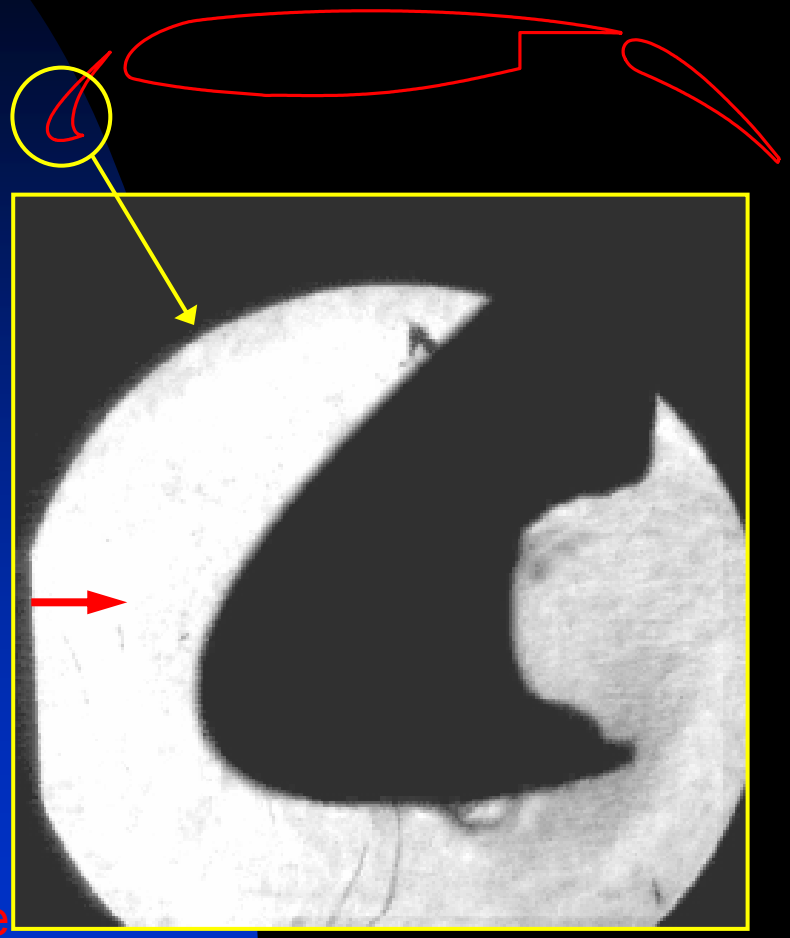
GLC305 airfoil
(chord = 36”, α = 0°, V_∞= 176mph)



NLF-414 airfoil
(chord = 48”, α = 8°, V_∞=176mph)

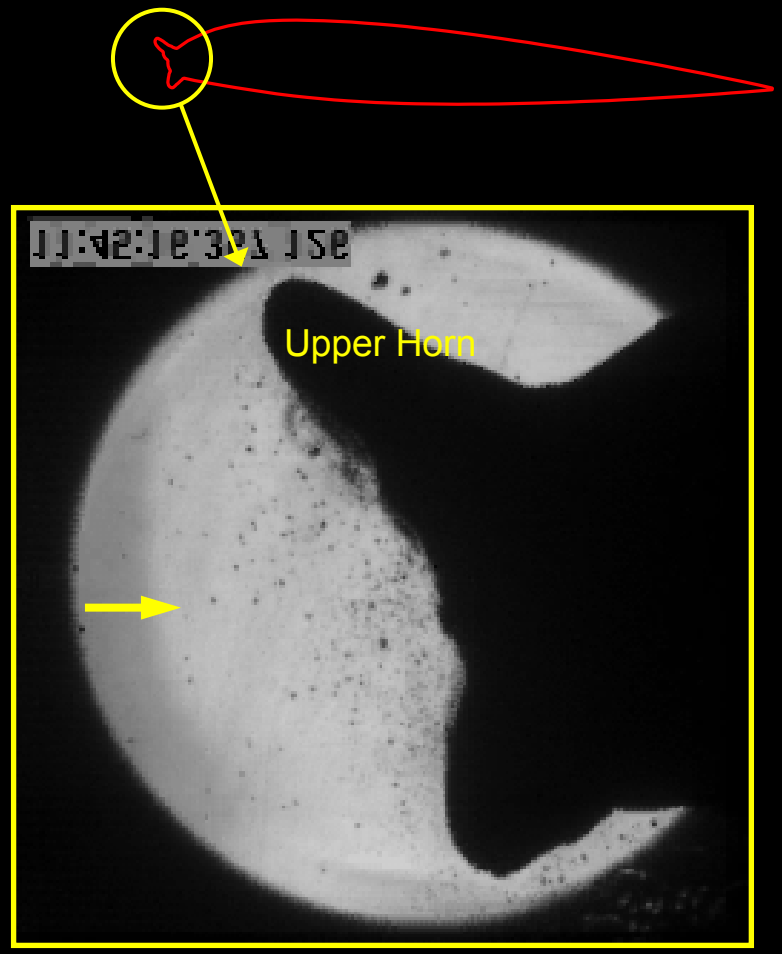
Experimental Investigation of Droplet Splashing (2005)

- Large droplets tend to splash on impact with a surface when significant kinetic energies are involved.



movie

Droplet splashing on the slat element of a high-lift airfoil (Dia=370 um, V_∞ = 130mph)



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Droplet splashing at the leading edge region of a NACA23012 airfoil (22.5-min ice shape)

Development of an Empirical Droplet Splash Model

Utilizes a splash factor, ψ, to alter the simulated droplet impingement distribution hence accounts for droplet splashing.

$$\text{if } \psi = 0, \quad \dot{m}_{\text{film}} = LWC_\infty V_\infty \beta \quad \text{per unit area}$$

$$\text{if } \psi = 1, \quad \dot{m}_{\text{film}} = 0$$

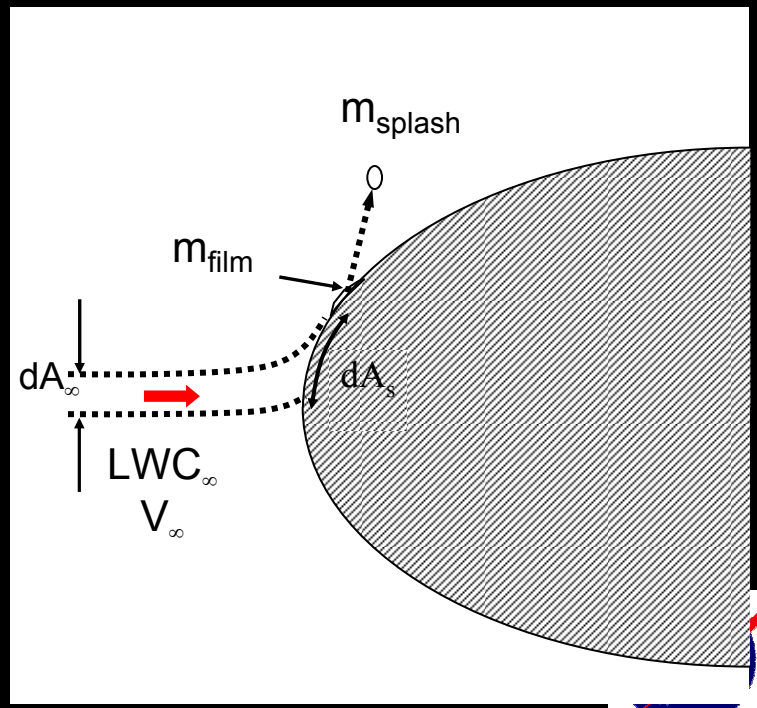
$$\text{if } 0 < \psi < 1, \quad \dot{m}_{\text{film}} = (1-\psi) LWC_\infty V_\infty \beta,$$

$$= \dot{m}_{film}\big|_{\psi=0} - \psi\, LWC_\infty V_\infty \beta$$

$$\therefore \quad \dot{m}_{\text{splash}} = \psi\, LWC_\infty V_\infty \beta \text{ per unit area}$$

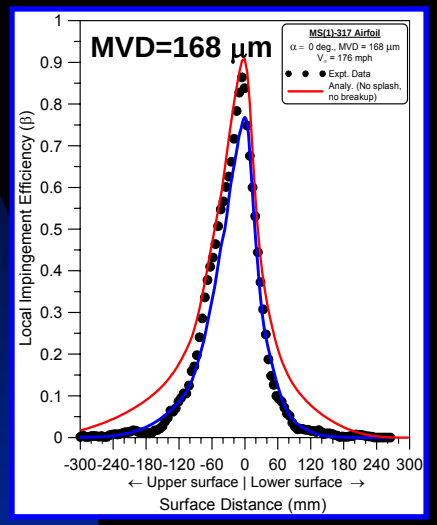
$$K = \text{Oh.Re}^{1.25} = \left(\frac{\rho_d^3 D_d^3 w^5}{\sigma_d^2 \mu_d} \right)^{1/4}$$

- Splash factor, $\psi = f(\text{MVD}, K)$. Obtained by calibrating with the experimental impingement distributions collated for cloud MVDs of 11, 20, 79, 92, 137 and 168 μm with the MS317 airfoil.
- K, the impact parameter, is a function of the water properties and normal component of the droplet impact velocity.

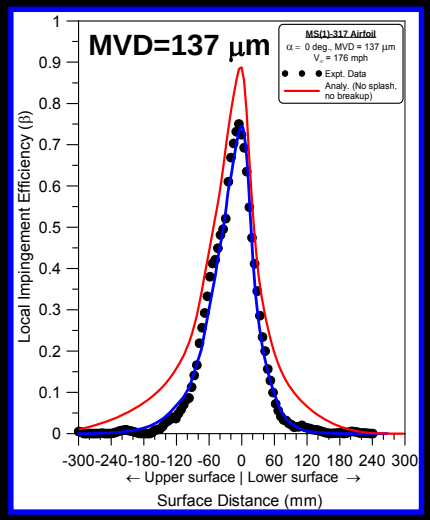


Application of the Splash Model -1

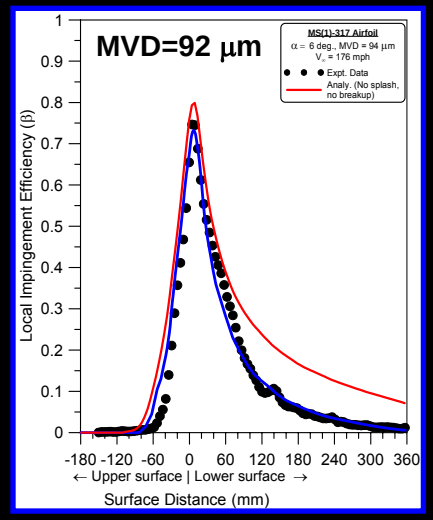
- Success was demonstrated for a range of airfoils e.g. MS317, GLC305, NLF-0414, MD 3-element, and at modest AOA (< 8°).



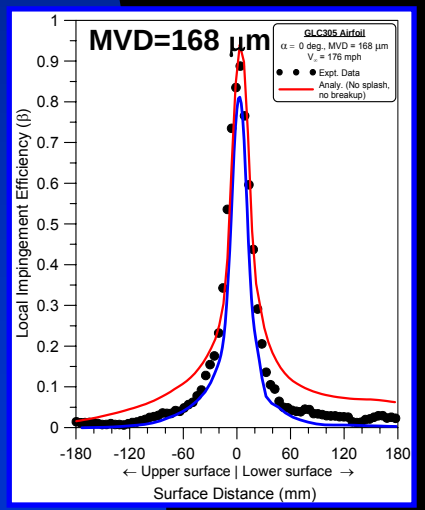
MS317: chord = 36”, α = 0°, MVD = 168 um, V_∞= 176mph



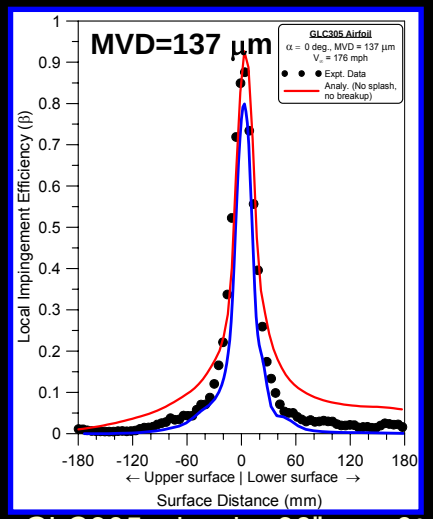
MS317: chord = 36”, α = 0°, MVD = 137 um, V_∞= 176mph



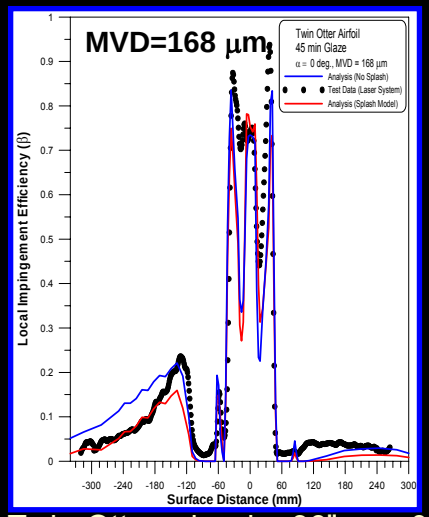
MS317: chord = 36”, α = 6°, MVD = 92 um, V_∞= 176mph



GLC305: chord = 36”, α = 0°, MVD = 168 um, V_∞= 176mph



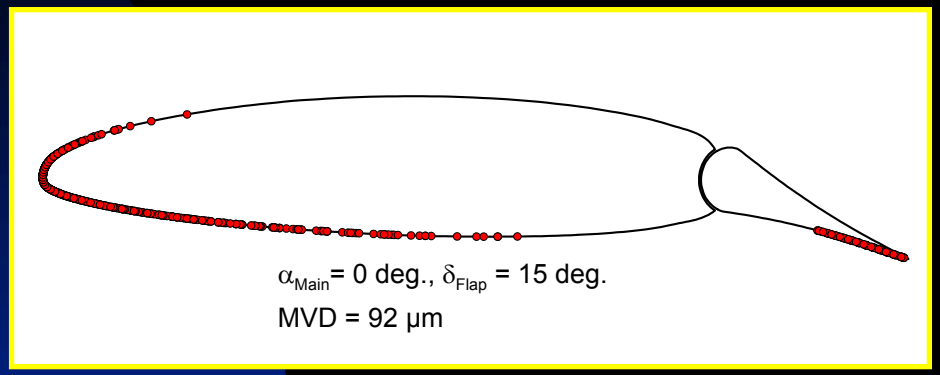
GLC305: chord = 36”, α = 0°, MVD = 137 um, V_∞= 176mph



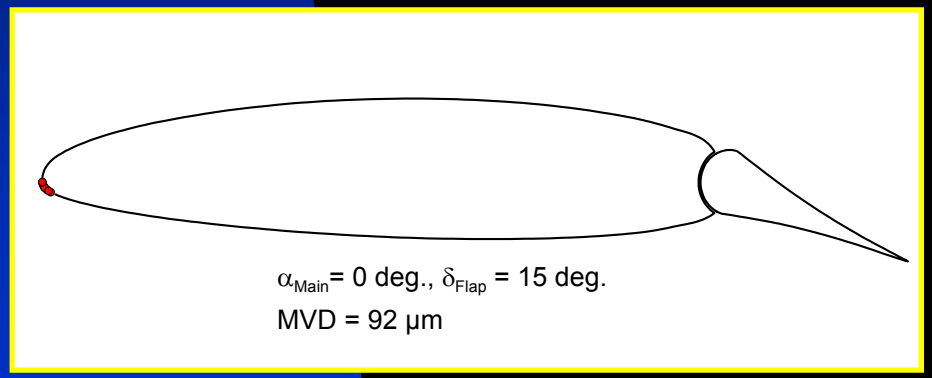
Twin-Otter: chord = 36”, α = 0°, MVD = 168 um, V_∞= 176mph

Application of the Splash Model - 2

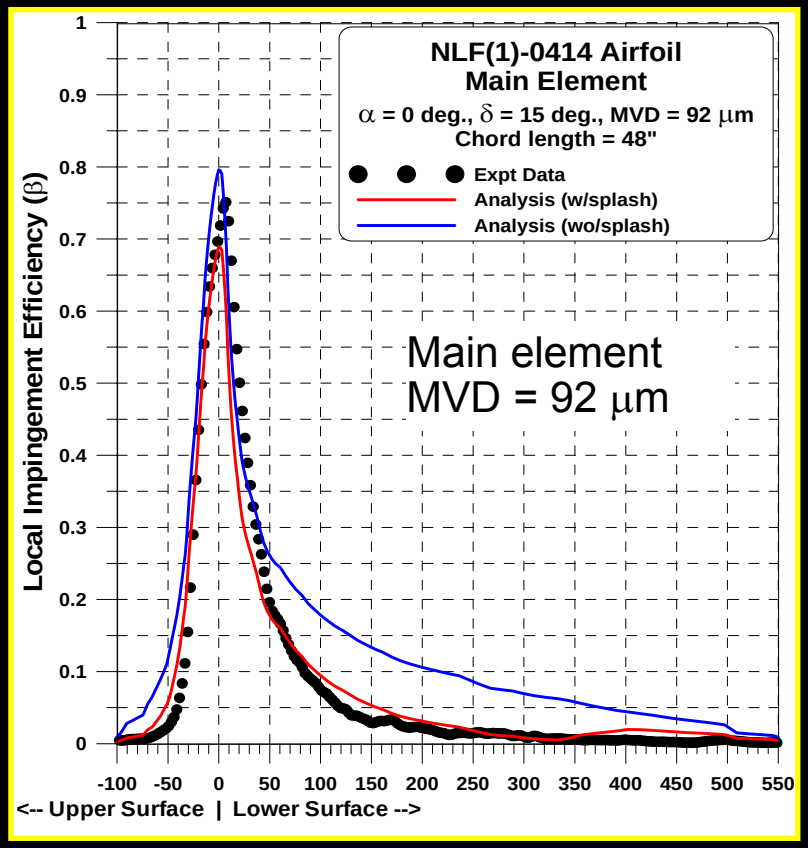
- In the case of a two-element airfoil, with flap deployed, droplet splashing occurred on both the main and flap elements.

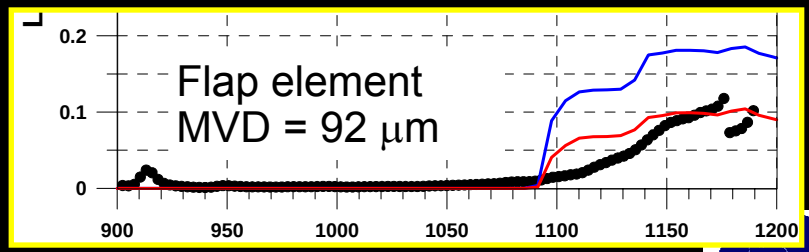


Primary droplet impact locations (due to freestream droplets).



Secondary droplet impact locations (due to splash ejecta).

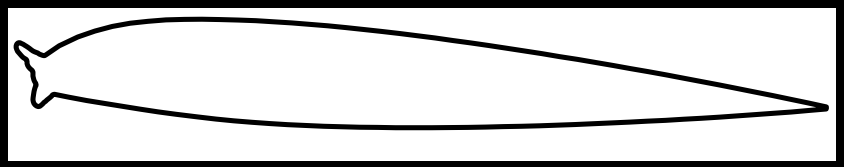


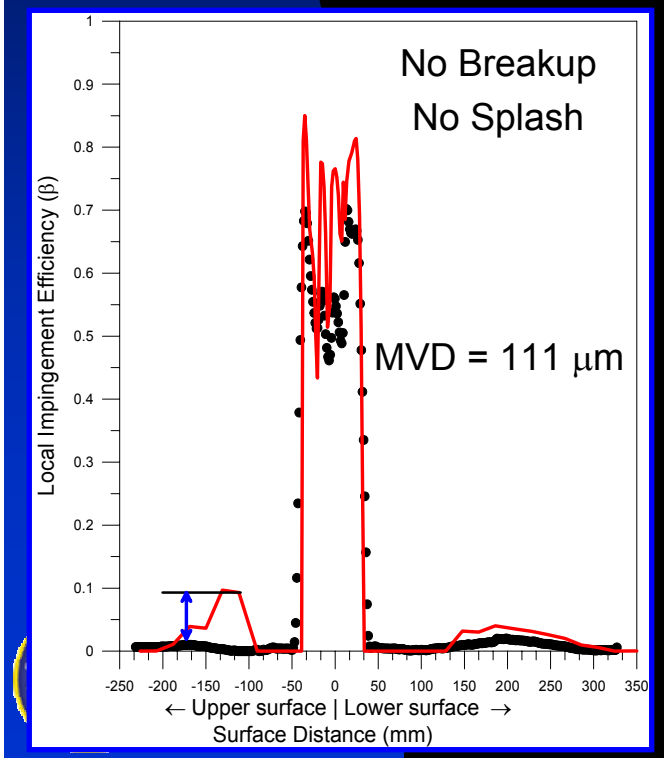


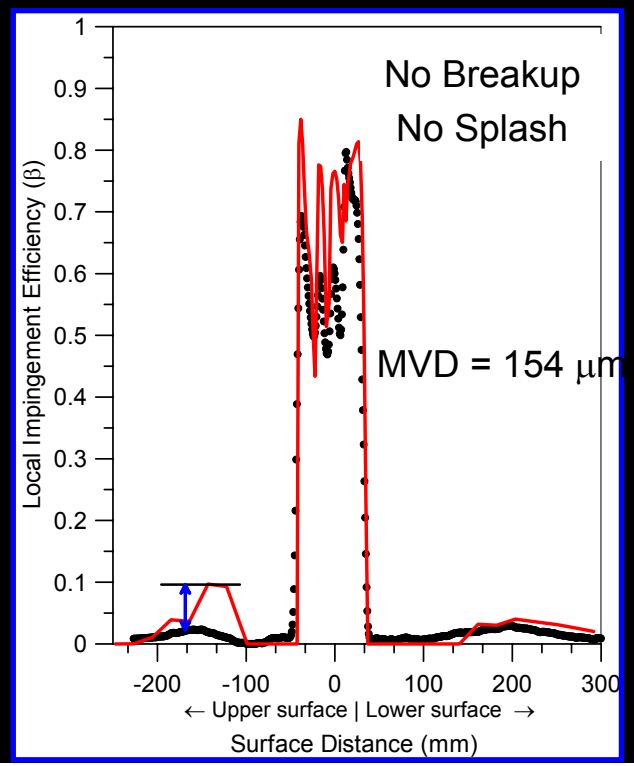
NLF- 414 Airfoil : chord = 48", MVD = 92 μm, AOA = 0° , δ_{flap} = 15°, V_∞= 176mph

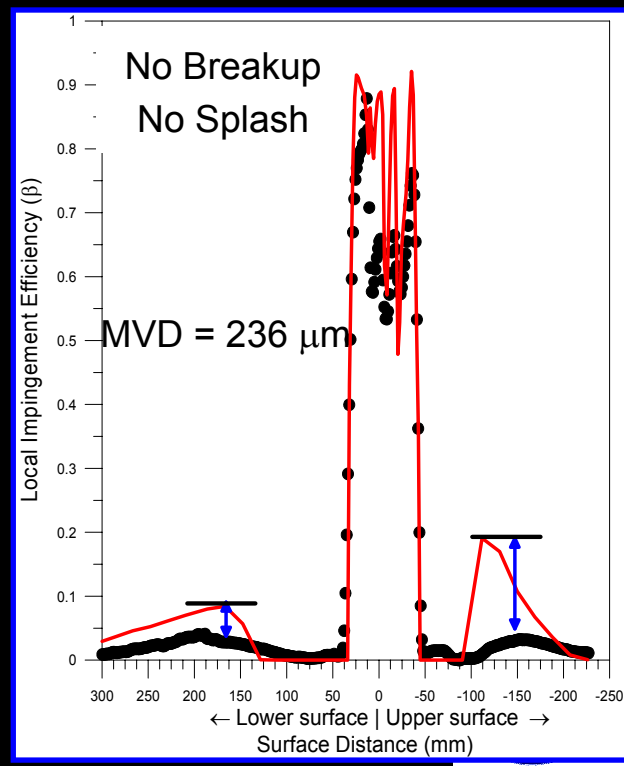
Effects of Droplet Breakup on the Droplet Impingement Distribution

- Discrepancies between predicted and experimental droplet impingement distributions were found in the NACA23012 airfoil with 22.5-min glaze ice despite the application of the droplet splash model.
- It was suspected that droplet breakup was the cause of the discrepancies.



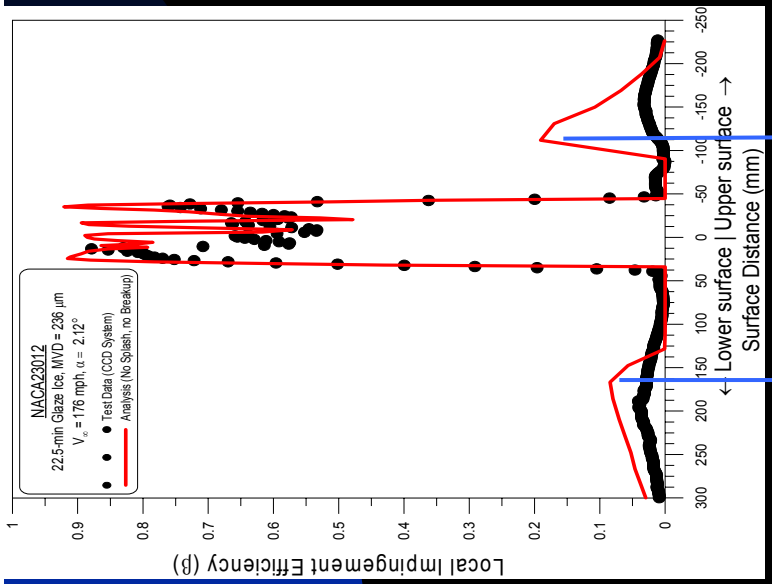




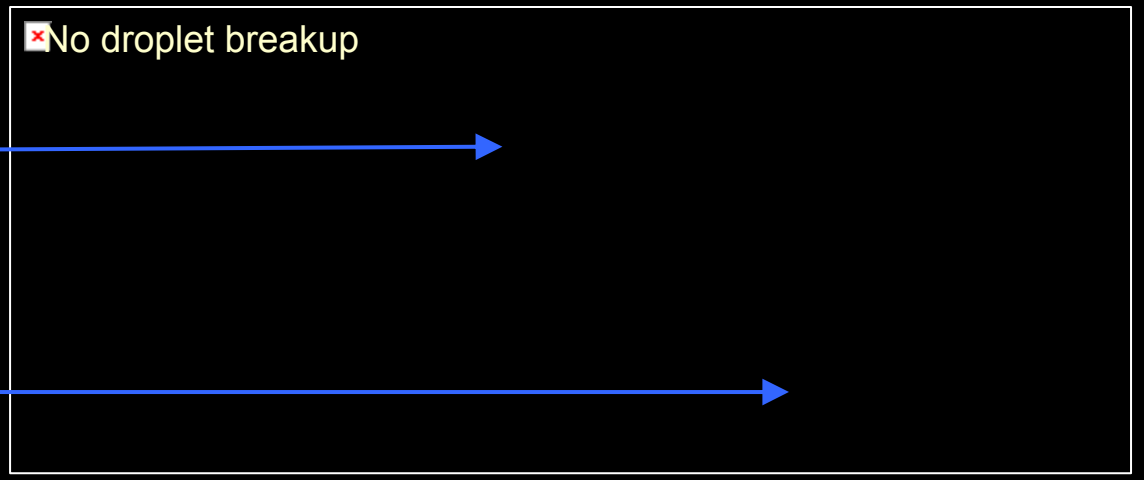


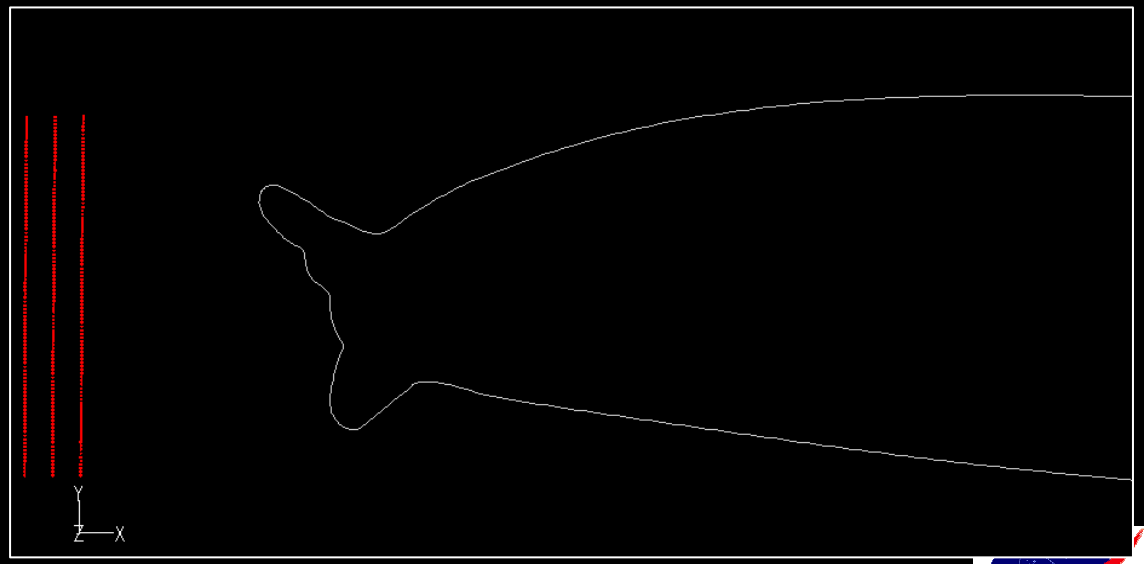
Numerical Investigation of Droplet Breakup using FLUENT

- FLUENT uses the Taylor Analogy Breakup (TAB) model to simulate breakup.
- Numerical analysis suggested that droplet breakup was occurring aft of the ice horns.



Droplet impingement distribution. NACA 23012 with 22.5 min ice shape, MVD = 236 μm, V_∞ = 176 mph



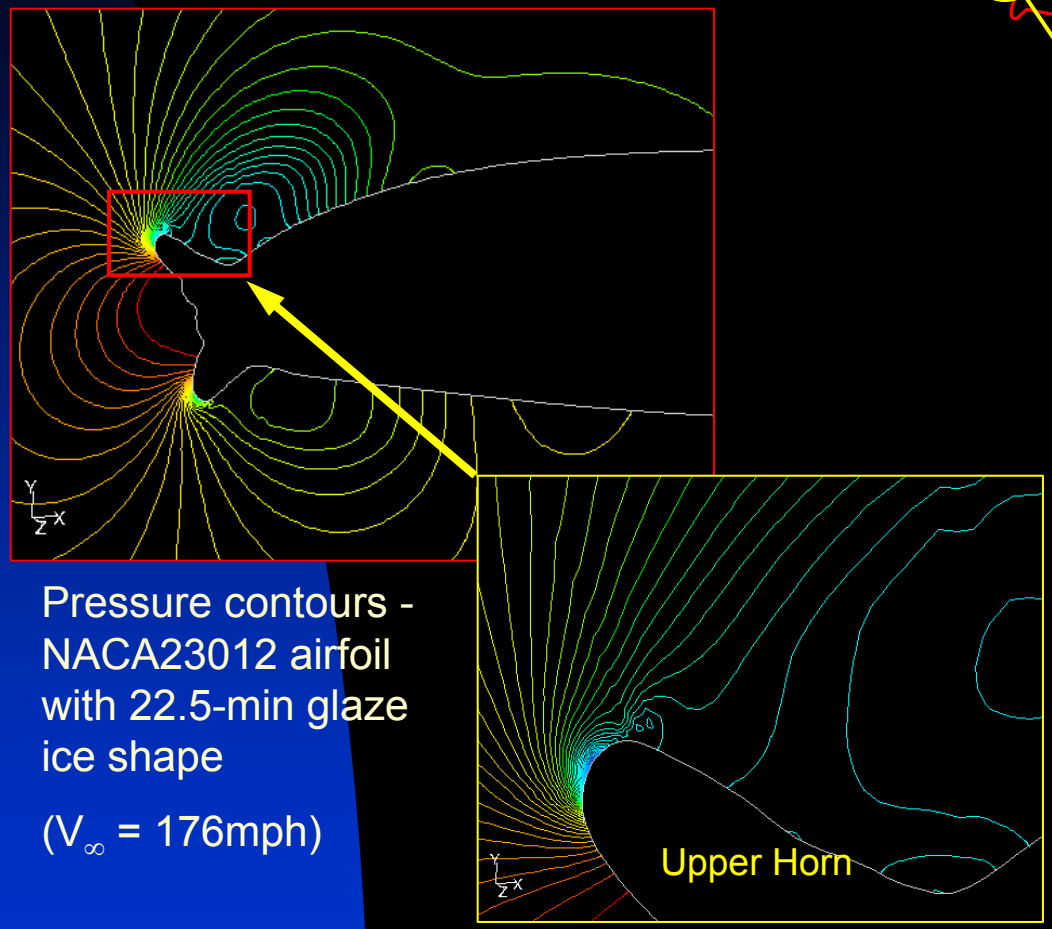


Simulation of discrete droplet breakup, dia. = 300 μm, V_∞ = 176 mph

movie

Experimental Investigation of Droplet Breakup (2005)

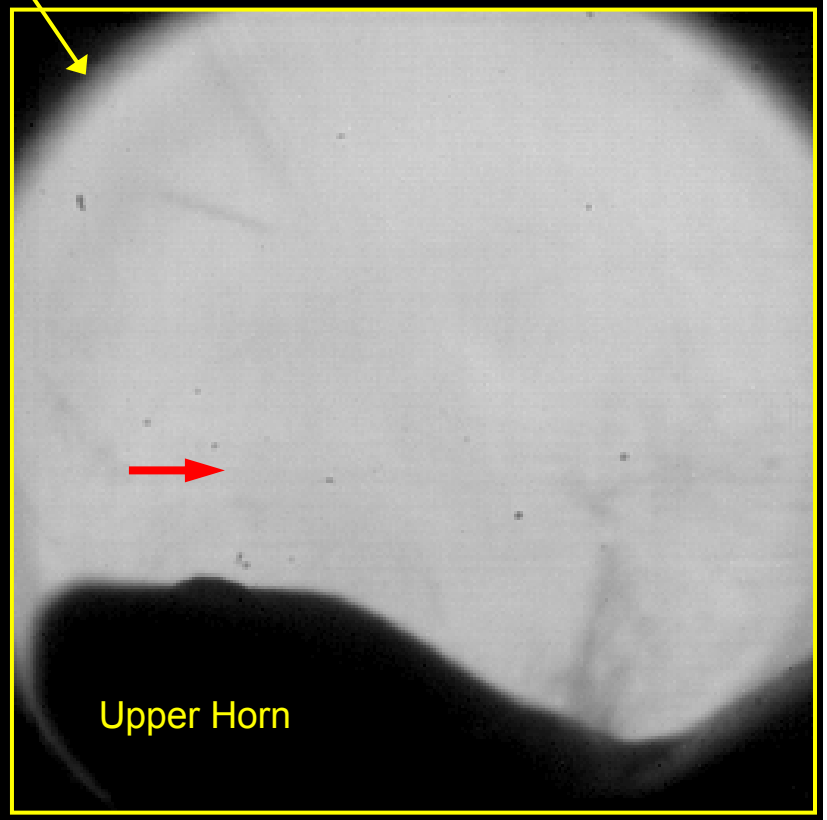
- Experiments conducted by WSU and NASA demonstrated droplet breakup near the upper horn of a 22.5-min glaze ice shape.



Pressure contours - NACA23012 airfoil with 22.5-min glaze ice shape

(V_∞ = 176mph)

movie



Droplet breakup near upper horn region of a NACA23012 airfoil (22.5-min ice shape, dia=370 um, V_∞ = 130mph)

Development of TAB Droplet Breakup Model

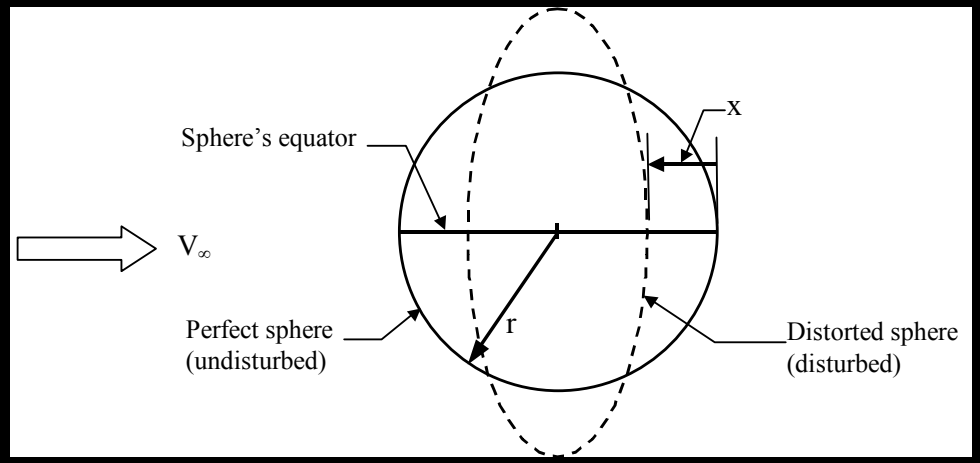
- Droplet distortion and breakup was modeled using the Taylor Analogy Breakup (TAB) model, which assumes that droplet oscillatory motion is analogous to that of a damped spring-mass system under-going a forced oscillation.
- Droplet breakup is assumed to occur when the displacement (x) is equal to the half-radius of an undisturbed droplet:

$$x > 0.5r$$

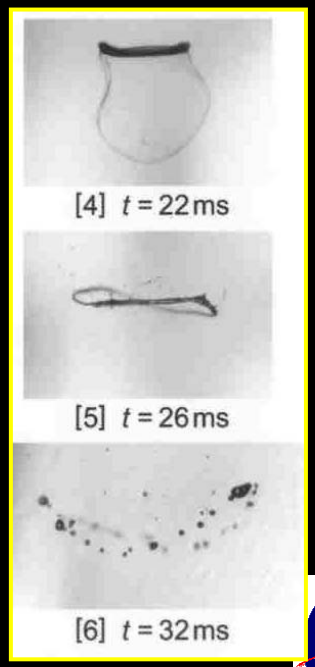
- To account for the increase in drag caused by the distortion of the droplet shape, the following drag coefficient was adopted:

$$C_D = C_{D,sphere}\,(1+2.632y)$$

Vibrational breakup



Simulation of droplet distortion



Bag breakup

Alternate Droplet Breakup Model (Weber No.)

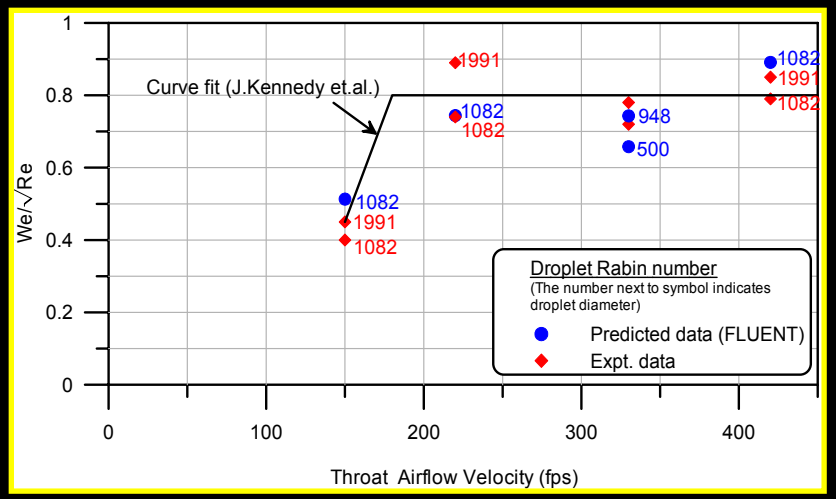
1. Characterize droplet breakup using Weber number:

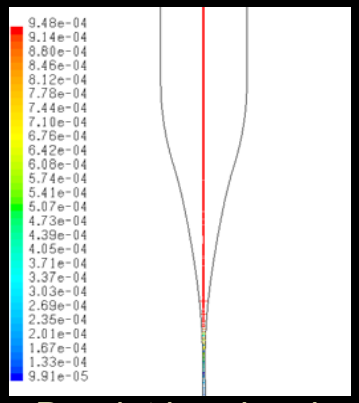
$$We = \frac{\rho_g \left| V_r \right|^2 D}{\sigma_d}$$

e.g. from Pilch and Erdman :

1) Vibrational breakup	We ≤12
2) Bag breakup	12 < We ≤ 50
3) Bag and stamen breakup	50 < We ≤ 100
4) Sheet stripping (Shear)	100 < We ≤ 350
5) Wave crest stripping	We > 350

2. Characterize droplet breakup using Rabin number : *Ra=We/√(Re)* (J. Kennedy)





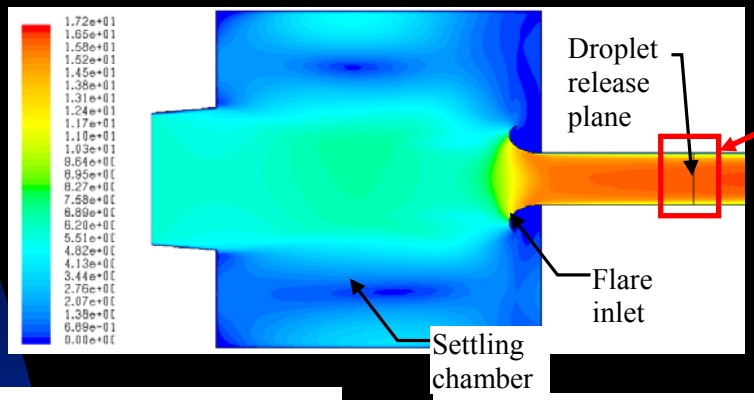
Droplet breakup in vertical tunnel

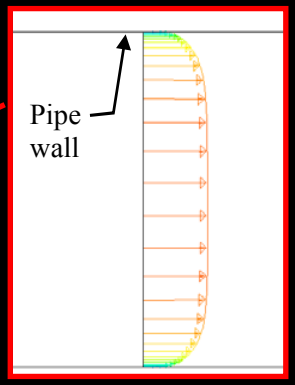
3. Characterize droplet breakup using Bond number : (G.Luxford)

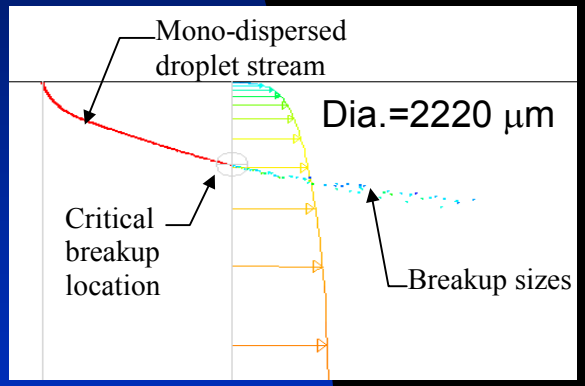
$$Bo = \frac{\rho_d D^2}{\sigma_d}\left(\frac{dV_r}{dt}\right)$$

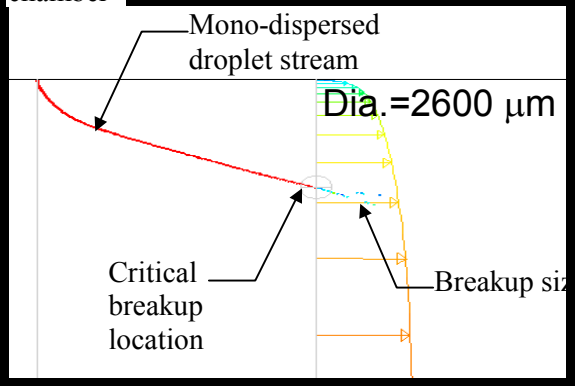
Validation of the TAB Model

- Validation was performed using published experimental data obtained in a vertical tunnel (J. Kennedy) and a horizontal tunnel (Wierzba).









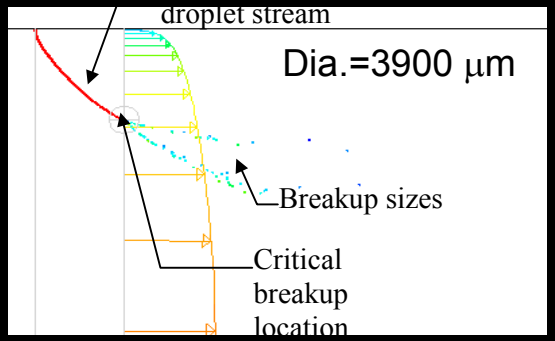


Table 2. Critical Weber numbers in horizontal tunnel

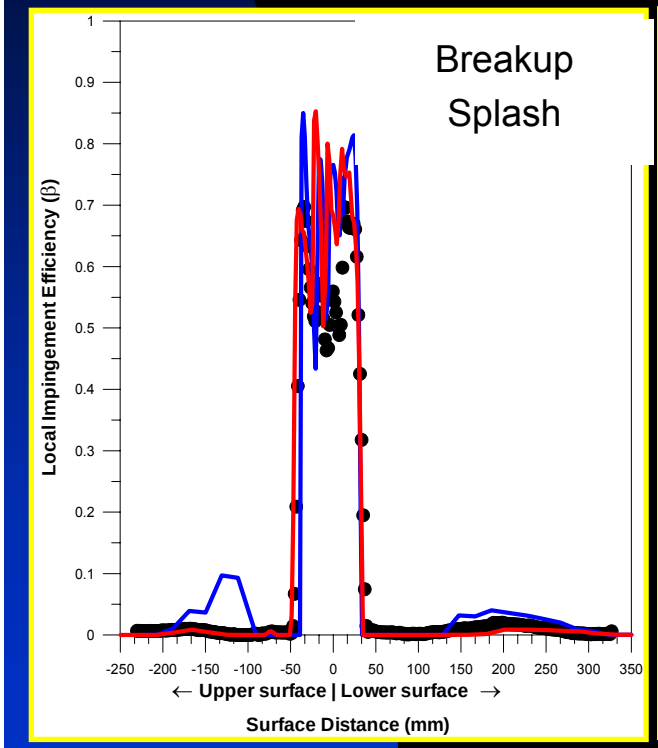
Droplet diameter (μm)	Droplet velocity (m/s)	Air velocity (m/s)	Weber number (predicted)	Weber number (expt.)
2220	0.914	17.0	9.4	Between 13.7 and 14.07
2600	1.130	17.5	11.4	
3900	1.170	17.0	16.0	

- Validation was assessed using critical Weber numbers.

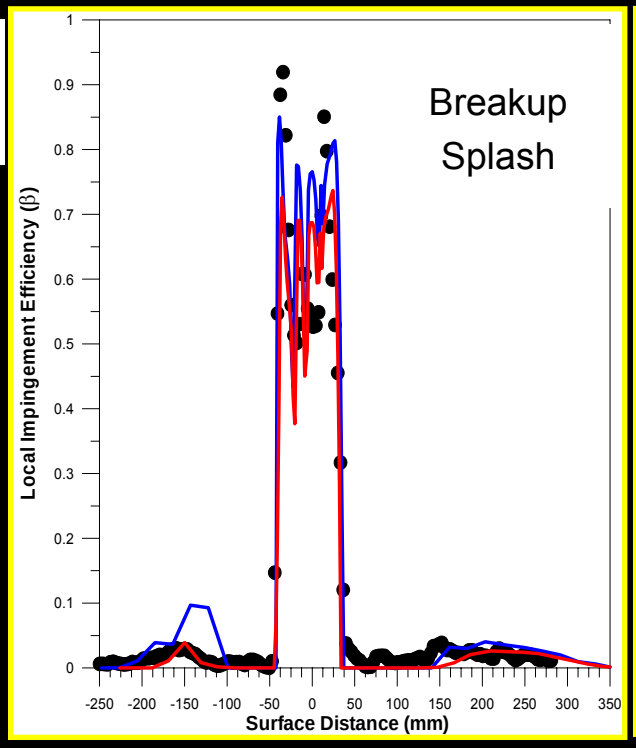
Application of the TAB Breakup Model

- Significant improvement between predicted and experimental droplet impingement distributions were obtained when both droplet breakup and splashing were applied to the analysis.

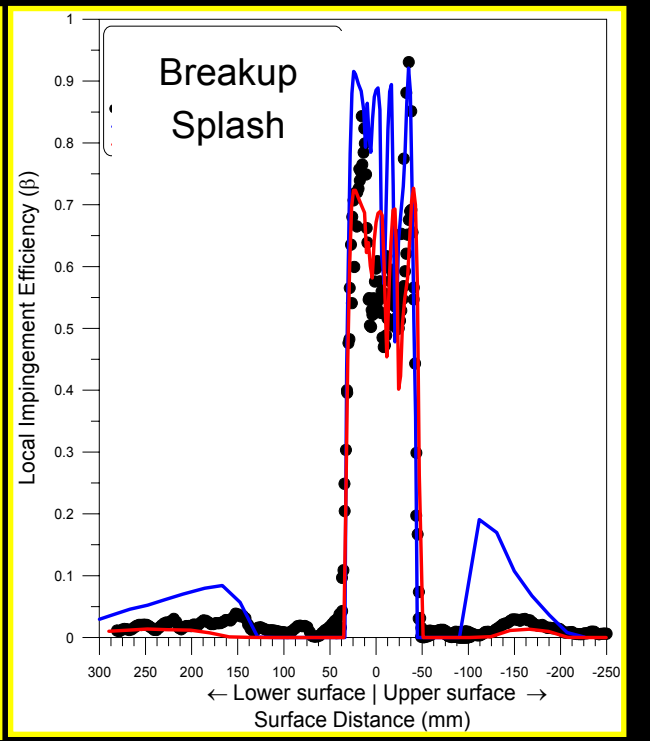
NACA23012 with 22.5-min glaze ice. Airfoil : chord = 36”, AOA = 0° , V_∞= 176mph



MVD = 111 μm



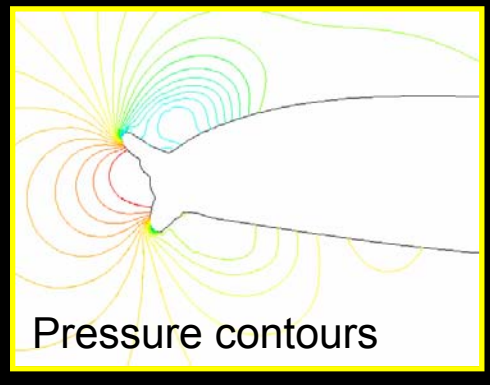
MVD = 154 μm

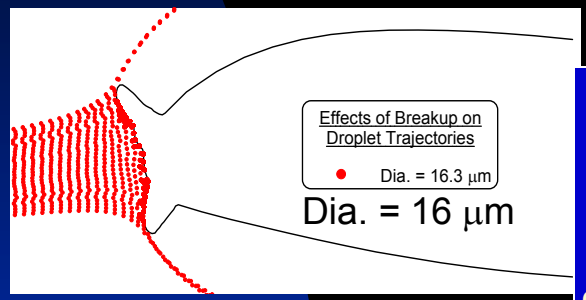


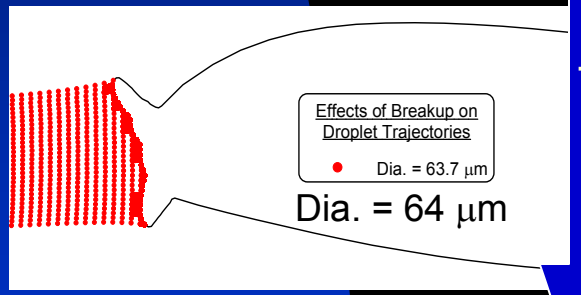
MVD = 236 μm

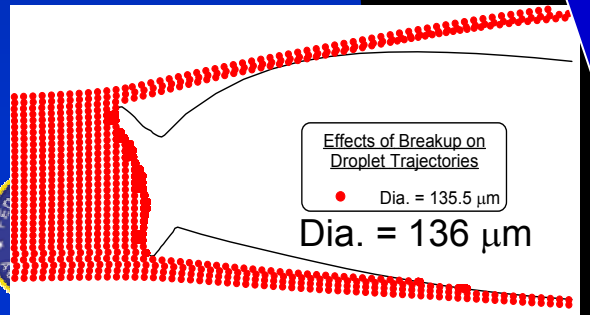
Analysis of the Discrete Droplet Breakup Characteristics

10-bin droplet size distribution for a cloud MVD of 236 μm. NACA 23012 with 22.5 min ice shape

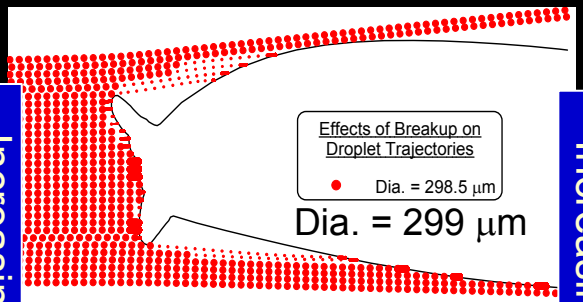


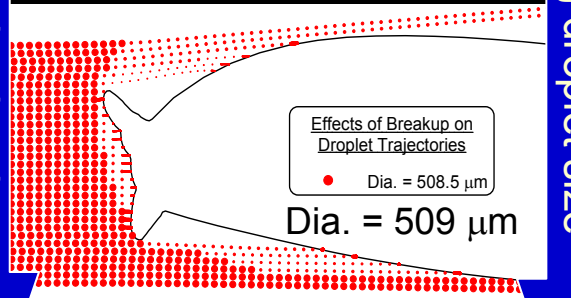


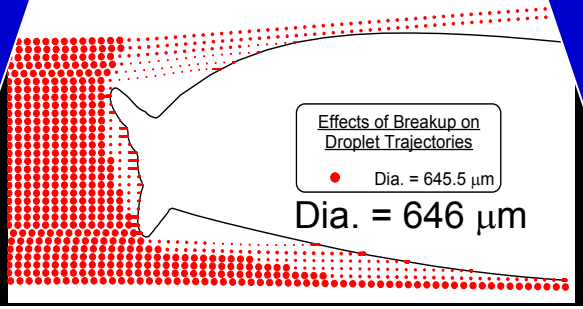




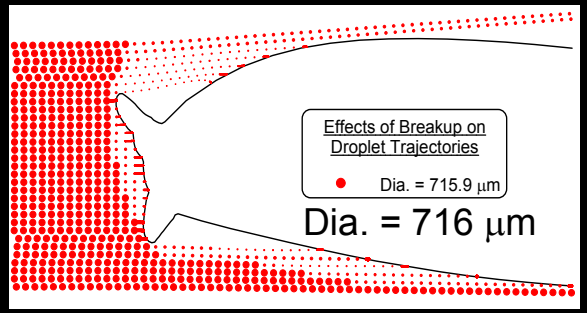
Increasing droplet size

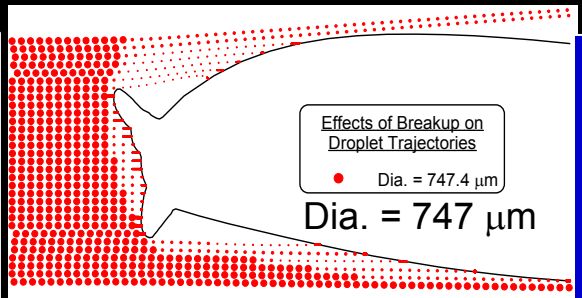


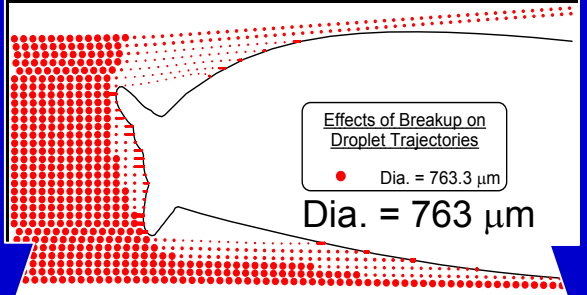


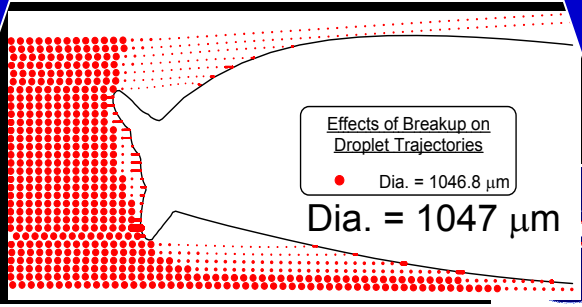


Increasing droplet size





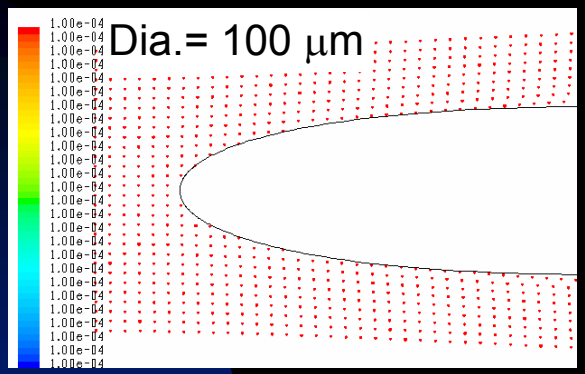




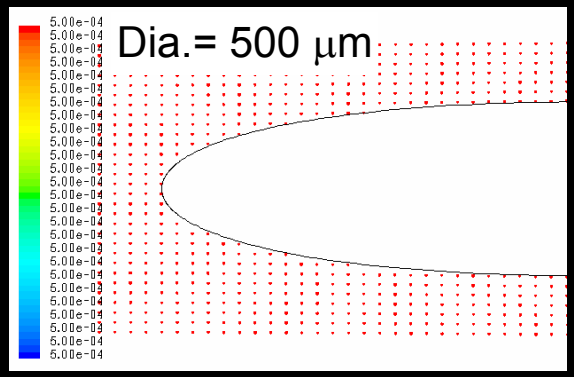
Increasing droplet size

Effect of Airfoil Size on Droplet Breakup

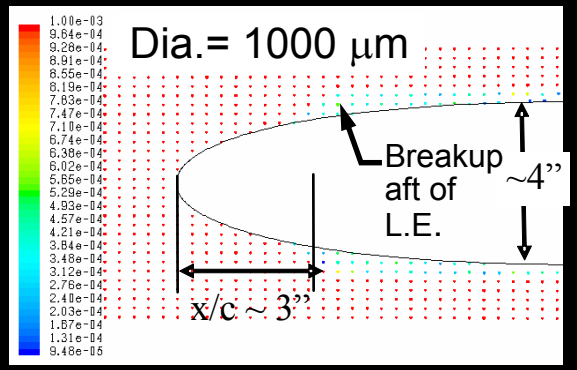
- Comparison of breakup characteristics between two NACA0012 airfoils with different chord sizes.



chord = 1-ft

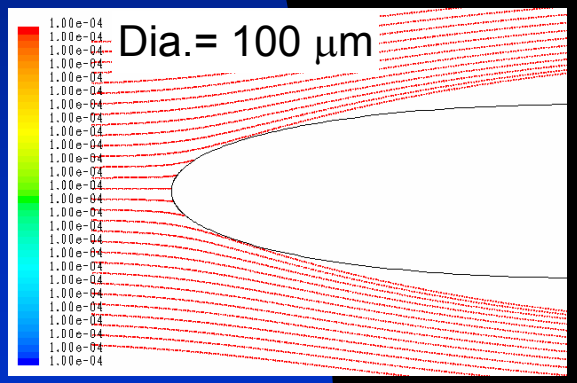


chord = 1-ft

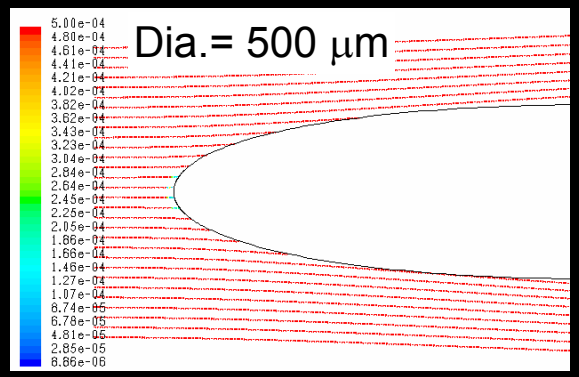


chord = 1-ft

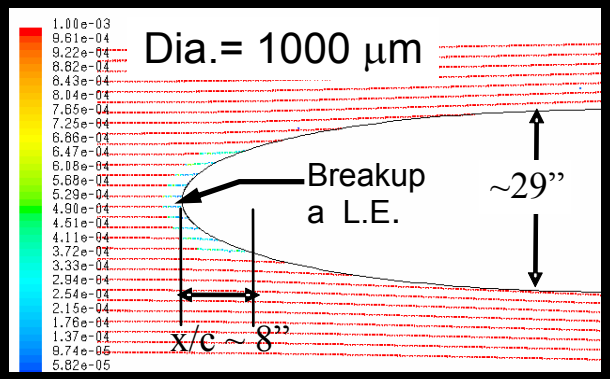
Increasing droplet size



chord = 20-ft



chord = 20-ft

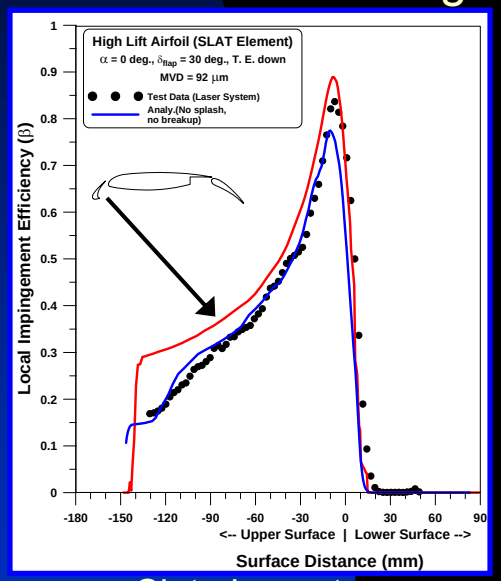


chord = 20-ft

Increasing droplet size

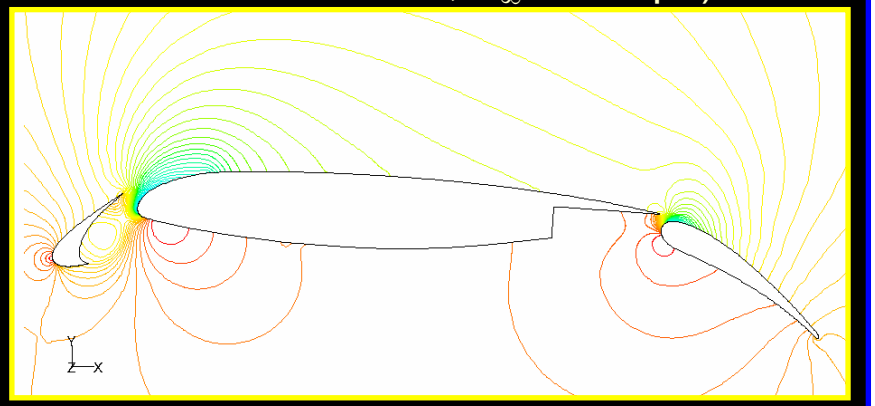
Effects of Droplet Re-Impingement on Droplet Impingement Distribution

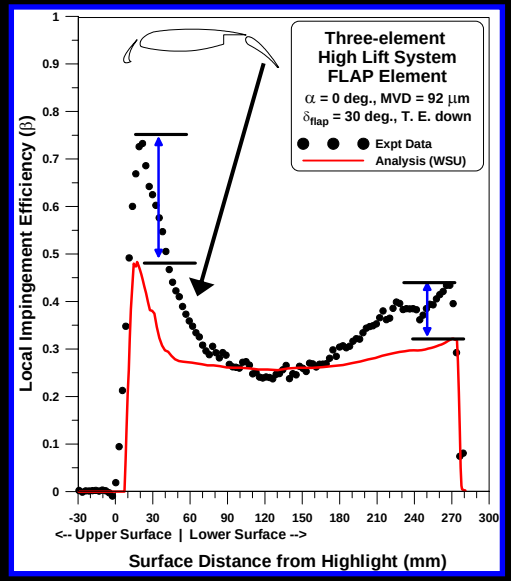
- Discrepancy between predicted and experimental droplet impingement distributions were found mainly in the flap element of a high-lift airfoil.
- Droplet breakup effect was negligible. Droplet splashing improved the analysis in the slat element. It was suspected that droplet re-impingement was occurring on the flap element.



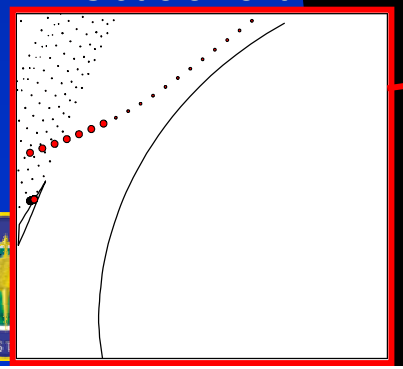
Slat element

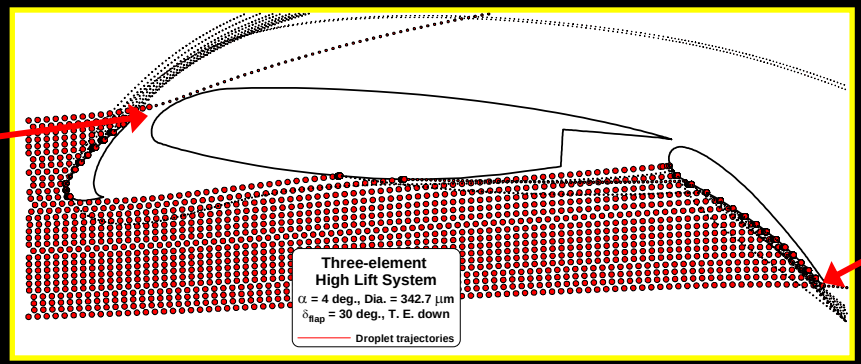
High-lift airfoil : chord = 36”, α = 0°, MVD = 92 um, V_∞=176mph)

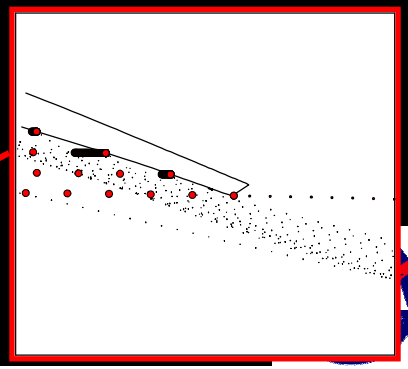




Flap element

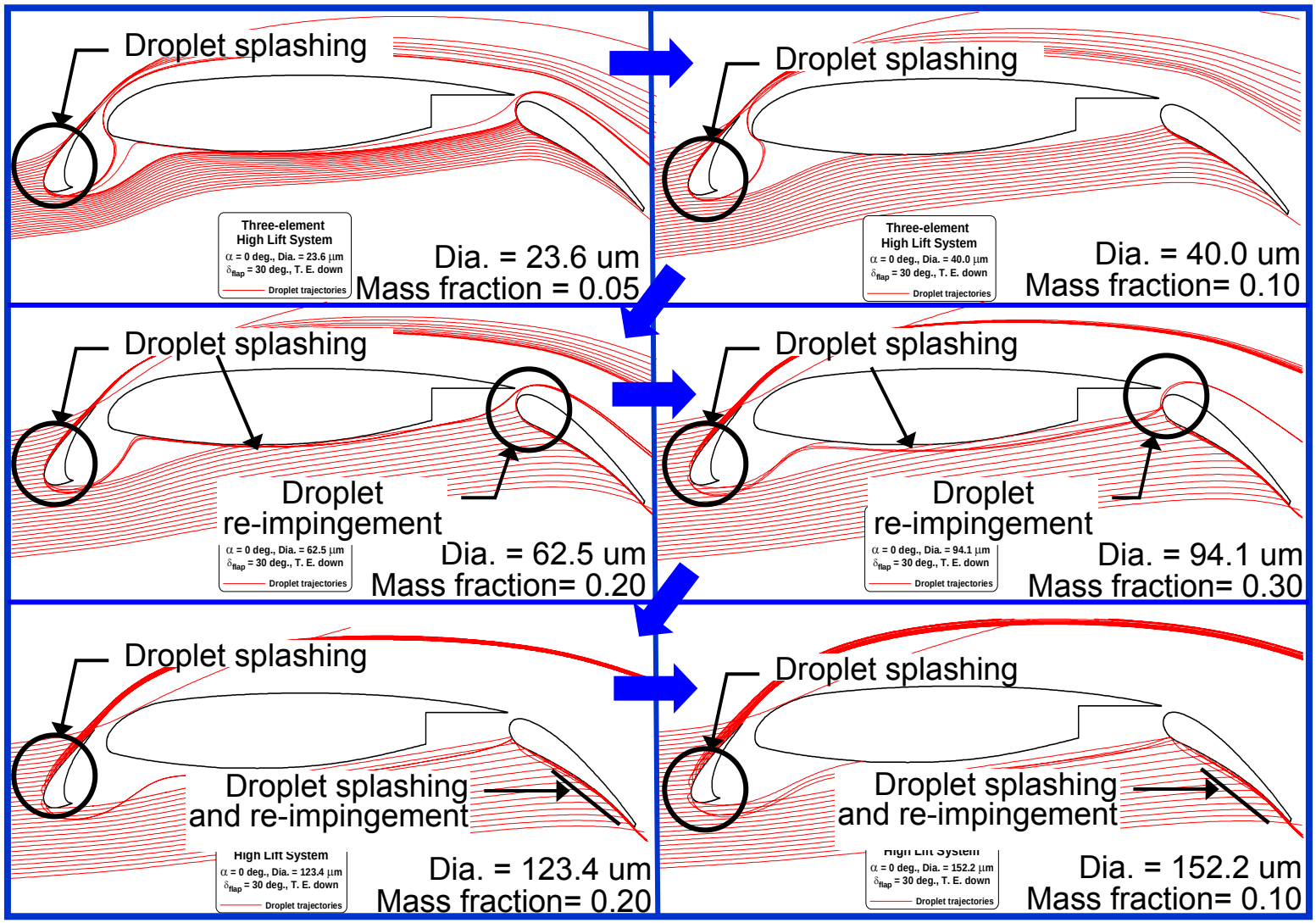






Simulation of droplet breakup (Dia. = 342 μm)

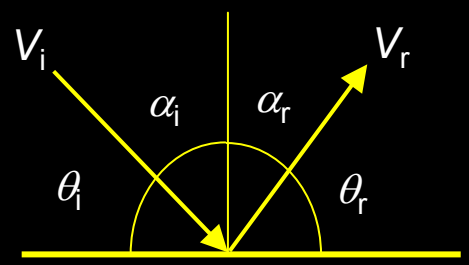
Analysis of the Discrete Droplet Trajectories



High-lift airfoil : chord = 36”, α = 0°, MVD = 92 um, V_∞=176mph

Development of Droplet Rebound and Re-impingement (R&R) Model

- Droplet rebound angles and size was based on experimental data obtained by Mundo, Sommerfeld & Tropea.



$$\alpha_r = 0.22\,\alpha_i + 1.066$$

$$\frac{D_r}{D_i} = 0.1$$

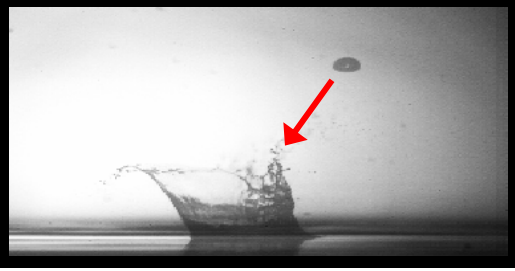
- Droplet rebound velocities were based on sand particle bounce, which seems to give realistic splashed droplet trajectories.

$$\frac{V_{t,r}}{V_{t,i}} = [0.988 - 1.66\,\theta_i + 2.11\,\theta_i^2 - 0.67\,\theta_i^3] \times \cos(\theta_r)$$

$$\frac{V_{n,r}}{V_{n,i}} = \sin(\theta_r)$$

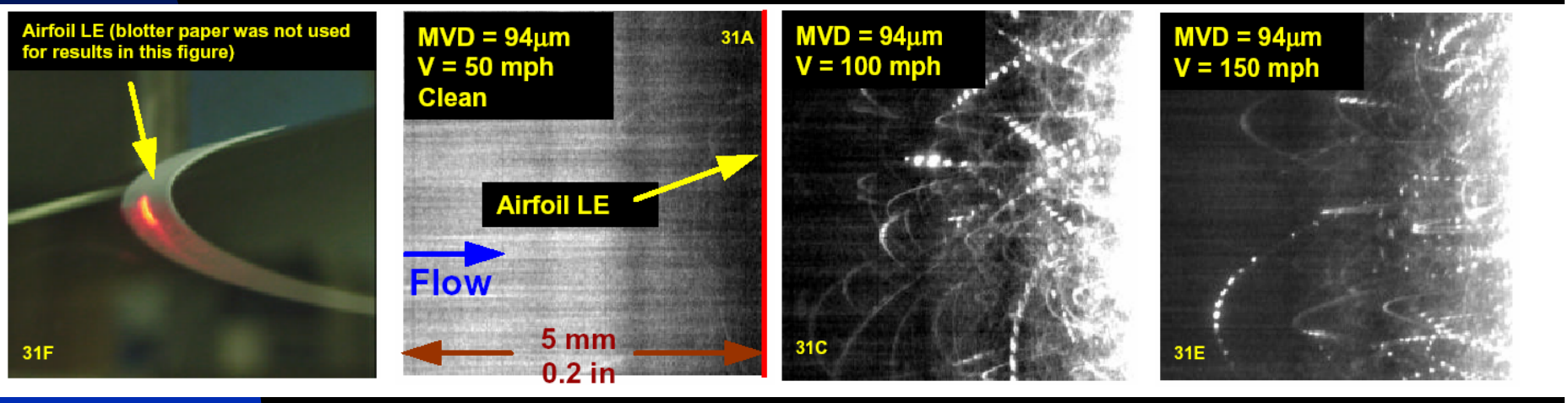
- Droplet splash mass was <u>assumed</u> to be equal to impinging droplet mass (applicable for droplet impact on wetted surface only.)

$$\frac{\dot{m}_{\text{splashed}}}{\dot{m}_\infty} = 1$$

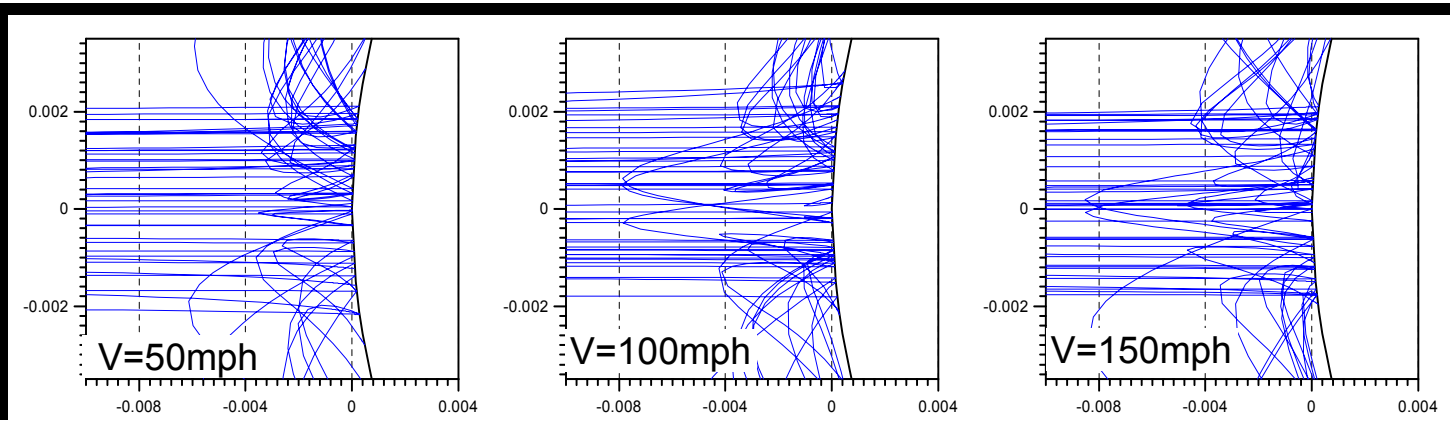


Qualitative Validation of the R&R Model

- Validation of the simulated droplet re-impingement was performed using high-speed images obtained at the L.E. of a NACA0012 airfoil.
- Droplet splash-back trajectories generally exhibited reasonable agreement with images.
- Slight discrepancies were found in the splash-back heights (simulated ~3 to 4 mm, measured ~ 1.0 to 3.0 mm), and simulated splash-back heights did not exhibit increase with tunnel speeds as measured. Therefore droplet rebound energy could be slightly over-estimated.

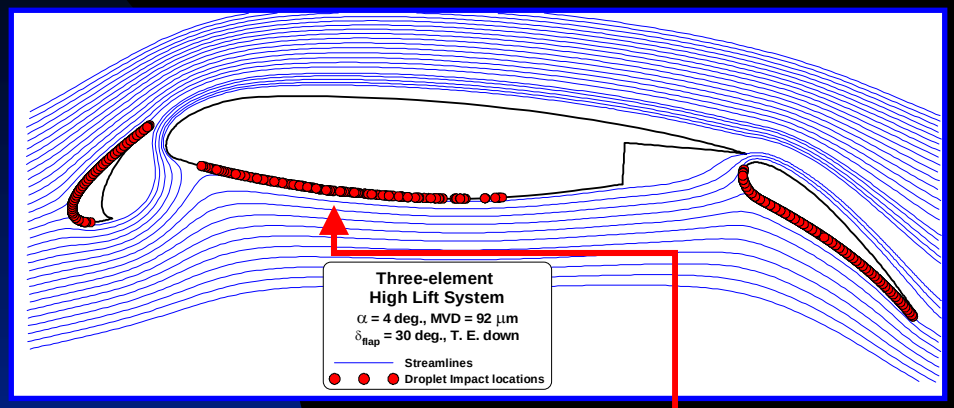


NACA0012 airfoil
chord = 21”, α = 0°,
MVD = 92 um,
V_∞= 50 to 150 mph

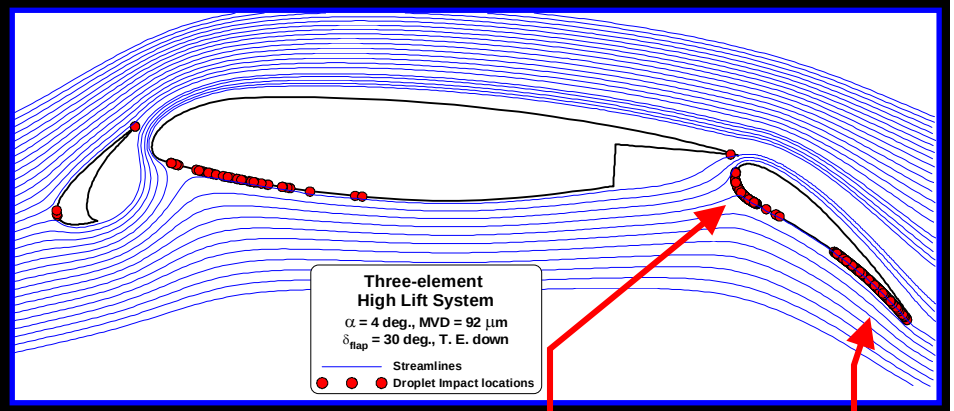


Application of the R&R Model

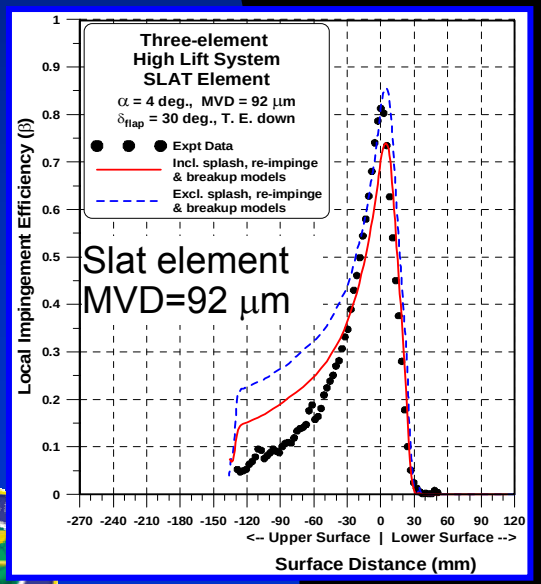
- Improvement in the droplet impingement was found in the flap element.
- Deficiencies still found in the main and trailing edge of flap elements.

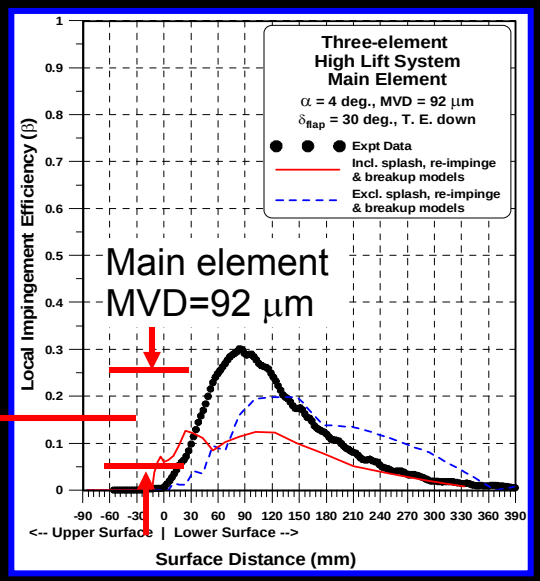


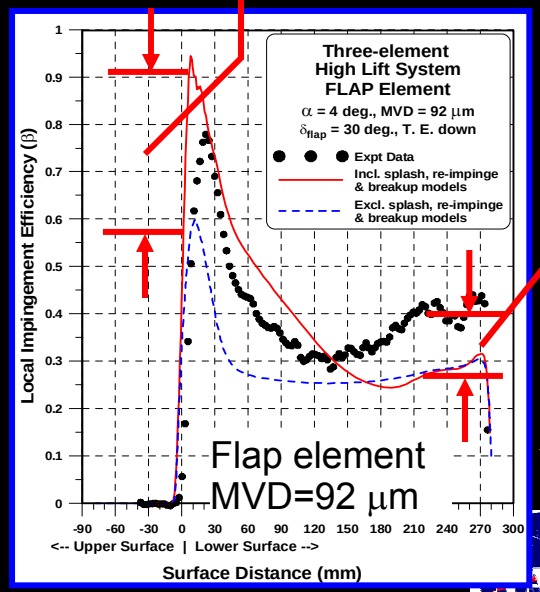
Primary droplet impact locations (due to freestream droplets)



Secondary droplet impact locations (due to splash ejecta)







High-Lift Airfoil: chord = 36”, MVD = 92 μm, AOA = 4°, δ_{slat} = 30°, V_∞= 176mph

Limitations and Assumptions

Droplet Splash Model

- Droplet splash model was developed from experimental droplet impingement tests obtained at 176 mph and chord size of 36 inches only.

Droplet Rebound Model

- Droplet rebound model simulates the splashed 'ejecta' as a single rebound droplet. In practice, 'ejecta' consists of a range of splashed droplet sizes, velocities and angles.
- The relationship between droplet impact and rebound angles were based on limited test conditions, i.e. dry surface, droplet sizes between 60 and 150 μm, impact velocities between 27 and 40 mph, and impact angles between 4° and 65°.
- Droplet rebound model is known to slightly over-predict rebound energies.
- The splashed mass ratio assumes droplet splashing from a wetted surface, e.g. droplet-droplet interactions. Published literature (ChengXin and Gosman[20]) suggested ratios between 0.2 and 1.1.

Droplet Breakup Model

- Droplet breakup model has been validated using published experimental data obtained in vertical and horizontal tunnels. Findings (Tan[13]) suggested breakup modes are limited to 'vibrational' and 'bag' types.

Overall Effects of Large Droplet Dynamic Behavior

Droplet Splash Model

- Droplet splashing reduces the amount of water flux on the aircraft surface. Splashed droplets from an ejecta can re-impinge on aft surfaces (depends on the aircraft attitude, surface geometries, flap and slat settings, etc).

Droplet Rebound Model

- Areas that experience droplet re-impingement can either exhibit an increase in water flux or undergo further splashing.

Droplet Breakup Model

- Droplet breakup also reduces the amount of water flux on the aircraft surface, usually aft of the adverse pressure regions.

Droplet Splash/Rebound/Breakup Model

- The large droplet spectrum of the Appendix C clouds (~100 μm) can experience some degree of droplet breakup and splashing but the overall effect on icing is minimal due to their low quantity.
- Droplets in SLD clouds would experience all the large droplet phenomena hence can affect the ice accretion rates and shapes.

Further Work

- Although droplet breakup, splash and rebound models performed reasonably well, they lack quantitative data for validation.
- Further assessment of these models with other wing geometries and inlets are planned.
- Current models are limited to experimental data collected at 176 mph only. Droplet impingement data are needed for a range of velocities, MVDs and airfoil sizes.