SUPERCOOLED LARGE DROPLET DEFORMATION AND BREAKUP NEAR THE LEADING EDGE OF LARGE TRANSPORT AIRFOILS

Mario Vargas

NASA Glenn Research Center, Cleveland, OH

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OUTLINE

- Space Act Agreement with INTA
- Current Research Work on Droplet Break-up
  - Objectives, Approach, Experimental Setup, Data Analysis, Results
- Summary of Droplet Break-up Research completed as of January 2011
- Current Work being done in preparation for 2011 Experiment
- Future Work

History of Space Act Agreement with INTA

- Agreement started in October of 2004
- Initial Research Work 2004-2007
  - Developed experimental methods to generate water spray representative of the range of conditions identified in FAA Appendix C
  - Evaluated rivulet break-up length and rivulet spacing versus water-film thickness for varying tunnel conditions
  - Film Weber number scaling developed for glaze icing in SLD
- Current Research Work 2007-Present
  - DROPLET BREAKUP

Current Research Work on Droplet Breakup

Objectives

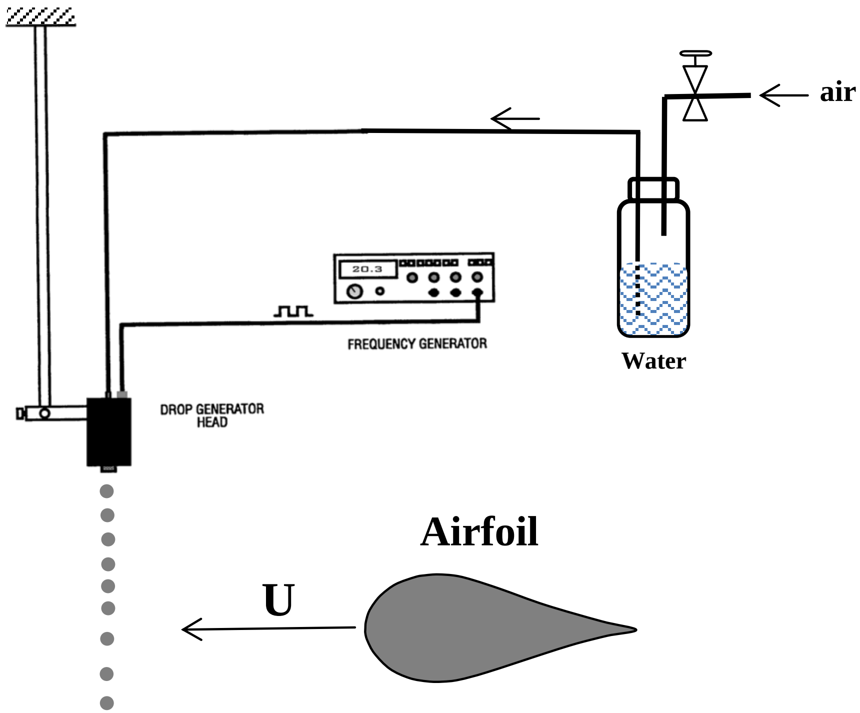
- Study and measure large droplet deformation and breakup near the leading edge of airfoils
- Gain understanding of the physical mechanisms and non-dimensional parameters, and develop an empirical model to predict droplet breakup
- Scale the results to predict droplet breakup near the leading edge of large transport airfoils
- Provide a database of measurements that can be used for validation of computational studies

Approach

- Experimental Approach
  - Rotating arm with test airfoil attached at the end
  - Droplets falling perpendicularly at one location along the airfoil path
- Use state of the art high speed imaging for observation and measurement of droplet deformation and breakup as they approach the leading edge of the airfoil (as seen in a frame of reference fixed on the airfoil)
- Measure horizontal and vertical displacement of droplets and calculate main non-dimensional parameters: velocity, acceleration, Weber, Reynolds and Bond numbers
- Analyze data to understand physical mechanisms, develop empirical model to predict droplet breakup and scale results to large airfoils

Approach

Conceptual View of Experiment

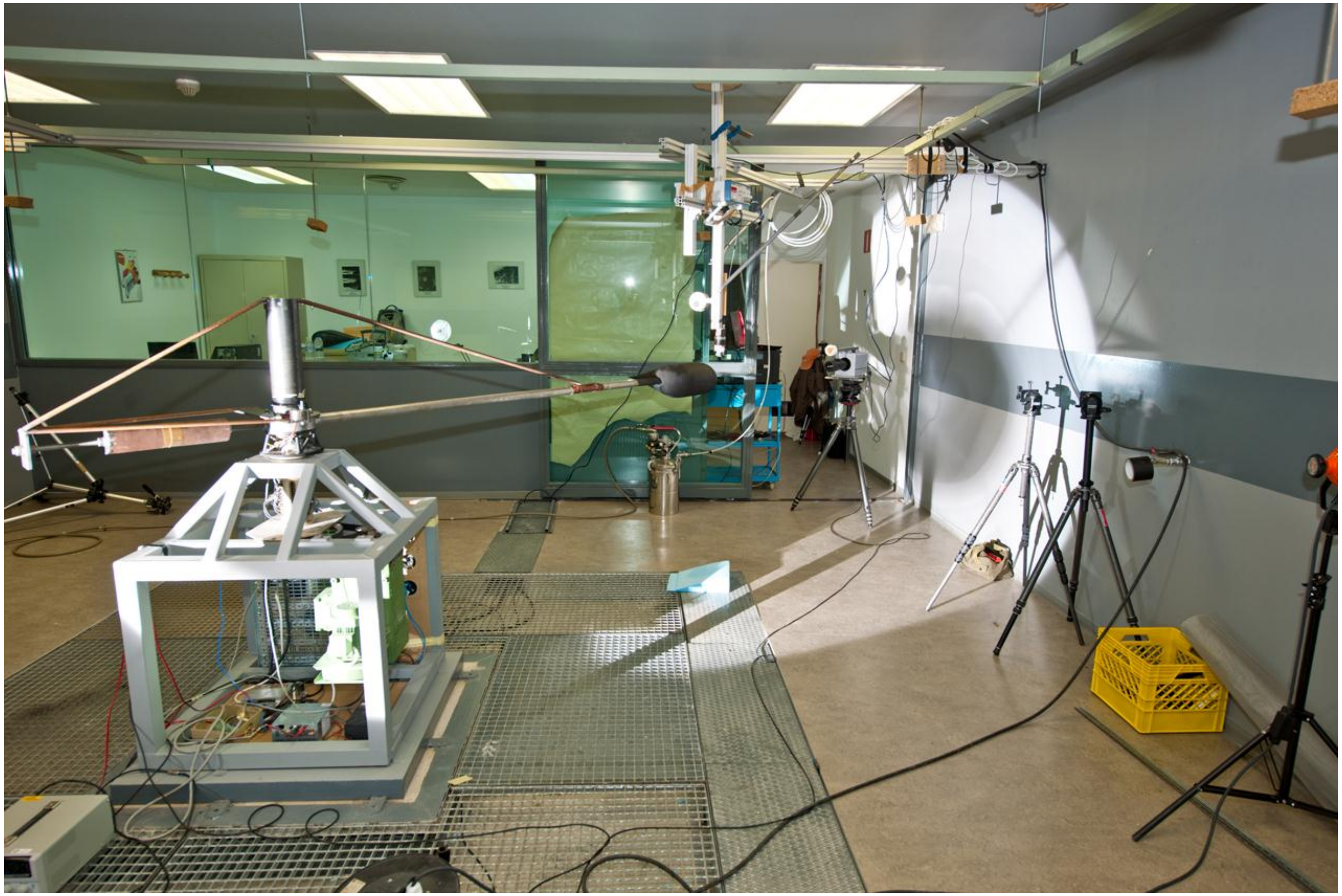


Experimental Set-Up

Rotating Arm

Experimental Set-Up

Rotating Arm



Experimental Set-Up
Rotating Arm

Experimental Set-Up
Test Matrix for High Speed Experiment

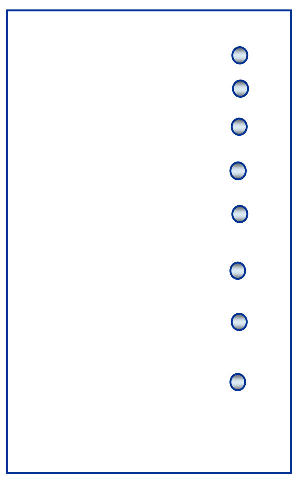
- 5 days of testing - 80 test points
- Airfoil velocities of 50, 60, 70, 80 and 90 m/sec
- For each velocity, runs were conducted for theoretical droplet sizes of 523, 415, 333, 191, 138 and 114 μm
- Two magnifications were used

Experimental Set-Up
Imaging Resolution and Field of View

Two magnifications and the corresponding field of views were used

For the case of 75,000 fps the resolution is 192Hx312V

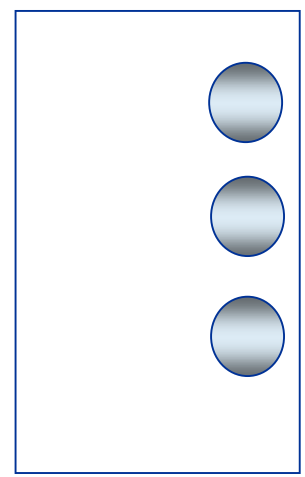
14.3 pixels per mm



312 pixels
21.8 mm

192 pixels 13.4 mm

69.0 pixels per mm



312 pixels
4.5 mm

192 pixels 2.8 mm

Data Analysis

- *Spotlight 8* software package used for data analysis
- Frame by frame study of the movies
- Zooming-in and out on single frames
- Tracking a single droplet in x-y directions
  - Measurement of horizontal and vertical displacement against time

Data Analysis

Airfoil Velocity = 90 m/sec; Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V

Frame Number = 101; Camera Time = 14,480 μsec

Droplet #2

Data Analysis

Airfoil Velocity = 90 m/sec; Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V

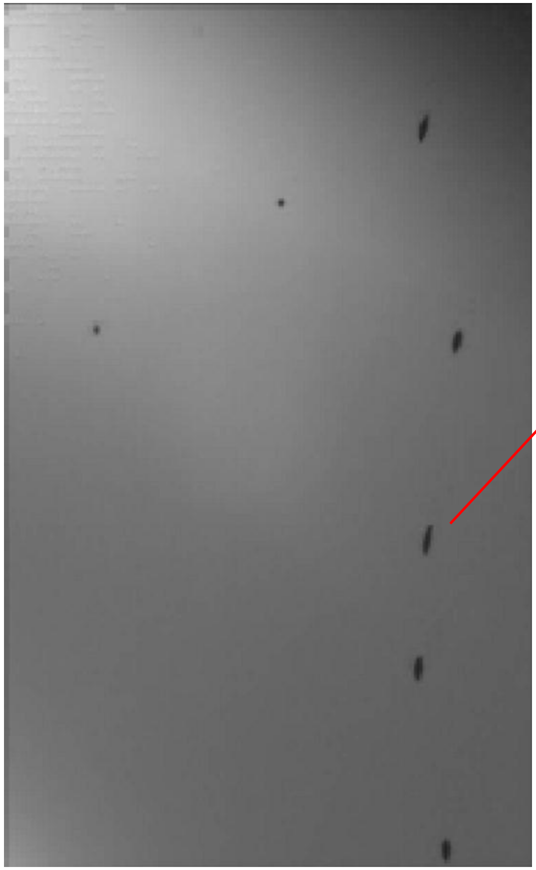
Frame Number = 174; Camera Time = 15,667 μsec

Droplet #2

Data Analysis

Airfoil Velocity = 90 m/sec; Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V

Frame Number = 190; Camera Time = 15,667 μsec

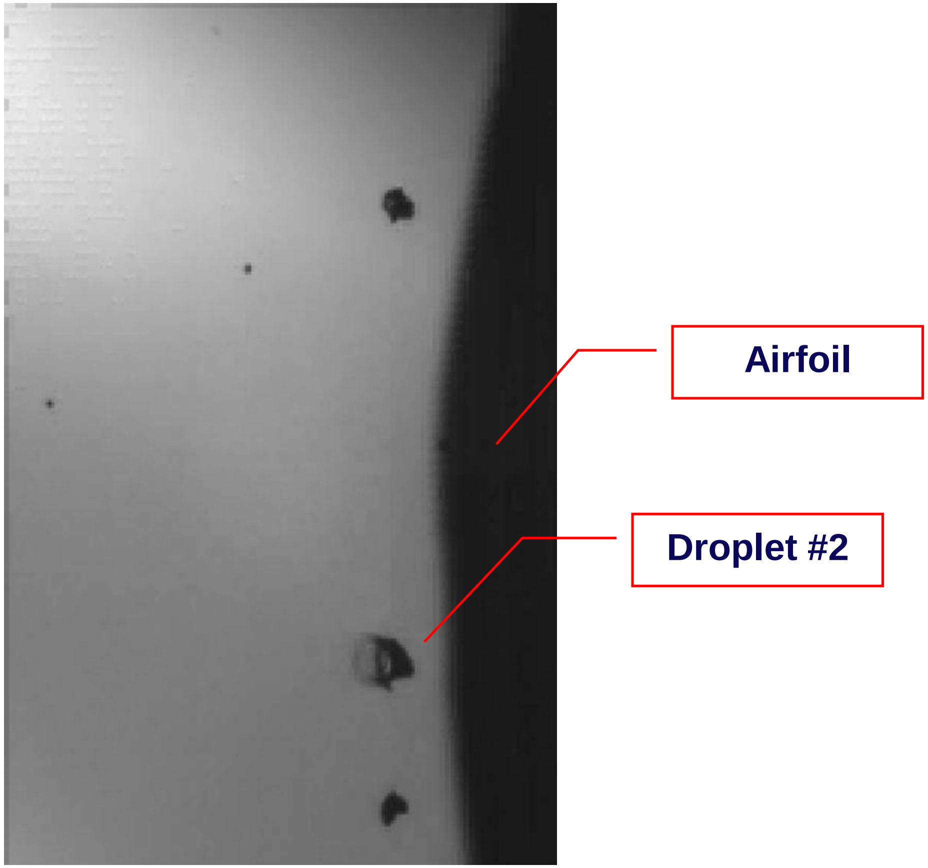


Droplet #2

Data Analysis

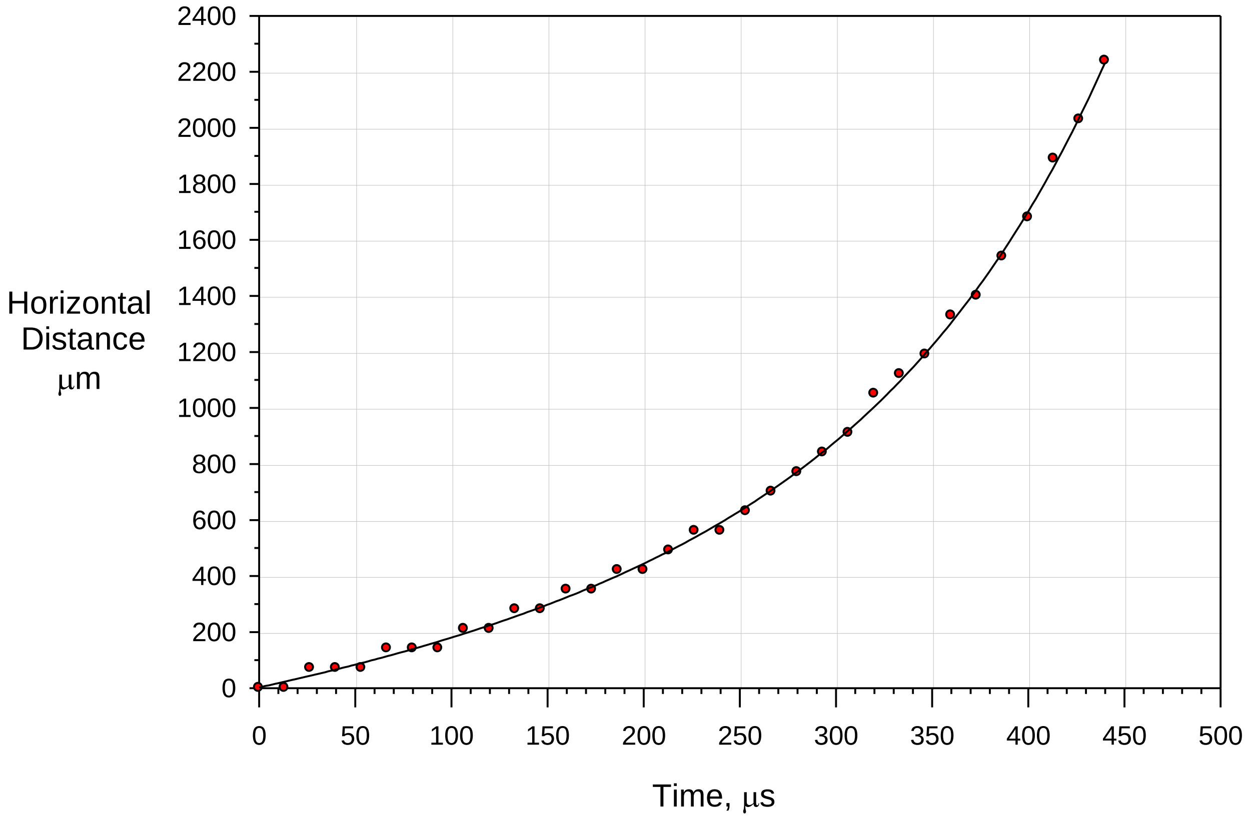
Airfoil Velocity = 90 m/sec; Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V

Frame Number = 207; Camera Time = 15,893 μsec



Results

Droplet #2, 01252010.19C; Drop Diameter = 490 μm; Airfoil Velocity = 90 m/sec
Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V; Tracking begins at frame 174



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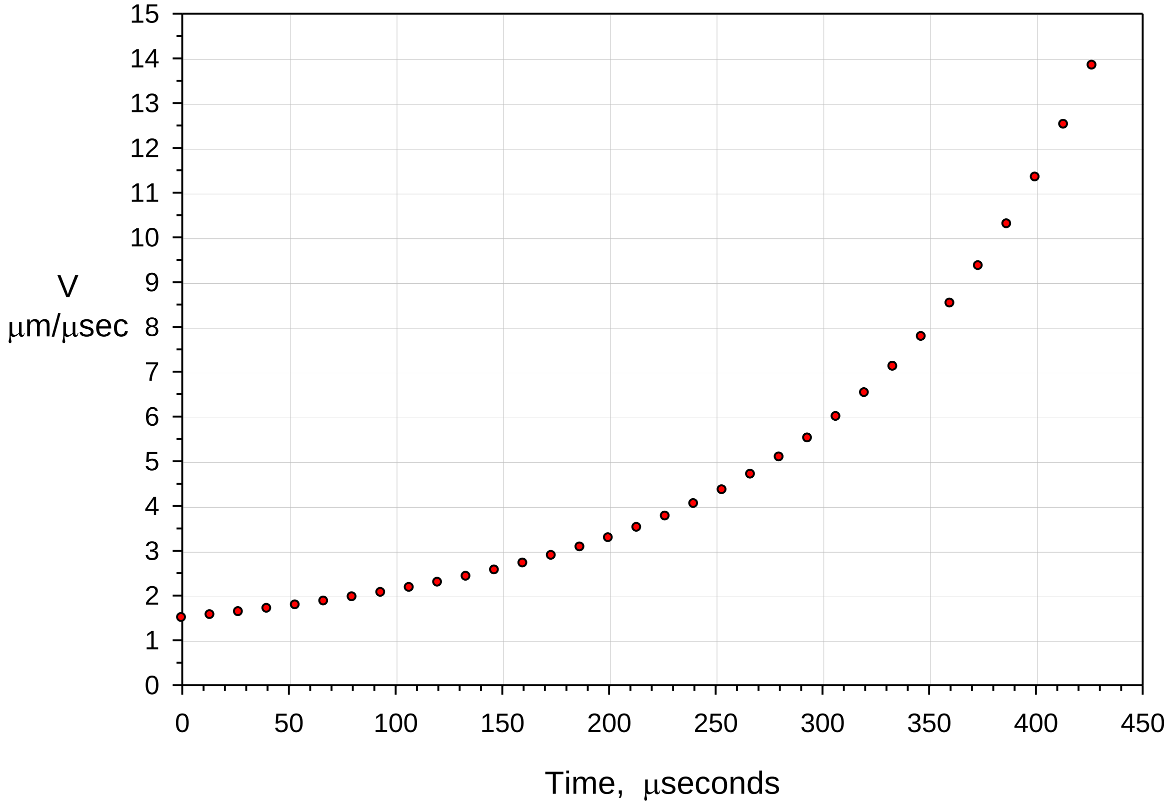

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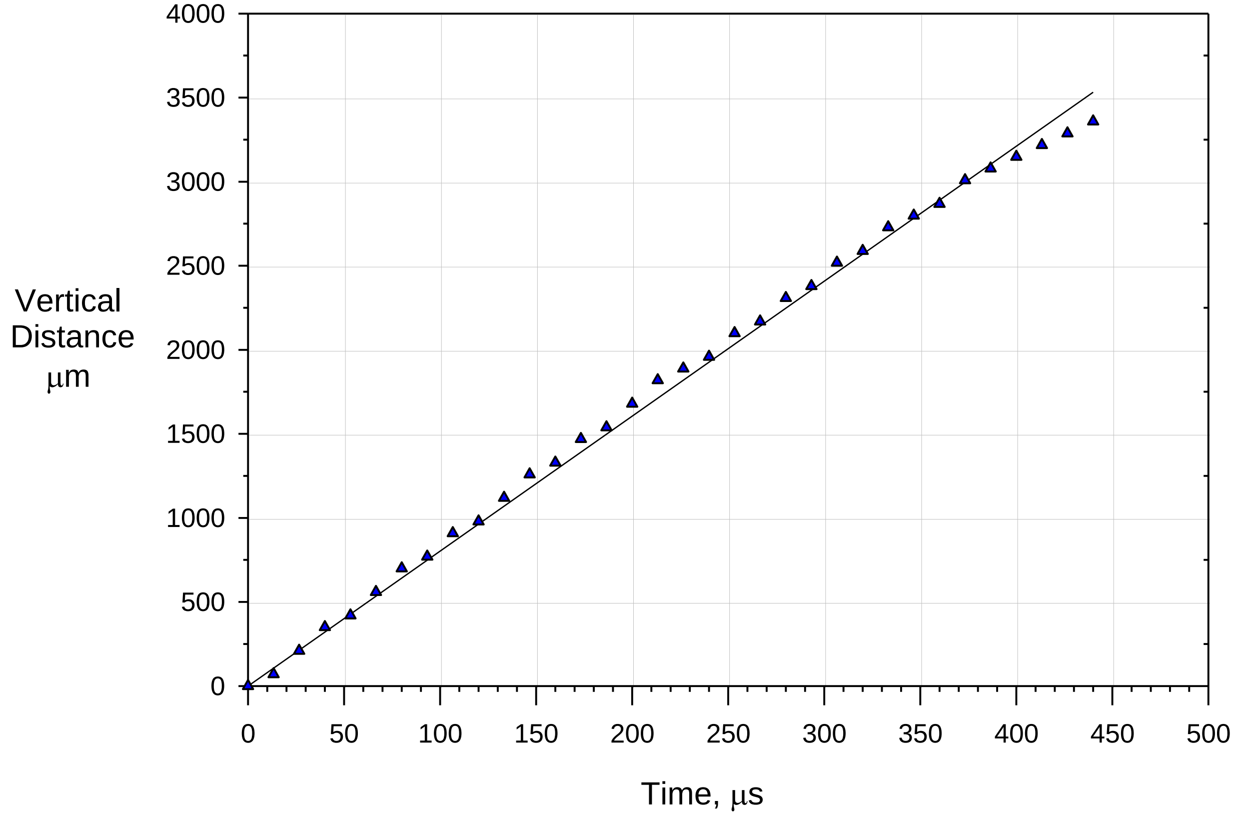
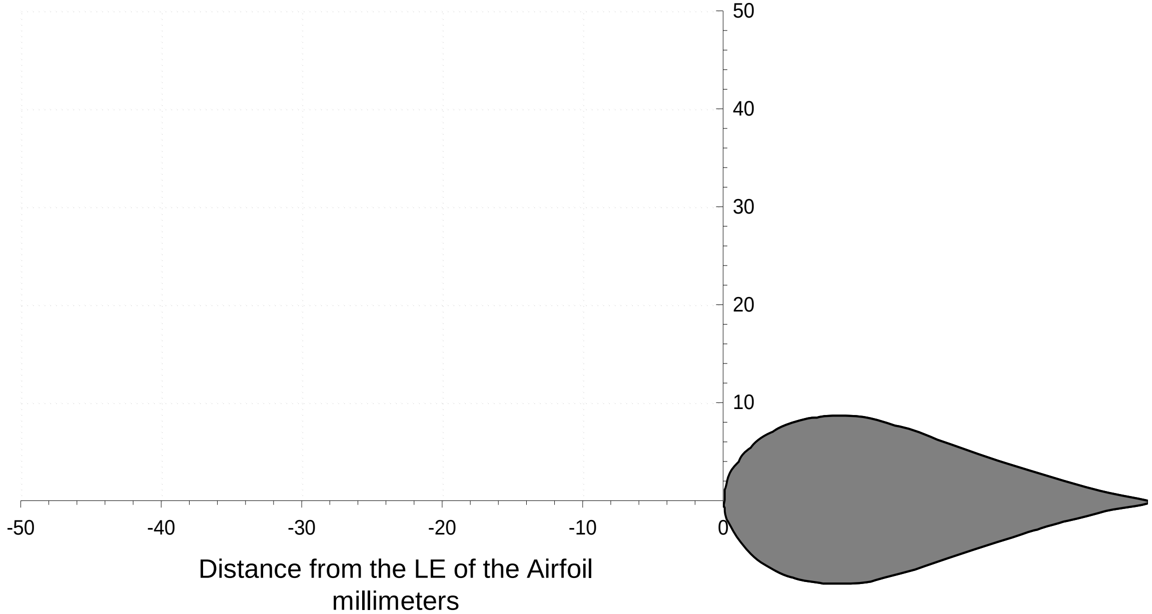


Results

Change of Frame of Reference

Frame of Reference at rest with respect to the LE of the Airfoil



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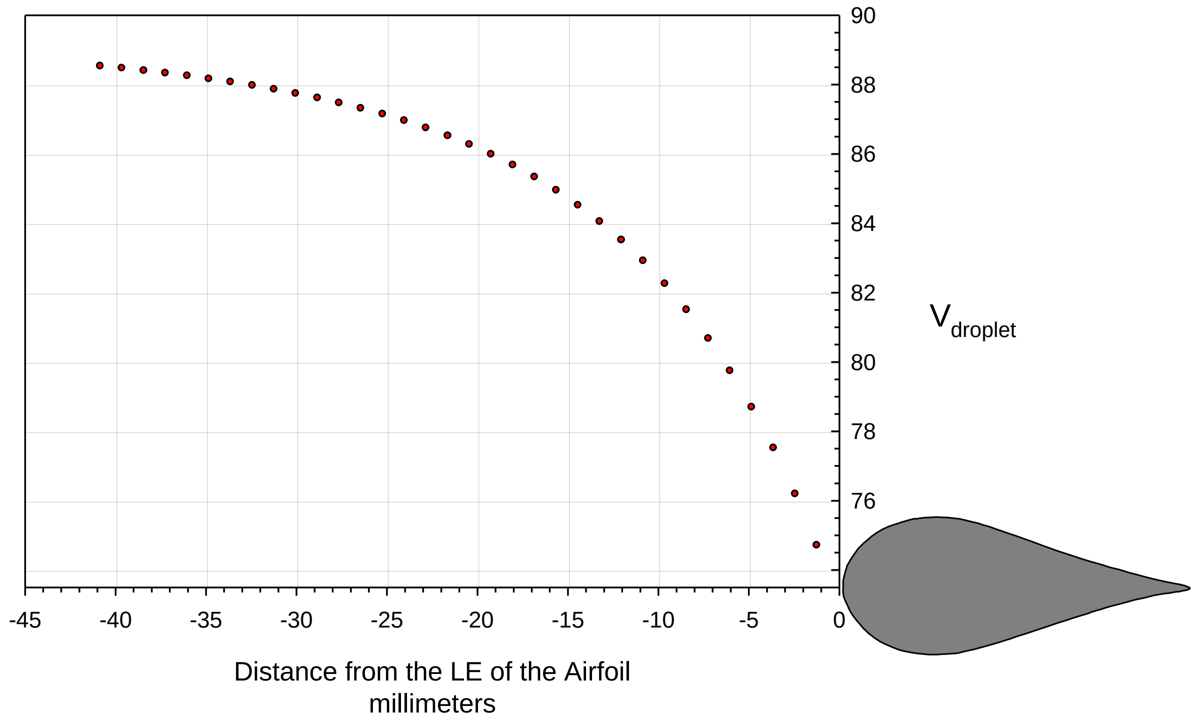

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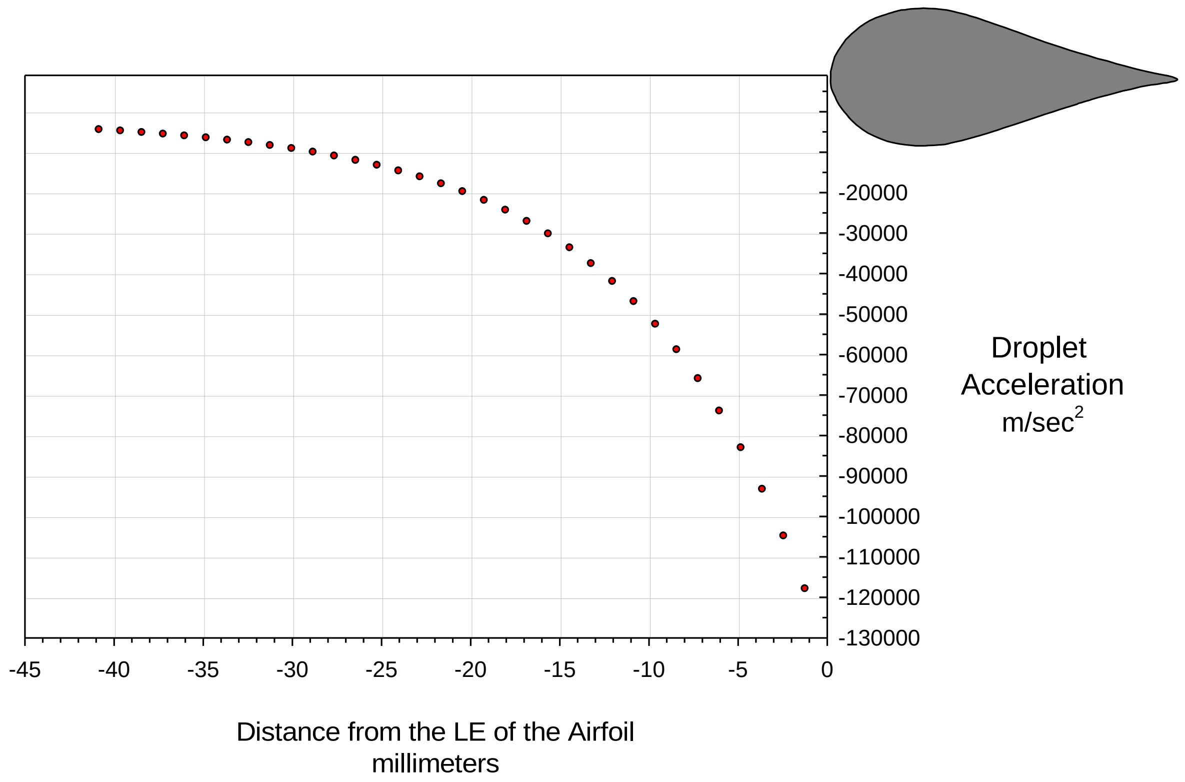

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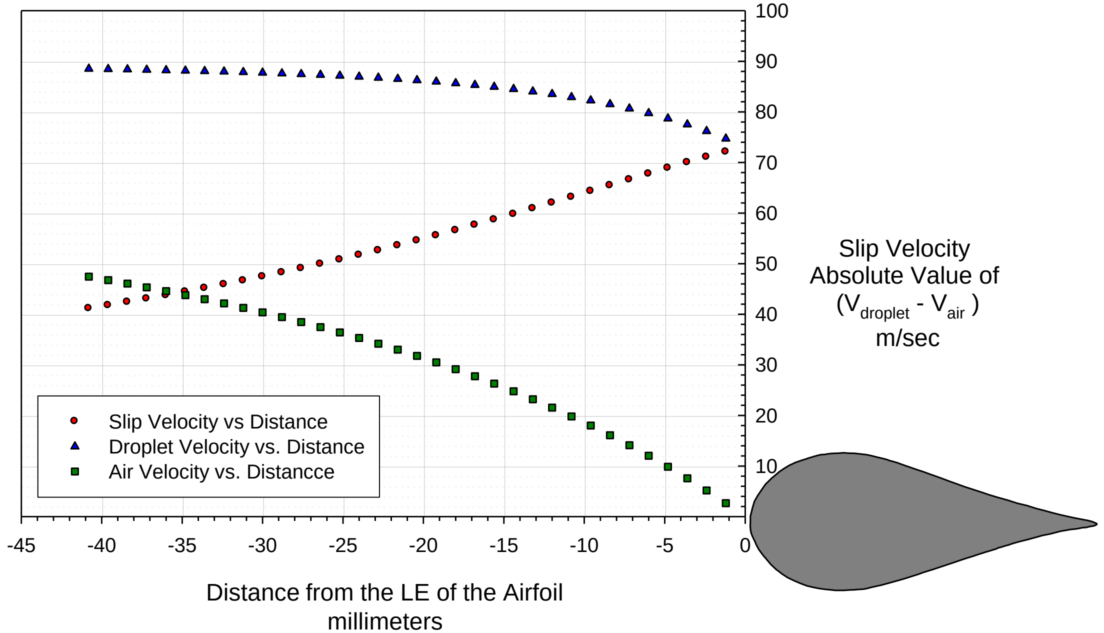

Weber Number

$$\textit{Inertia Forces} = ma \propto \rho L^3 \frac{dv}{ds}\frac{ds}{dt} \propto \rho L^3 V \frac{V}{L} \propto \rho V^2 L^2$$

$$\textit{Surface Tension Forces} \propto L\sigma$$

$$We = \frac{\rho_{air}\left|V_{air} - V_{droplet}\right|^2 D}{\sigma_{water/air}}$$

⇐ *Forces trying to pull the drop apart*

⇐ *Forces trying to hold the drop together*

Results

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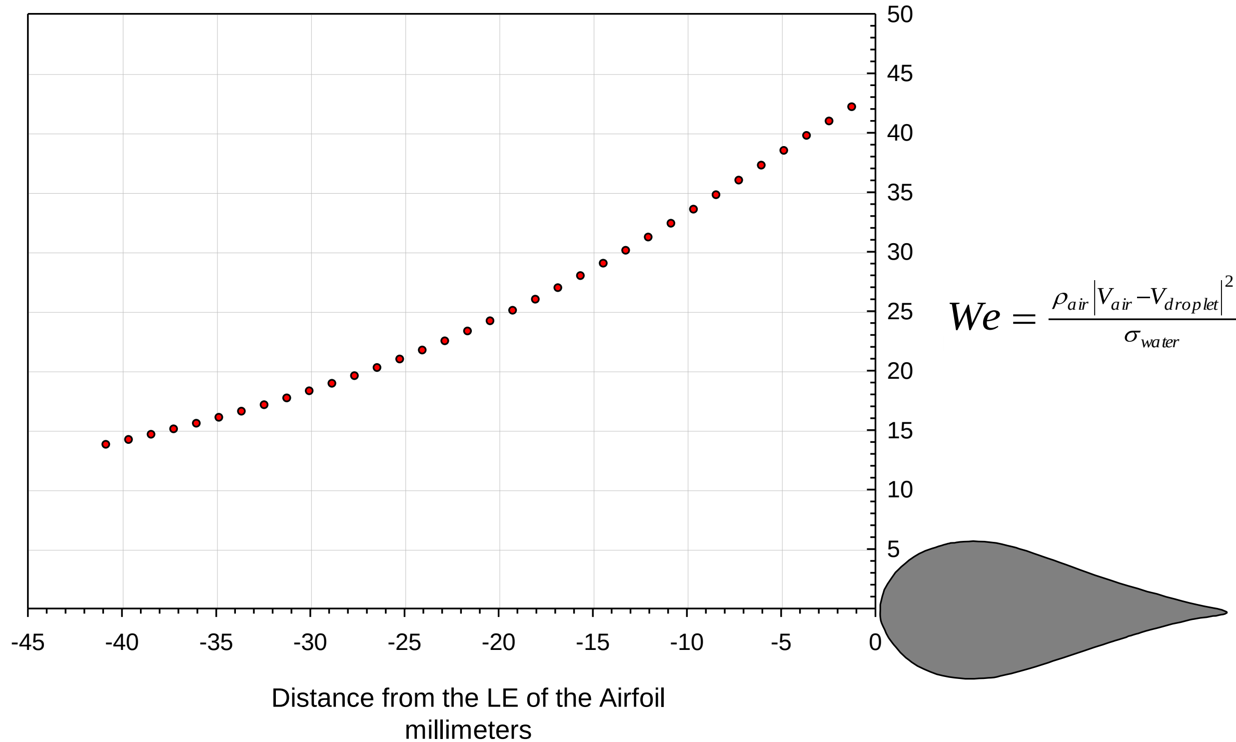

$$We = \frac{\rho_{air}\left|V_{air} - V_{droplet}\right|^2 D}{\sigma_{water}}$$

Results

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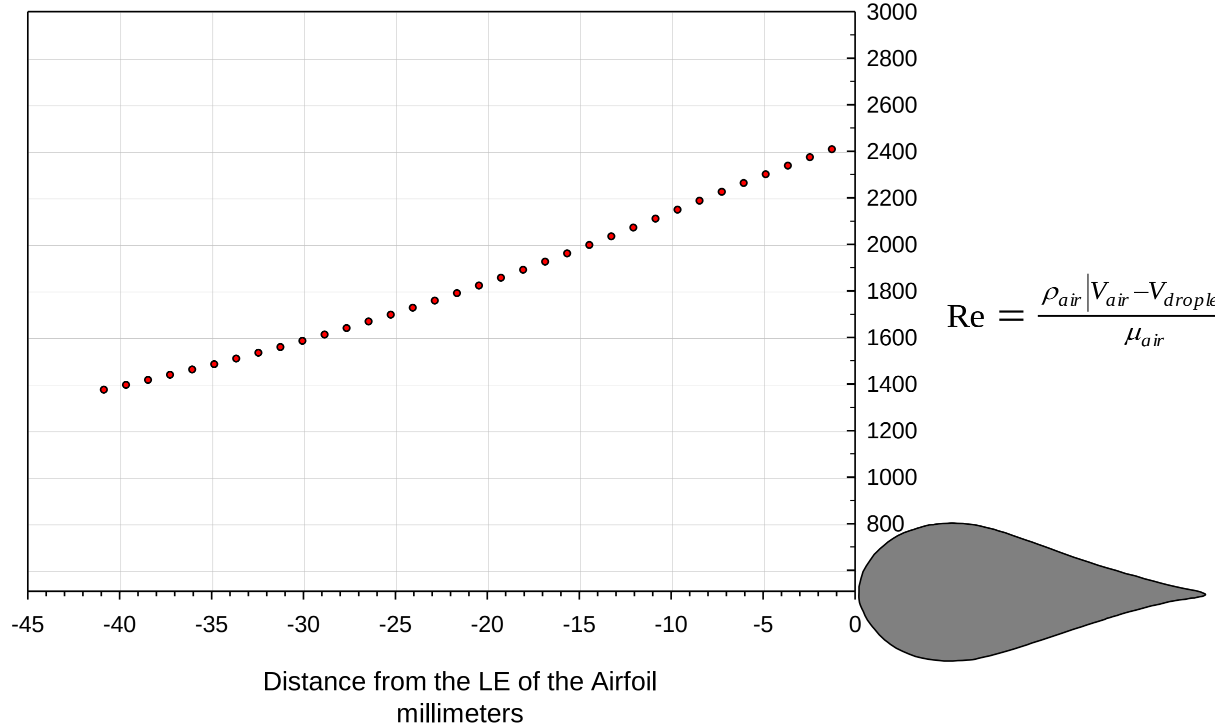

$$\mathrm{Re} = \frac{\rho_{air}\left|V_{air} - V_{droplet}\right| D}{\mu_{air}}$$

Results

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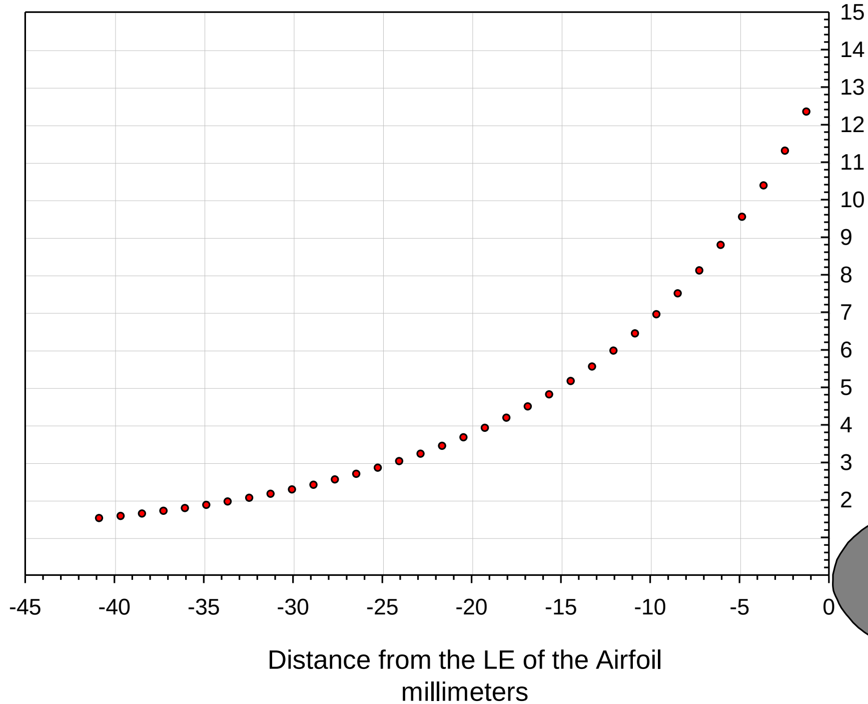
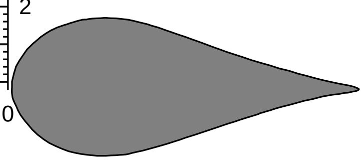


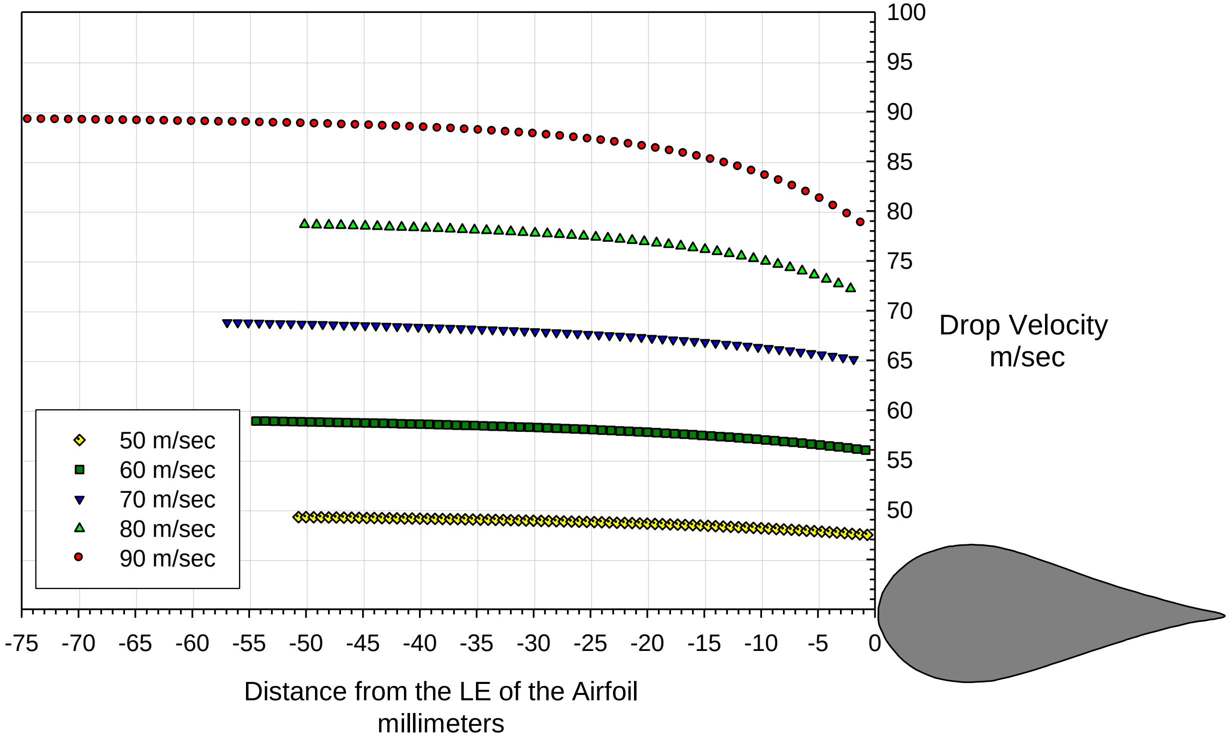
$$C_d = \frac{4}{3}\frac{\rho_{water}}{\rho_{air}}\frac{D}{\left|V_{air}-V_{droplet}\right|^2}\frac{dV_{droplet}}{dt}$$



Results

Velocity Effect

Drop Diameter = 490 μm; Camera Frame Rate = 75,000 fps; Resolution = 192Hx312V



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Velocity Effect

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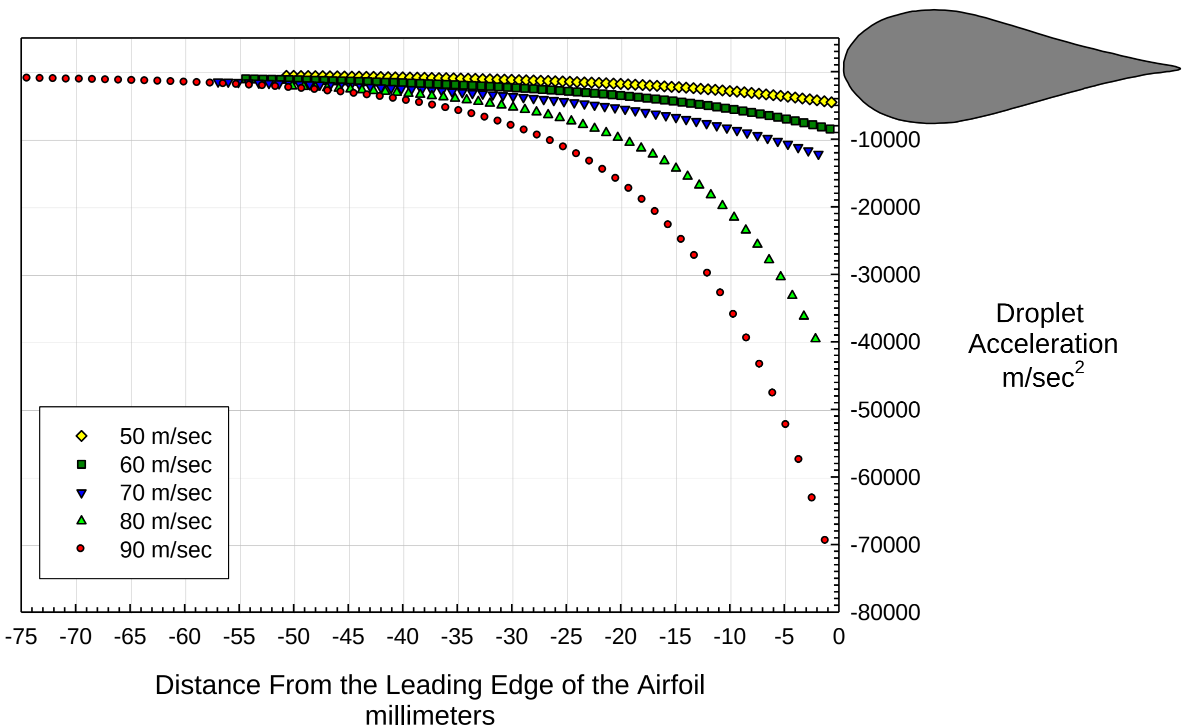

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Velocity Effect

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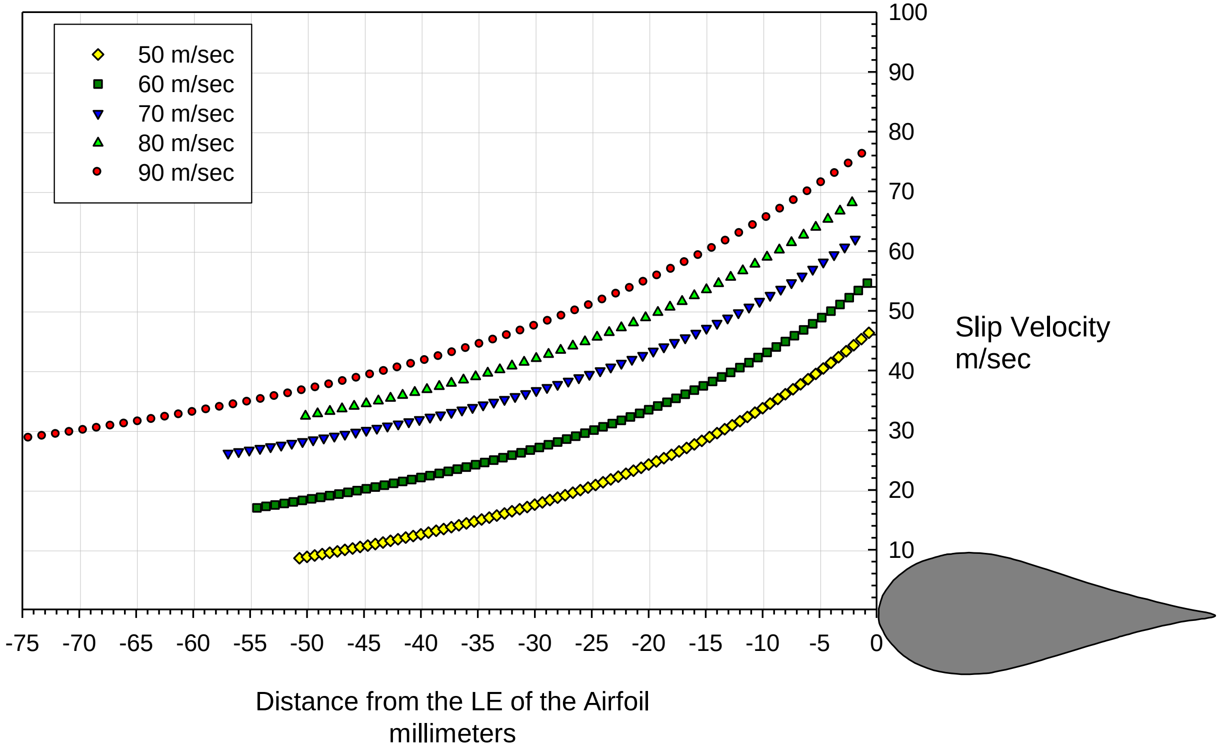

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Velocity Effect

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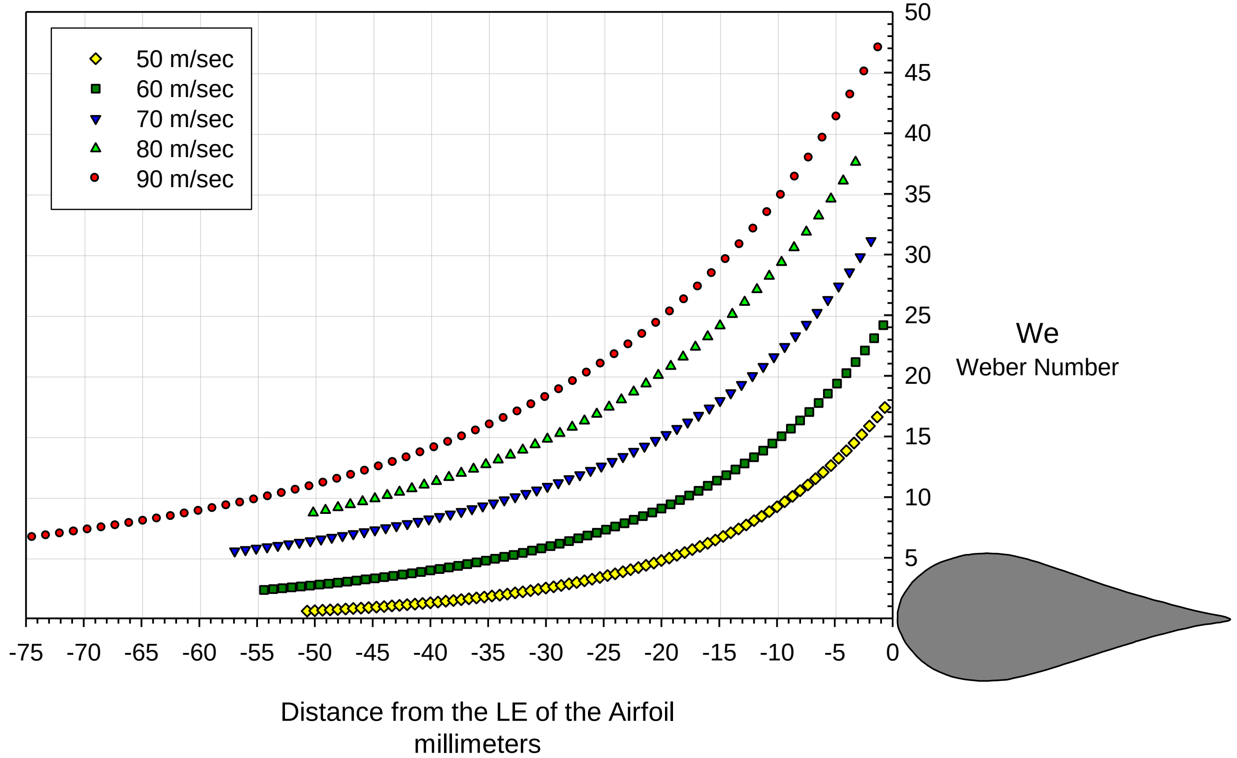
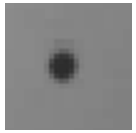
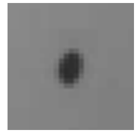
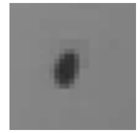
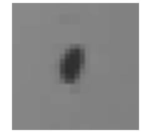
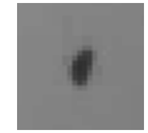
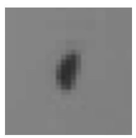
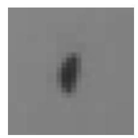
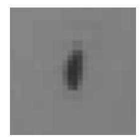
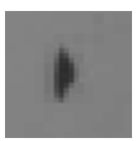
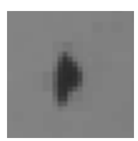
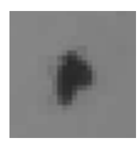
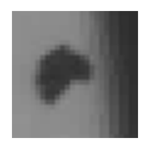


Results

Droplet Deformation and Breakup

						
Time	0 μsec	13.3 μsec	80.0 μsec	146.7 μsec	213.3 μsec	280.0 μsec
Distance	-81.4 mm	-69.6 mm	-63.6 mm	-57.6 mm	-51.6 mm	-45.6 mm
Weber No.	~ 0	7.3	8.2	9.3	10.6	12.1

						
Time	346.7 μsec	413.3 μsec	480.0 μsec	546.7 μsec	613.3 μsec	680.0 μsec
Distance	-39.6 mm	-33.6 mm	-27.6 mm	-21.6 mm	-15.6 mm	-9.6 mm
Weber No.	14.0	16.4	19.3	23.2	28.2	34.9

				
Time	706.7 μsec	733.3 μsec	760.0 μsec	786.7 μsec
Distance	-7.2 mm	-4.8 mm	-2.4 mm	0 mm
Weber No.	38.2	42.0	46.2	51.0

Main Results

- The pattern of deformation and breakup of the droplets follows the Bag type observed and reported by other researchers in past studies with other experimental configurations.
- All the observed droplet breakups occurred just before the droplet hit the airfoil. For velocities of 50 m/sec and 60 m/sec no droplet breakup was observed. A limited number of droplet breakups were observed at 70 m/sec. Nearly all the droplet breakups were observed at 80 and 90 m/sec.
- Values of the Weber number along the path of the droplet increase as the droplet approaches the airfoil.
- Measurements on droplets of 490μm in diameter at each airfoil velocity of 50, 60, 70, 80 and 90 m/sec showed that at a higher airfoil velocity, the droplet experiences higher Weber numbers for longer times.

Summary of Research Completed as of Jan 2011

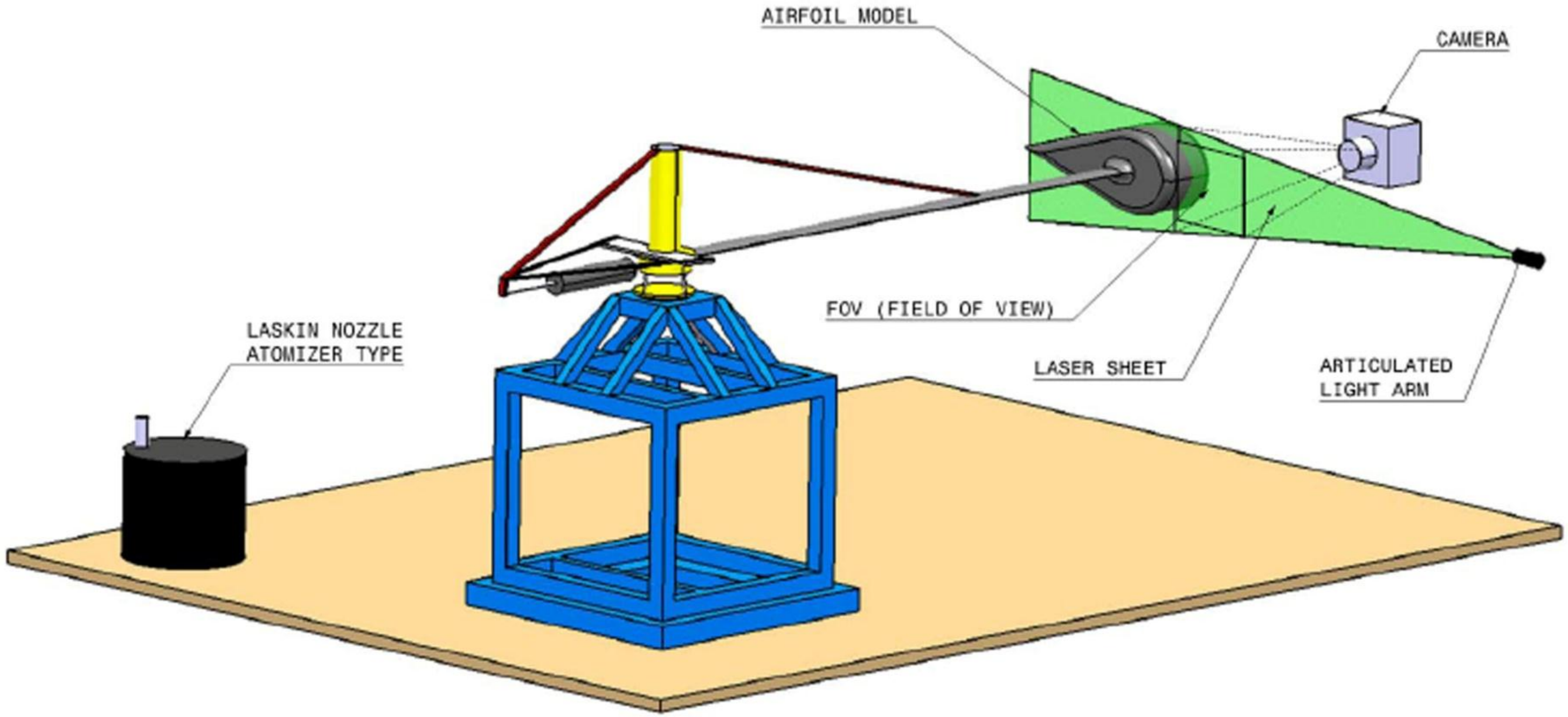
- In 2007, NASA and INTA began an experimental research program to obtain droplet breakup data on an airfoil configuration
- A droplet breakup rotating rig was designed and built at INTA
- The first sets of experiments were conducted at low speeds (15-66 m/s) in November of 2008
- A high speed experiment (50-90 m/s) was conducted in January of 2010
- Results were presented at the 2010 AIAA Atmospheric and Space Environments Conference in Toronto, Canada

Current Work

- Error analysis on the measurements from the high speed experiment
- Continue measurements and calculations with the data from the high speed experiment
  - The database consists of about 400 droplets
- Understand the meaning of the drag coefficient calculations
- Road Map of Future Work
- Preparations for experiment to be conducted in July 2011
- Submitted Paper for the 2011 SAE International Conference in Chicago
- Air flow field characterization in the facility using PIV system

AIR FLOW FIELD CHARACTERIZATION

Experimental setup – Vertical Plane



FUTURE WORK

- Observation and measurement of droplet deformation and breakup on three geometrically scaled versions of the DBKUP 002 airfoil
- One model scaled down to ½ size of the DBKUP 002, another scaled up 1.5 times the size and another scaled up 2 times the size
- Experiment planned for July 2011
- This additional research will allow us to learn how to scale the droplet deformation, breakup and measurements to larger transport airfoils

End of Presentation