

Mechanism of Water Droplet Breakup near the Leading Edge of an Airfoil

This work presents results of an experimental study on droplet deformation and breakup near the leading edge of an airfoil. The experiment was conducted in the rotating rig test cell at the Instituto Nacional de Técnica Aeroespacial (INTA) in Madrid, Spain. The airfoil model was placed at the end of the rotating arm and a monosize droplet generator produced droplets that fell from above, perpendicular to the path of the airfoil. The interaction between the droplets and the airfoil was captured with high speed imaging and allowed observation of droplet deformation and breakup as the droplet approached the airfoil near the stagnation line. Image processing software was used to measure the position of the droplet centroid, equivalent diameter, perimeter, area, and the major and minor axes of an ellipse superimposed over the deforming droplet. The horizontal and vertical displacement of each droplet against time was also measured, and the velocity, acceleration, Weber number, Bond number, Reynolds number, and the drag coefficients were calculated along the path of the droplet to the beginning of breakup. Droplet deformation is defined and studied against main parameters. The high speed imaging allowed observation of the actual mechanism of breakup and identification of the sequence of configurations from the initiation of the breakup to the disintegration of the droplet. Results and comparisons are presented for droplets of diameters in the range of 500 to 1800 micrometers, and airfoil velocities of 70 and 90 meters/second.



Mechanism of Water Droplet Breakup near the Leading Edge of an Airfoil

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Outline

- Objectives
- Background
- Approach
- Experiment Set-up
- Data Analysis
- Results
- Conclusions

Objectives

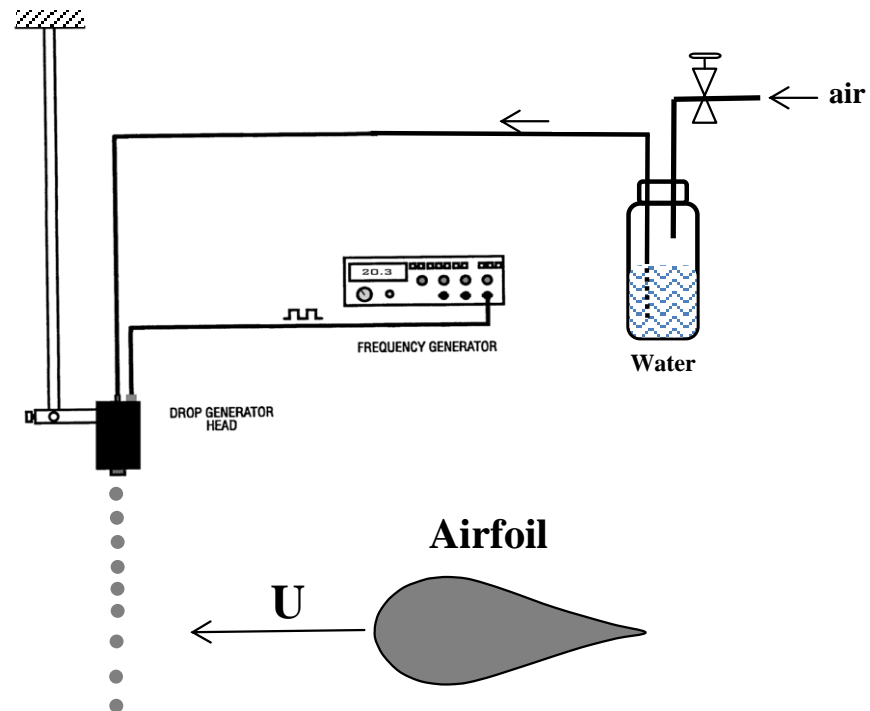
- Continue and extend previous studies of droplet deformation and breakup
 - Conduct testing on airfoils of same geometry but different chord size
 - Increase range of droplet diameter tested
 - Detailed observation of the actual mechanism of droplet breakup
- Use state of the art high speed imaging for observation of droplet deformation and breakup
- Develop a digital imaging processing analysis program to measure droplet deformation along its path

Background

- In 2007 the National Aeronautics and Space Administration (NASA) and the Instituto Nacional de Técnica Aeroespacial (INTA) in Madrid, Spain, began an experimental research program to obtain droplet deformation and breakup data on an airfoil configuration
- A droplet breakup rotating rig was designed and built at the INTA installations near Madrid
- The first experiments were conducted at low speeds (15-66 m/sec) in 2008 and high speed (50-90 m/sec) in 2010
- Results presented today come from an experiment conducted at high speed (50-90 m/sec) in 2011

Approach

Conceptual View of Experiment



Experimental Set-Up

Rotating Arm



Experimental Set-Up Camera, Airfoil, Droplet Generator



Airfoils Tested

Chord: 0.210 meters (8.3 inches)

Chord: 0.470 meters (18.5 inches)

Chord: 0.710 meters (28.0 inches)

Experimental Set-Up

Test Matrix

- 7 days of testing – 154 runs
- Airfoil velocities of 50, 60, 70, 80 and 90 m/sec
- For each velocity, runs were conducted for theoretical droplet sizes in the range of 400 to 1400 μm
- Main camera frame rate was 75,000 fps with image size of 192x312 pixels
- Image resolution was 14.26 pixels/millimeter
- A subset of the analyzed data is presented for the large airfoil (chord = 0.710 m)

Data Analysis

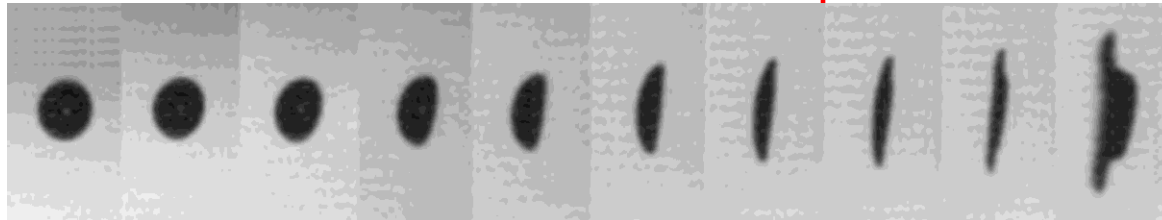
- The camera software was used to generate movie clips for each pass of the airfoil and to convert them from raw to avi format
- The software program for the analysis of the data was developed using MATLAB with the digital imaging processing toolbox
- The first part of the program reads the movie clip, converts each frame from grayscale to binary and measures the image processing parameters for a selected droplet
 - Frame number, time, x and y coordinates of the centroid, area, perimeter, major and minor axis of an ellipse superimposed on the droplet, equivalent diameter
- The second part of the program tracks the droplet horizontal and vertical displacements and calculates velocity of the droplet with respect to the airfoil (frame of reference at rest with respect to the airfoil with the origin at the stagnation point), position of the droplet with respect to the airfoil, slip velocity, acceleration, Weber number, Reynolds number, Bond number and drag coefficient.

Results

Droplet Deformation

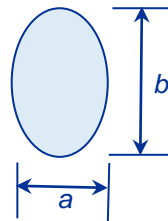
Run 072011.14C droplet #1, droplet diameter = $1062\mu\text{ m}$, airfoil chord = 0.710 m, airfoil velocity = 90 m/sec

... deformation ————— | ————— breakup —————> ...



Frame #	20	60	100	140	160	180	190	194	200	210
Time, μsec	253	787	1320	1853	2120	2387	2520	2573	2653	2787
x-distance from airfoil, mm	225	177	129	82	58	34	23	18	11	0
Vslip, m/sec	15.5	19.8	25.9	35.4	42.9	54.0	61.8	65.3	71.3	82.6
We	4.21	6.90	11.77	21.99	32.20	51.36	67.05	75.07	89.42	119.95
Re	1120	1433	1872	2559	3102	3911	4469	4728	5161	5977
Bo	2.14	2.50	3.20	8.10	21.55	71.34	134.75	174.41	257.47	495.06
Cd	0.68	0.48	0.36	0.49	0.89	1.85	2.75	3.10	3.84	5.50

Droplet Deformation
 b/a



Data Analysis

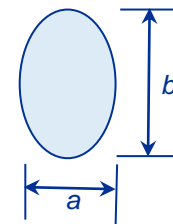
Equivalent Droplet Diameter

$D_{\text{based on area}}$ = diameter of a circle with the same area as the area measured in the images

$$D_{\text{based on area}} = \sqrt{\frac{4 \cdot \text{Area}}{\pi}}$$

$D_{\text{based on volume}}$ = diameter of a sphere with the same volume as the volume of the oblate spheroid

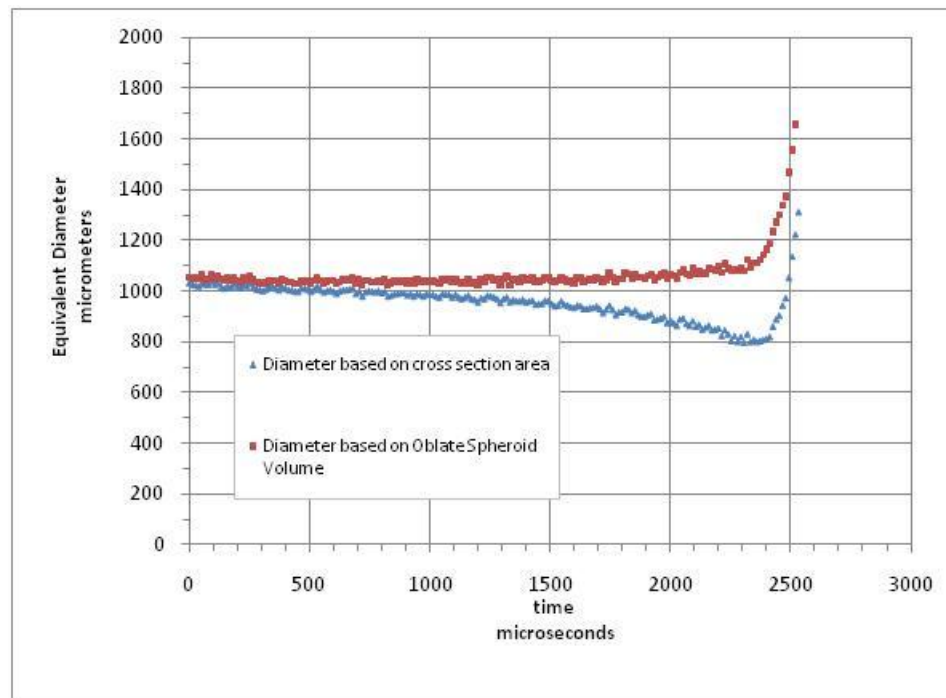
$$D_{\text{volume}} = \sqrt[3]{b^2 \cdot a}$$



Results

Droplet Diameter vs. Time

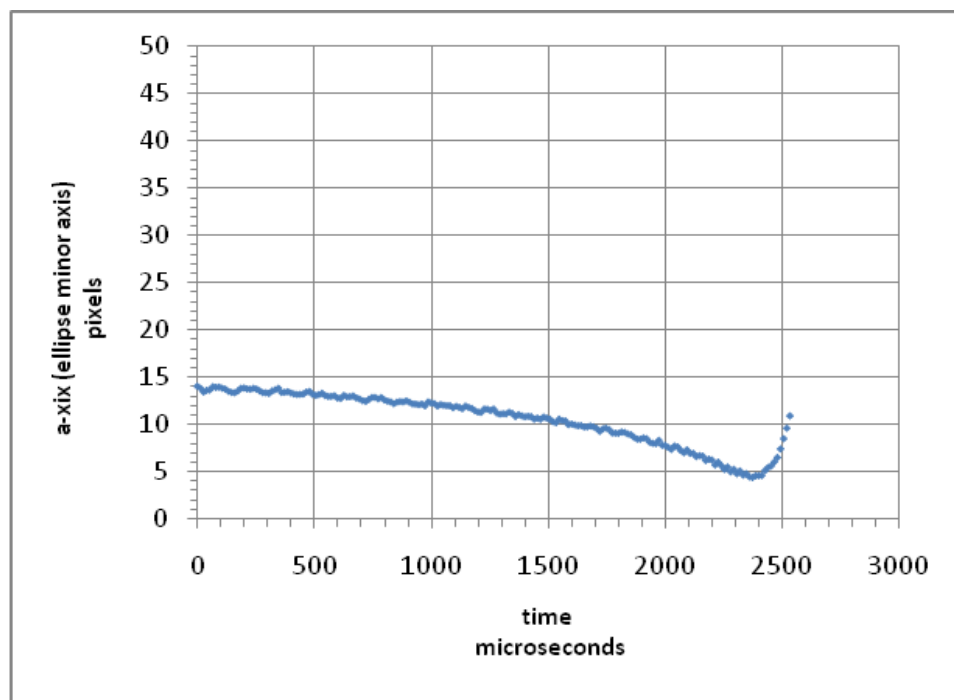
Run 072011.14C droplet #1, droplet diameter = 1062 μm , airfoil chord = 0.710 m, airfoil velocity = 90 m/sec



Results

Droplet Width vs. Time

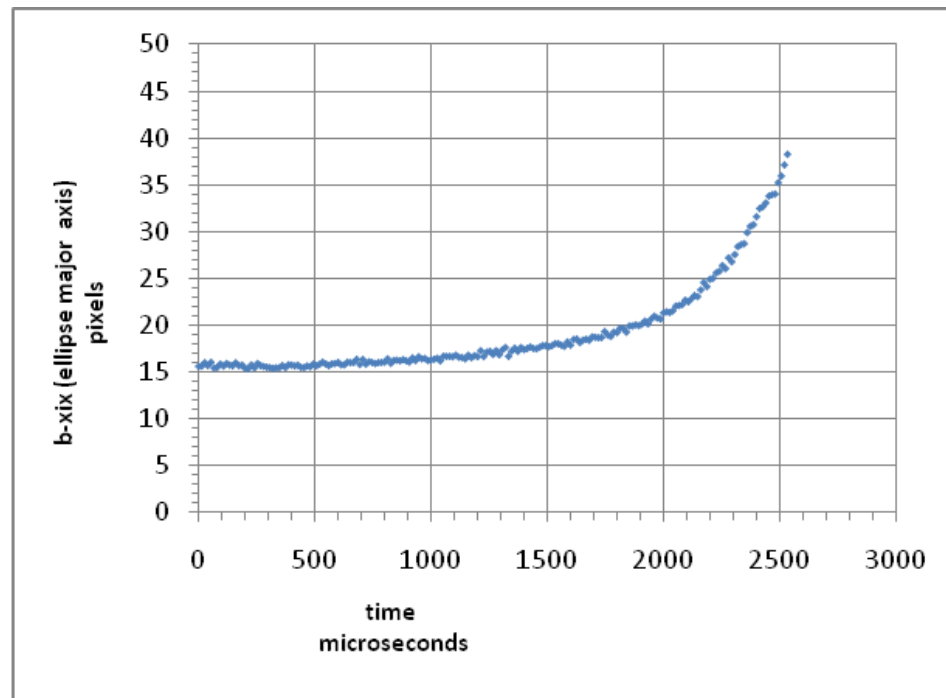
Run 072011.14C droplet #1, droplet diameter = 1062 μm , airfoil chord = 0.710 m, airfoil velocity = 90 m/sec



Results

Droplet Height vs. Time

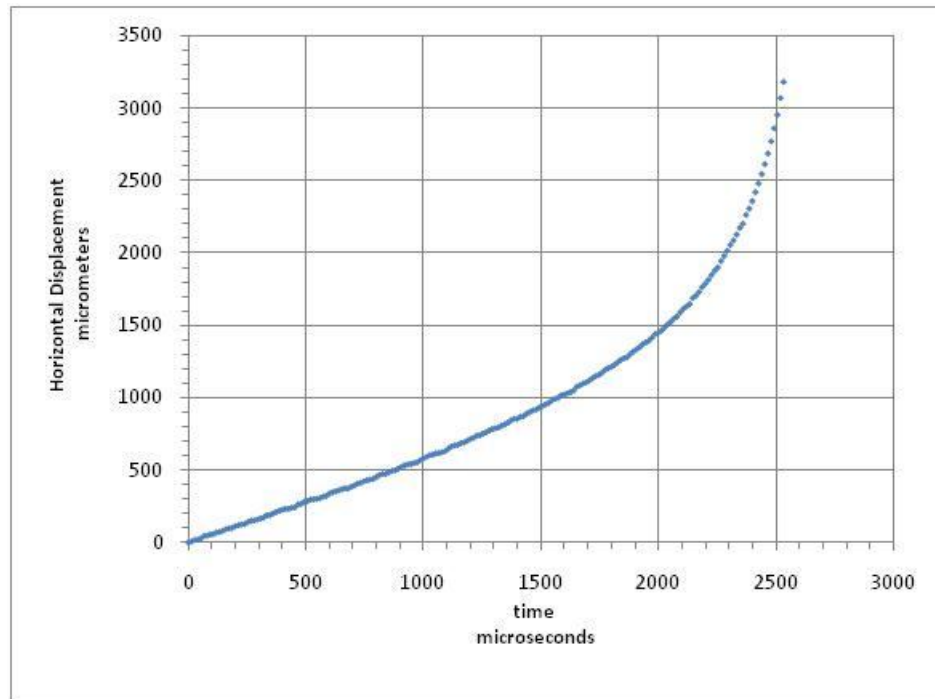
Run 072011.14C droplet #1, droplet diameter = 1062 μm , airfoil chord = 0.710 m, airfoil velocity = 90 m/sec



Results

Horizontal Displacement vs. Time

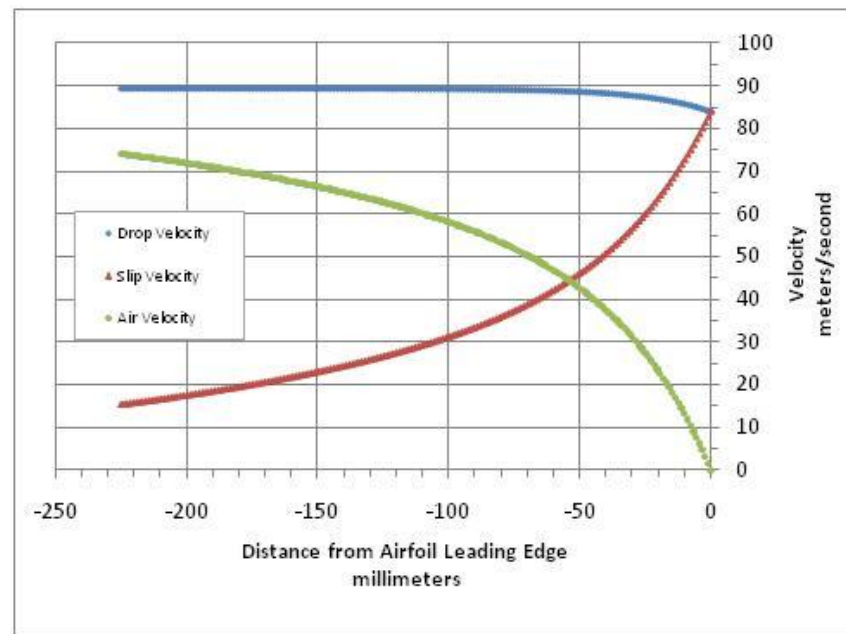
Run 072011.14C droplet #1, droplet diameter = 1062 μm , airfoil chord = 0.710 m, airfoil velocity = 90 m/sec



Results

Drop Velocity, Air Velocity, Slip Velocity vs. Distance from Airfoil

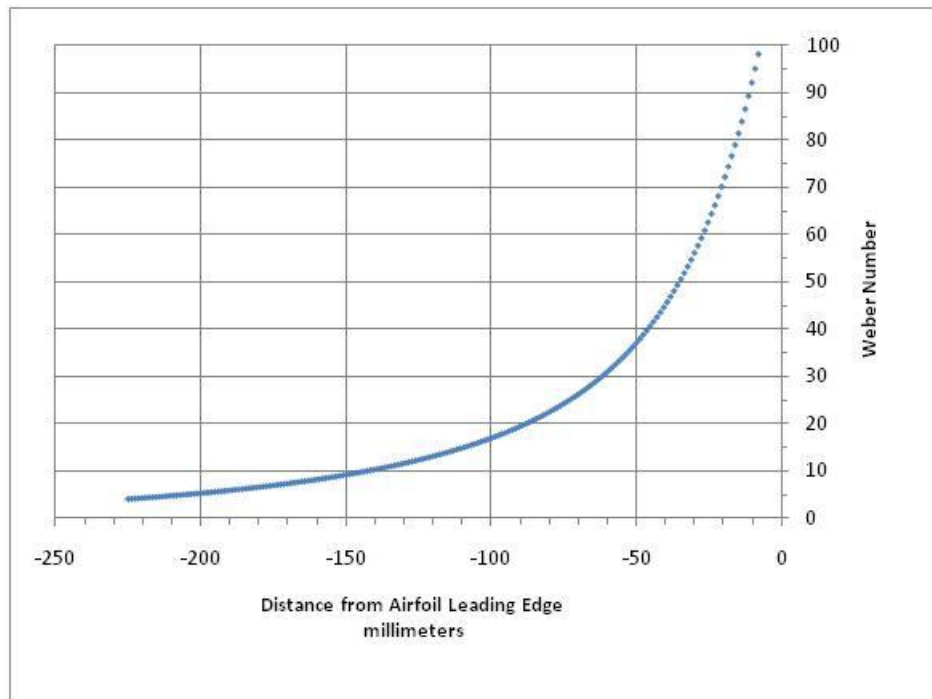
Run 072011.14C droplet #1, droplet diameter = 1062 μm , airfoil chord = 0.710 m, airfoil velocity = 90 m/sec



Results

Weber Number vs. Distance from Airfoil

Run 072011.14C droplet #1, droplet diameter = 1062 μm , airfoil chord = 0.710 m, airfoil velocity = 90 m/sec

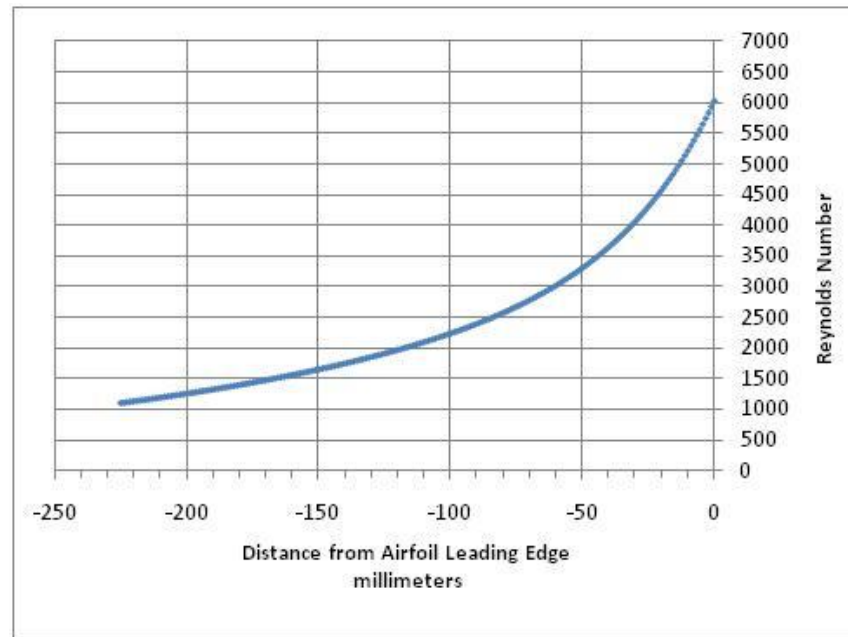


$$We = \frac{\rho_{air} \cdot V_{slip}^2 \cdot D}{\sigma_{w/a}}$$

Results

Reynolds Number vs. Distance from Airfoil

Run 072011.14C droplet #1, droplet diameter = 1062 μm , airfoil chord = 0.710 m, airfoil velocity = 90 m/sec

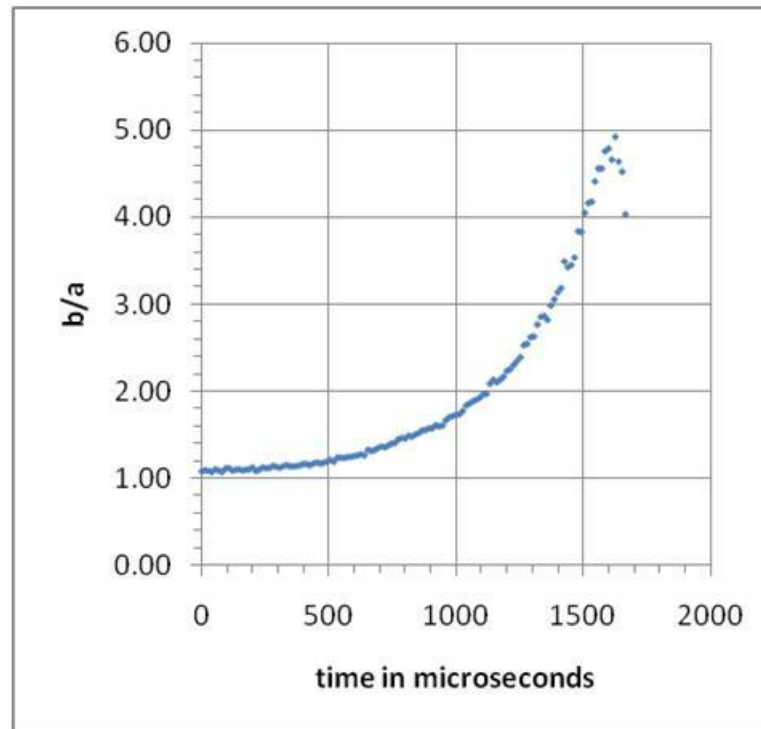
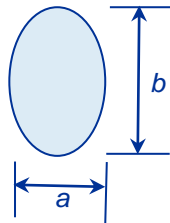


$$\text{Re} = \frac{\rho_{air} \cdot V_{slip} \cdot D}{\mu_{air}}$$

Results

Droplet Deformation

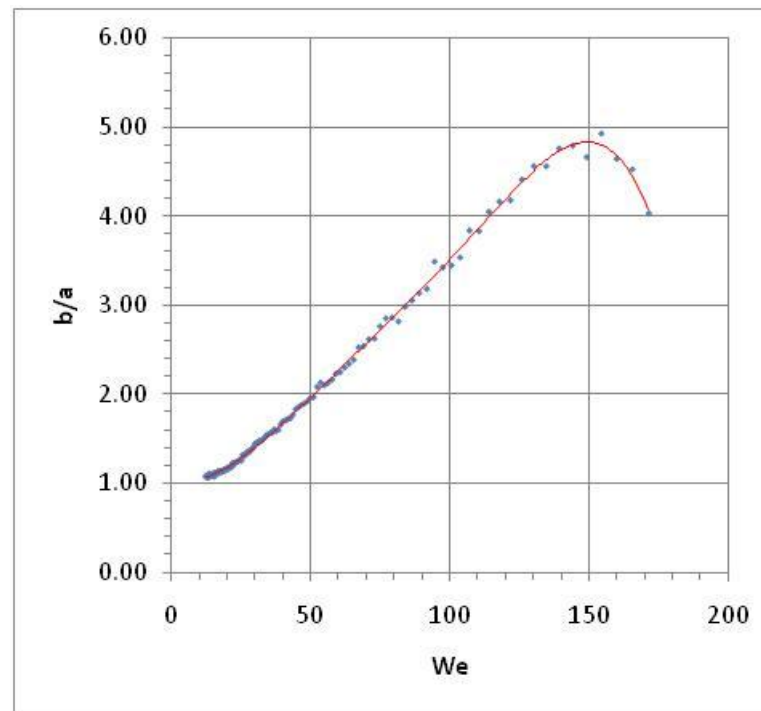
Run 072611.15B droplet #2, droplet diameter = 1431 μm , airfoil chord = 0.710 m, airfoil velocity = 90 m/sec



Results

Droplet Deformation

Run 072611.15B droplet #2, droplet diameter = 1431 μm , airfoil chord = 0.710 m, airfoil velocity = 90 m/sec

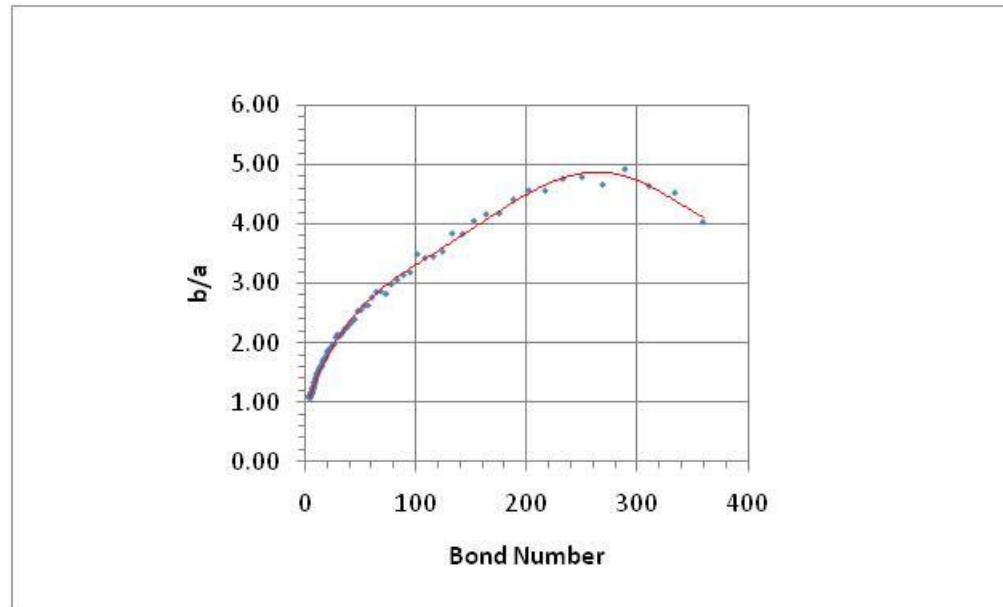


$$We = \frac{\rho_{air} \cdot V_{slip}^2 \cdot D}{\sigma_{w/a}}$$

Results

Droplet Deformation

Run 072611.15B droplet #2, droplet diameter = 1431 μm , airfoil chord = 0.710 m, airfoil velocity = 90 m/sec

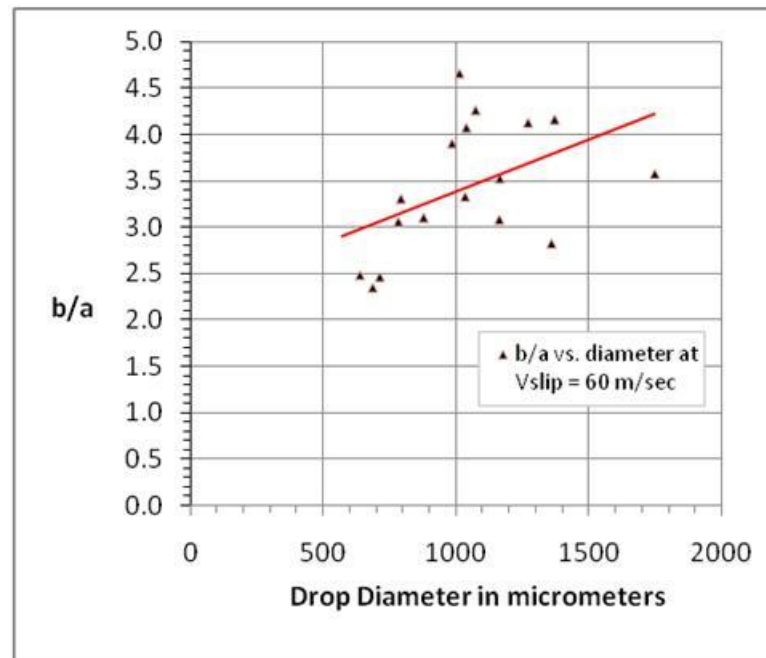


$$Bo = \frac{\rho_{water} \cdot a_{droplet} \cdot D^2}{\sigma_{w/a}}$$

Results

Droplet Deformation

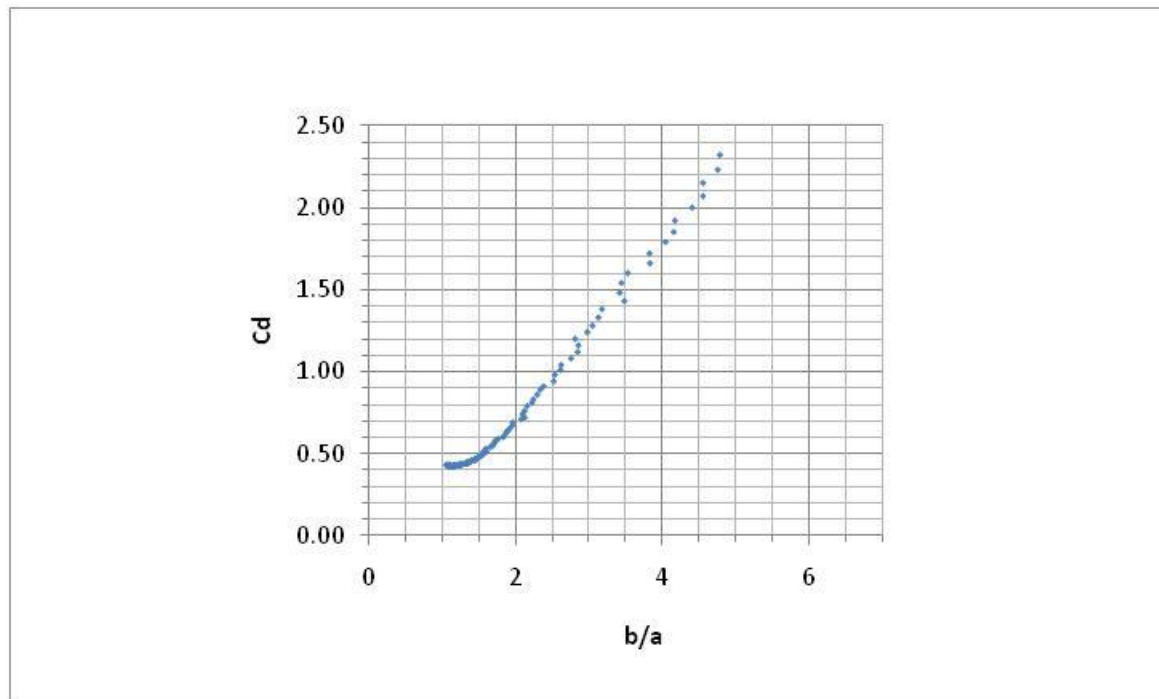
Constant slip velocity = 60 m/sec, airfoil chord = 0.710 m, airfoil velocity = 90 m/sec



Results

Drag Coefficient

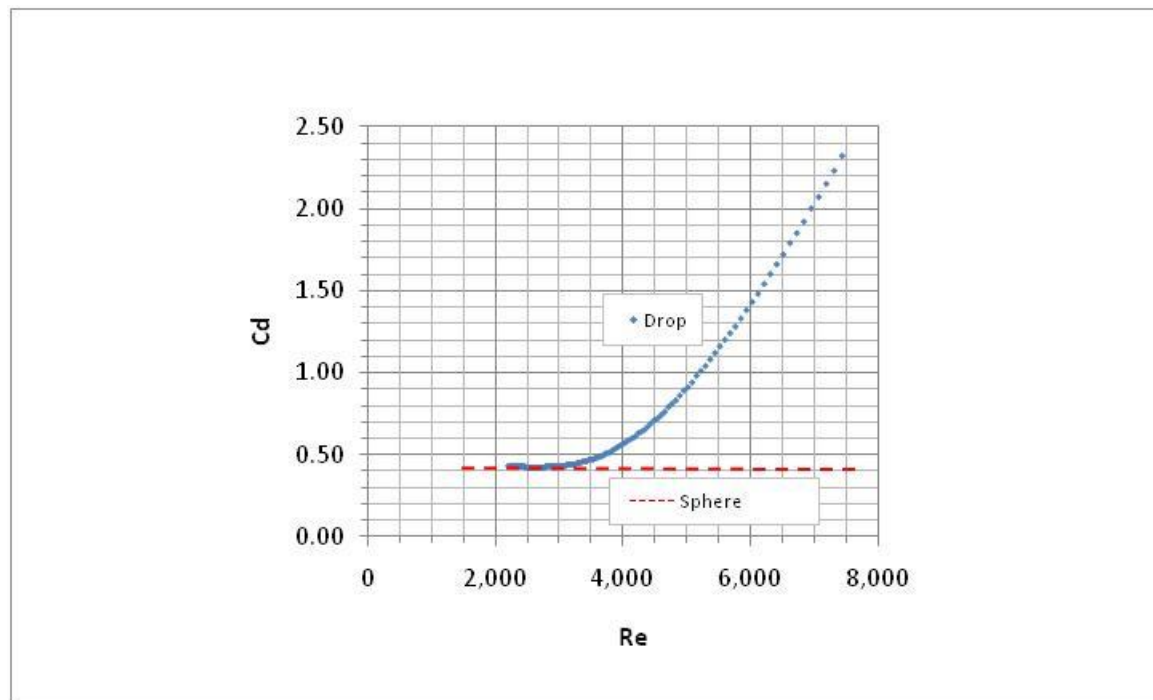
Run 072011.14C droplet #1, droplet diameter = 1062 μm , airfoil chord = 0.710 m, airfoil velocity = 90 m/sec



Results

Drag Coefficient

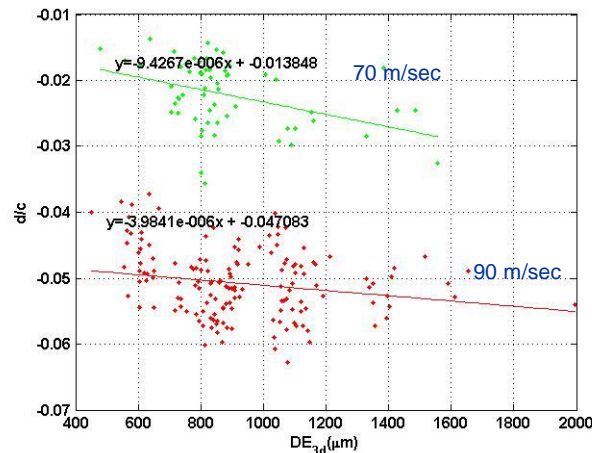
Run 072011.14C droplet #1, droplet diameter = 1062 μm , airfoil chord = 0.710 m, airfoil velocity = 90 m/sec



Results

Distance at which Droplets begin Breakup

- Distance measurements for droplets of different sizes for the 0.710 m and 0.470 m airfoils
 - Data showed high degree of scattering
 - Comparing the distance at which droplets begin breakup is not correct unless the droplets share the same history with respect to the parameters that determine their deformation and breakup
 - For both airfoils all droplets began breakup within distances of 0.02chord to 0.09chord
 - Distance at which the droplets begin their breakup, non-dimensionalized against the chord of the airfoil, was plotted against the diameter of the droplets for velocities of 70 m/sec (green data points) and 90 m/sec (red data points)



Results

Droplet Breakup

Run 072011.14B.1 droplet #1, droplet diameter = 1032 μm , airfoil chord = 0.710 m, airfoil velocity = 90 m/sec



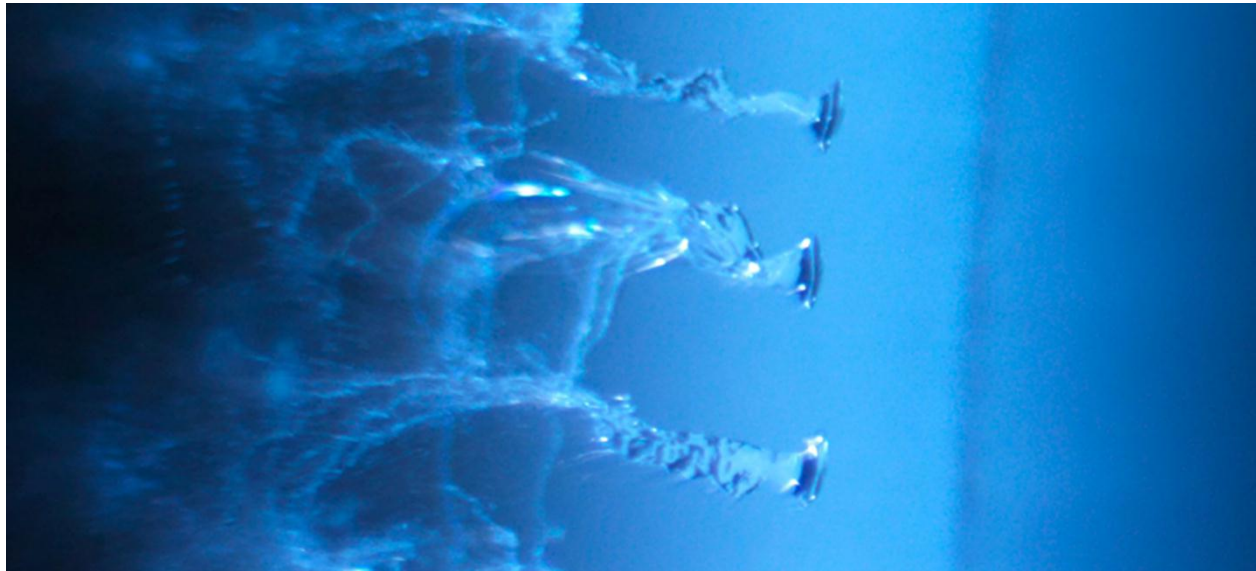
Frame #	190	194	198	203	205
Time (μsec)	2520	2573	2627	2653	2720
x-distance (mm)	32	28	23	17	15



Frame #	207	209	212	215	218
Time (μsec)	2747	2773	2813	2853	2893
x-distance (mm)	13	11	8	5	2

Results

Droplet Breakup



Conclusions

- Droplet deformation and breakup follows a well defined pattern with some modifications for the small droplets (diameters close to 100 μm) and very large droplets (diameters larger than 1500 μm).
- Measured droplet width decreases as the droplet approaches the airfoil and reaches a minimum value at the initiation of the droplet breakup.
- Droplet diameter based on the volume of the oblate spheroid, remained constant until the initiation of breakup providing additional evidence that the spheroid is rotationally symmetric
- For a sample of nineteen droplets with diameters from 500 μm to 1800 μm , deformation increased exponentially against time, linearly against Weber, Reynolds and Bond number.

Conclusions

- Drag coefficient increased linearly with deformation before the beginning of the actual breakup, and increased linearly with the Reynolds number.
- Data for different velocities and two airfoils showed that droplet breakup occurs within 0.02chord to 0.09chord . For the large airfoil ($\text{chord} = 0.710$) at 90 m/sec the droplets broke up earlier (further away from the leading edge) than at 70 m/sec
- Images of the final stages of droplet breakup showed a cloud of water behind the core-tail of the original droplet, indicating that at least some of the mass results in a cloud of small droplets carried away by the flow

END OF PRESENTATION