Ice Particle Impacts on a Moving Wedge

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Outline

- Background

- Objectives

- Approach

- Experiment Set-up

- Data Analysis

- Results

- Conclusions

Background

- Aircraft engine ingestion of ice crystals can cause, at operation conditions, permanent or temporary loss of thrust due to ice accretion accumulation and/or shedding in the engine core

- The ice accretion and shedding can affect the performance and/or control of the compressors leading to surging or stalling and in some cases causing permanent damage to the units

- It can cause reduction of the clearance between stationary and moving parts affecting their performance

- The combustor efficiency and stability may also be affected leading to flame outs

Background

- Research efforts have been directed to study the physics involved when ice crystals impact on a surface

- The studies aim to identify the main parameters involved, the post-impact particle size and velocity distributions, and the main qualitative features of the impact and fragmentation

- In these studies the ice crystals are modeled with spherical ice particles. This is needed because complete characterization of the ice particles in a natural environment is being studied

Background

- The Icing Branch at NASA Glenn and Penn State University have been involved in experimental studies related to ice crystal impacts on internal engine components

- Ice crystal impacts are also important in planetary studies. Planning for the collection of ice crystal samples by instrumentation in spacecraft sent to investigate planetary environments requires knowledge of ice crystal impact physics. This interest brought scientists from the John Hopkins University Applied Physics Laboratory to team with NASA and Penn State University researchers who were studying ice crystal impacts on aircraft engines

Background

- Ice particle impacts can be studied in two main configurations: stationary or moving

- In a stationary configuration the ice particles are directed towards a stationary target

- In a moving configuration the target is moving at a high velocity and impacts an ice particle moving at a lower velocity
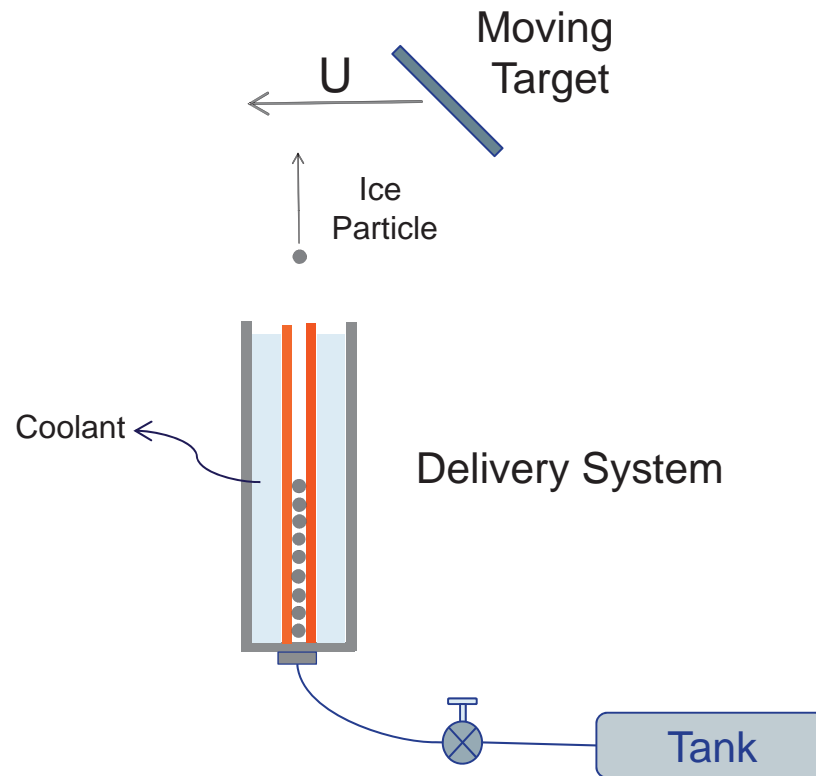
Ice Particle Impacts
Example of a stationary Flat Plate Experimental Configuration
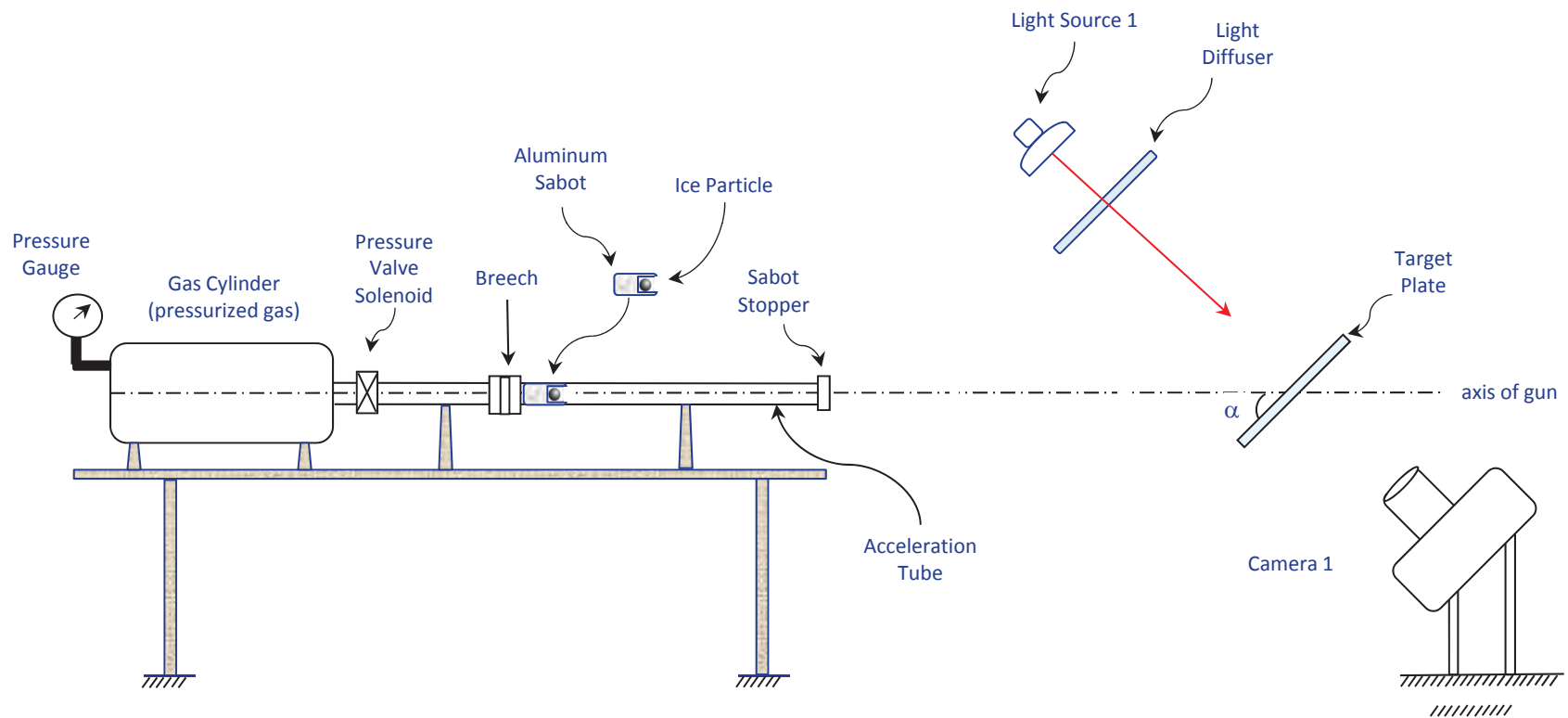
Ice Particle Impacts

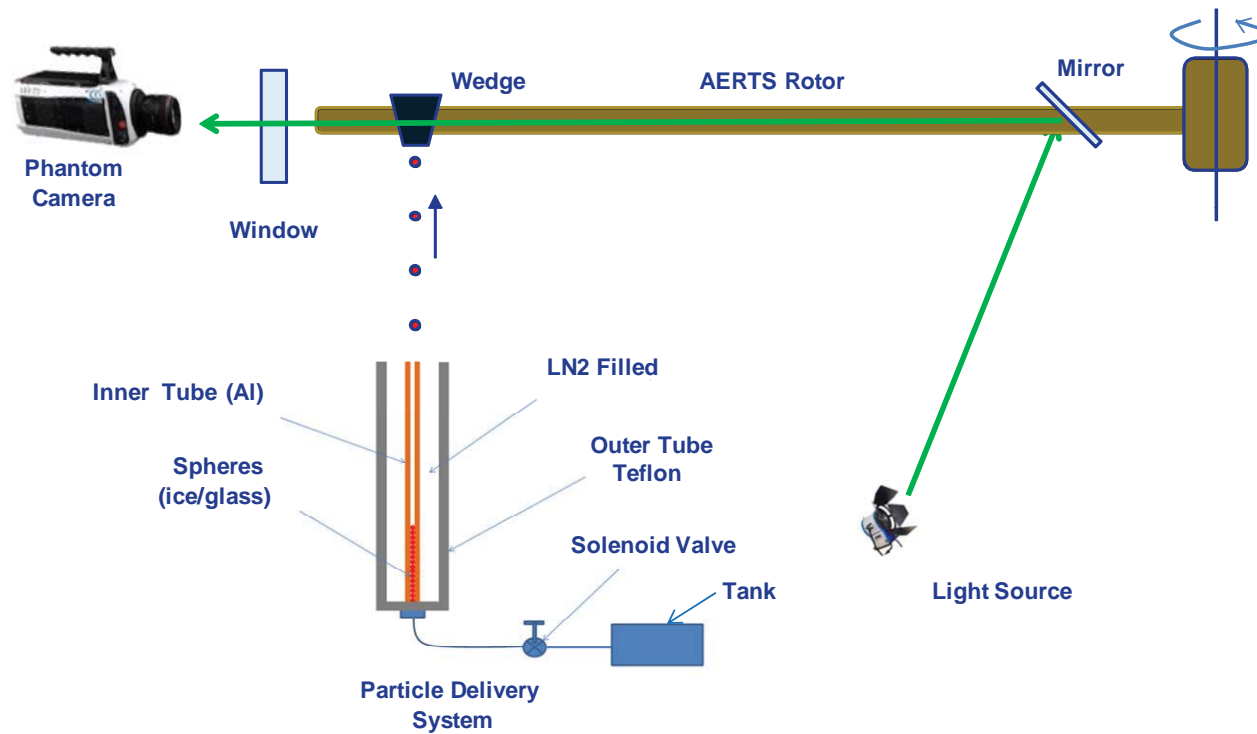## Example of a Moving Target Experimental Configuration

Objectives

- Develop a methodology to make ice particles and design and fabricate a pressure gun to deliver them

- Modify and instrument the Environment Rotor Test Stand (AERTS) located at Penn State University to be used as the carrier of the moving target

- Determine if the pressure gun and the rotating wedge could be synchronized to consistently obtain ice particle impacts on the target wedge

- Capture the event with high speed imaging and observe the effect of velocity and wedge angle on the post-impact fragment behavior
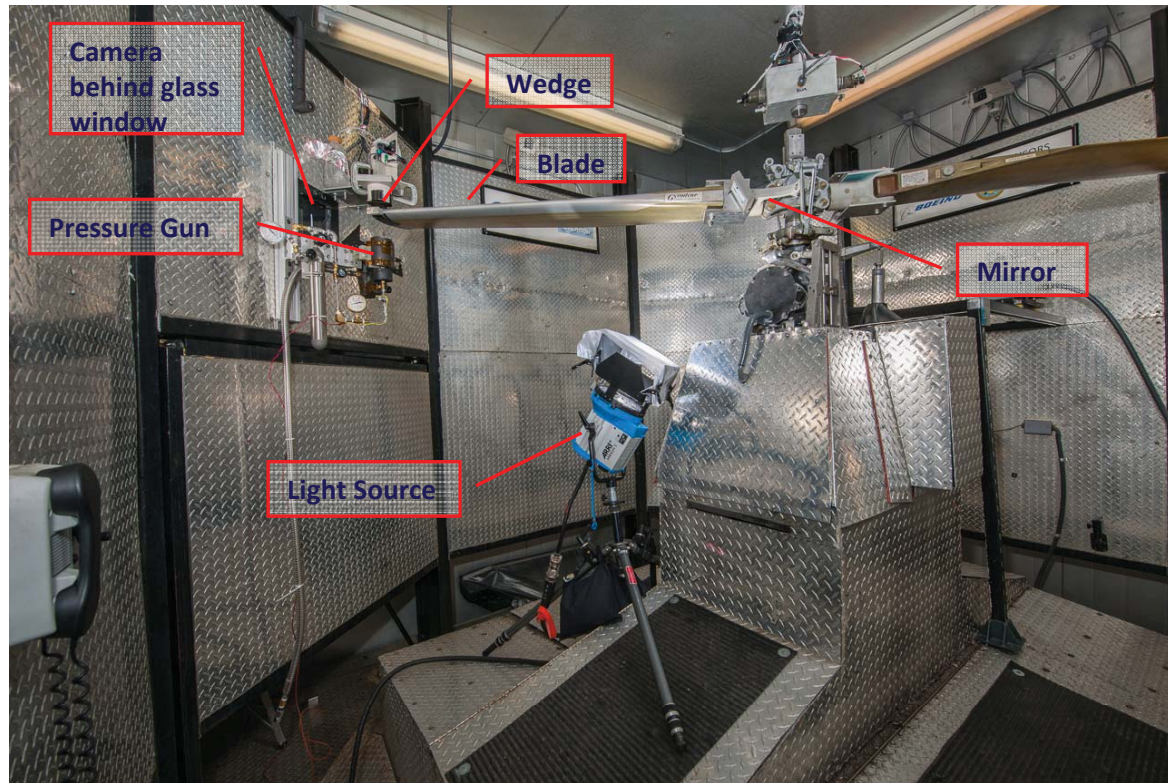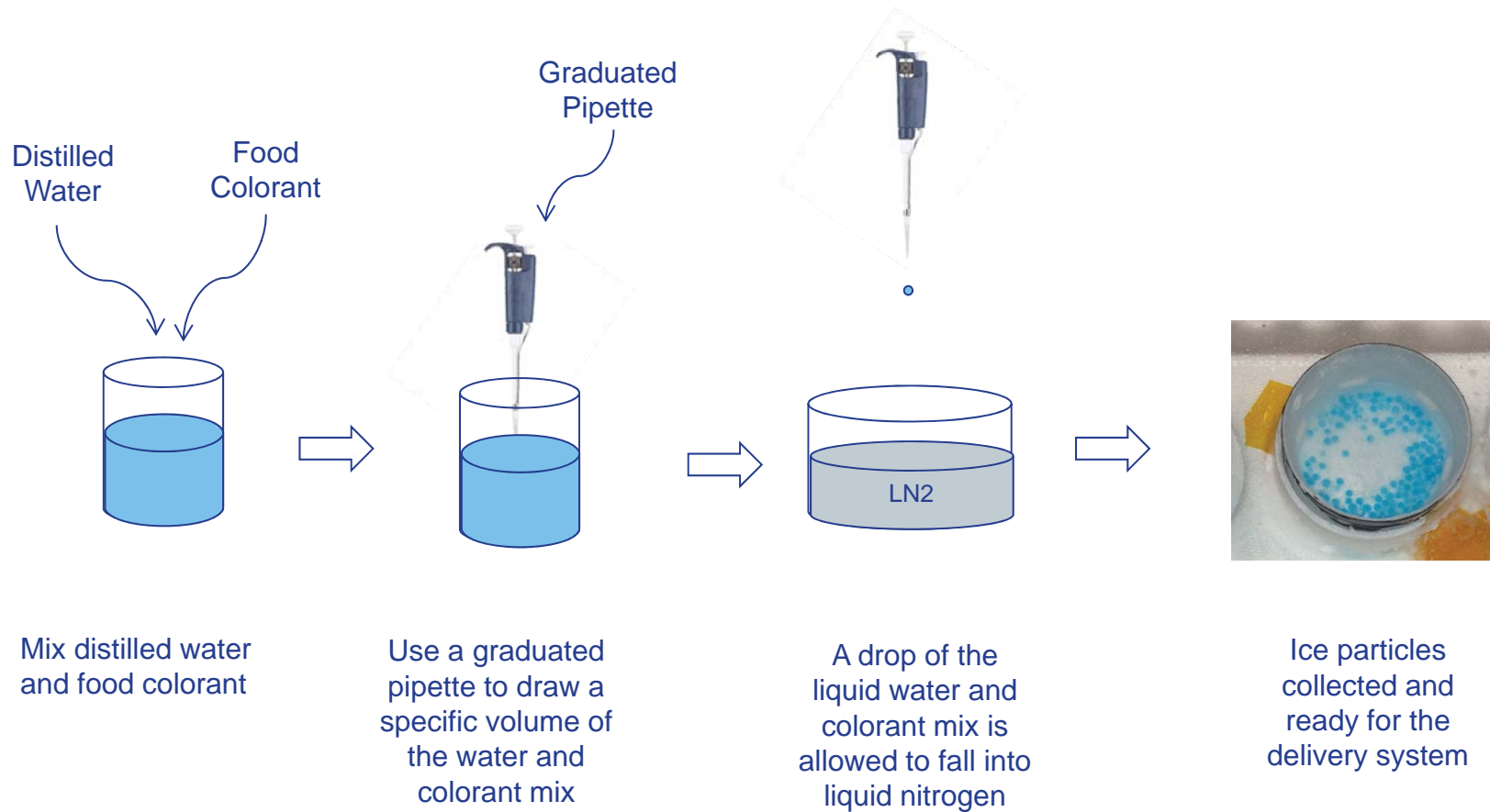
Approach

Conceptual View of Experiment

Phantom Camera

Window

Wedge

AERTS Rotor

Mirror

Inner Tube (Al)

Spheres (ice/glass)

LN2 Filled

Outer Tube Teflon

Solenoid Valve

Tank

Light Source

Particle Delivery System

Approach

Experimental Set-Up at the Environment Rotor Test Stand (AERTS) facility at PSU

Approach

Fabrication of Ice Particles

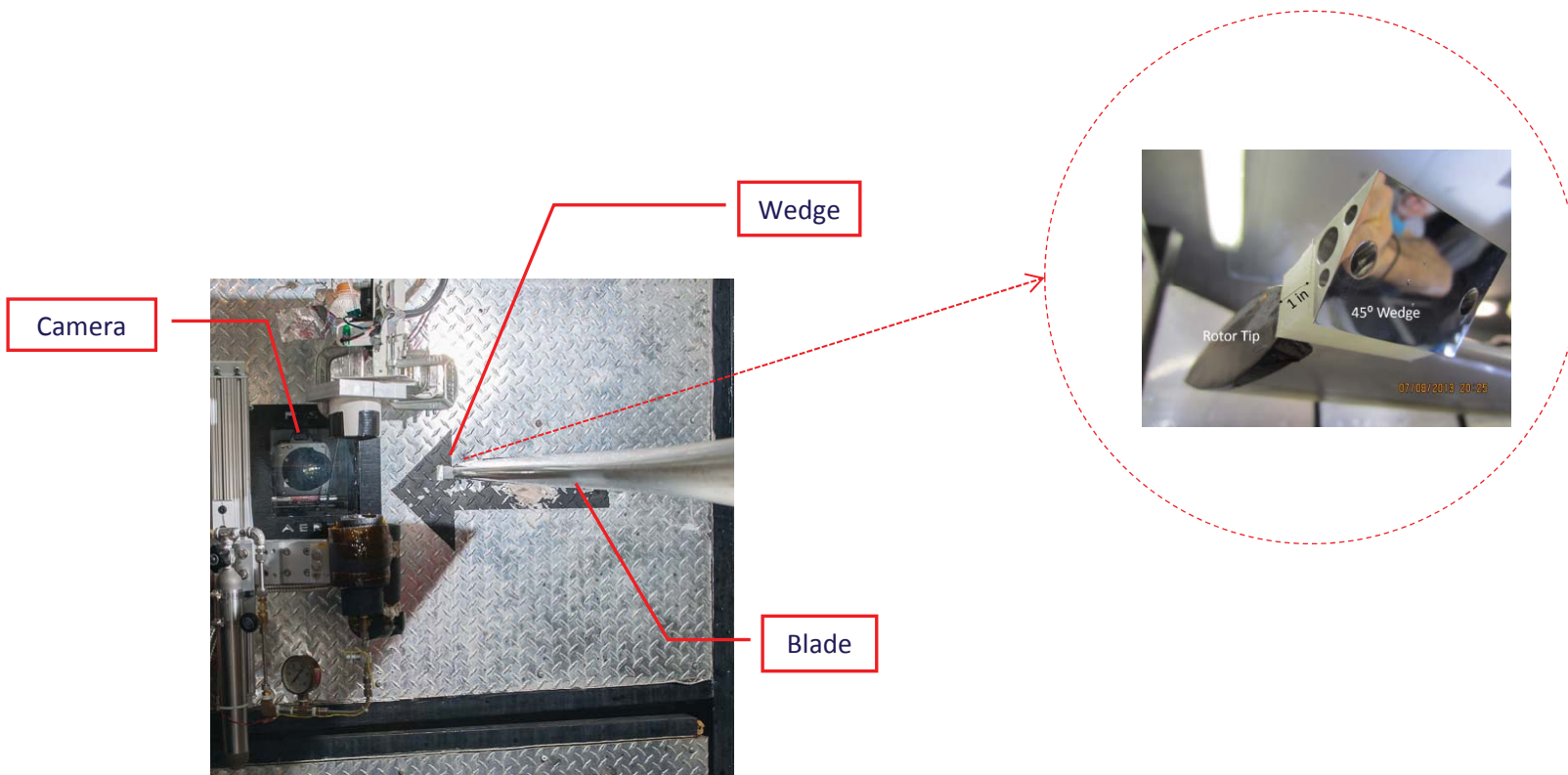Distilled Water

Food Colorant

Graduated Pipette

LN2

Mix distilled water and food colorant

Use a graduated pipette to draw a specific volume of the water and colorant mix

A drop of the liquid water and colorant mix is allowed to fall into liquid nitrogen

Ice particles collected and ready for the delivery system

Experimental Set-Up
Pressure Gun

Inner and Outer Tubes

Tank

Solenoid Valve

Experimental Set-Up
Target

Wedge

Camera

Blade

Rotor Tip

1 in

45° Wedge

07/08/2013 20:25
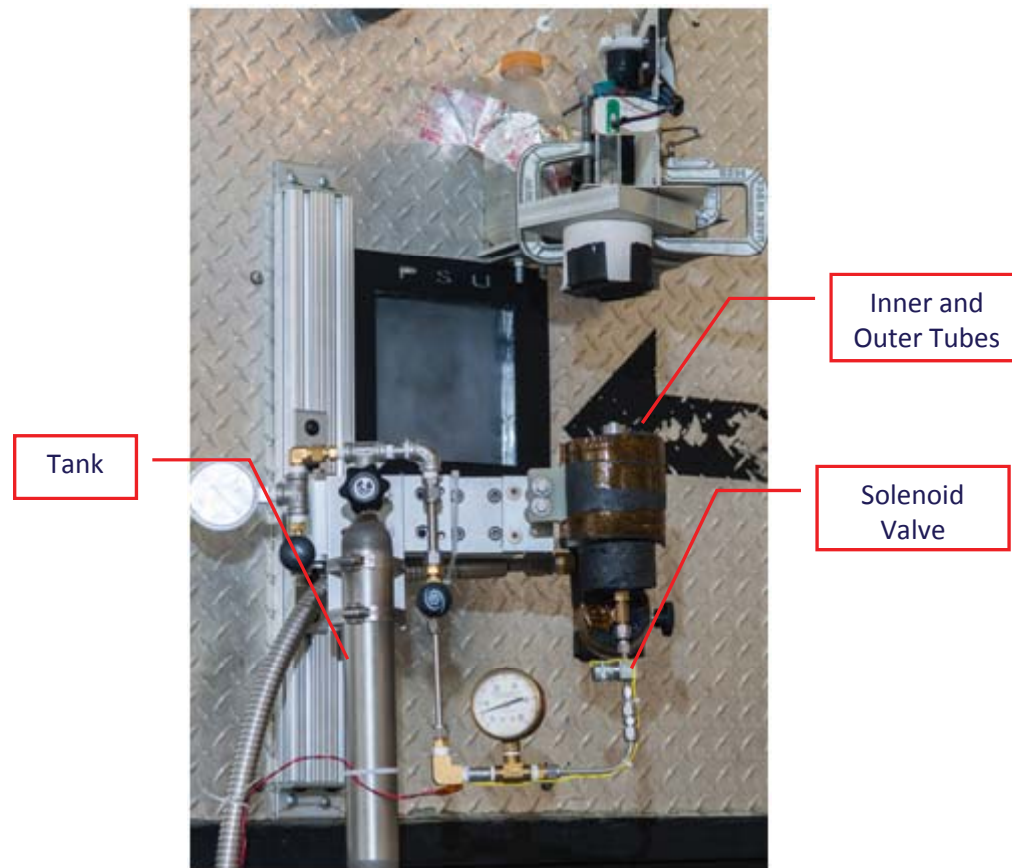
Experimental Set-Up
Timing Methodology

Time Delay = τ

Wedge

High Speed Camera

Time Delay = φ

Signal triggered by Hall sensor

Frozen Drop Dispenser
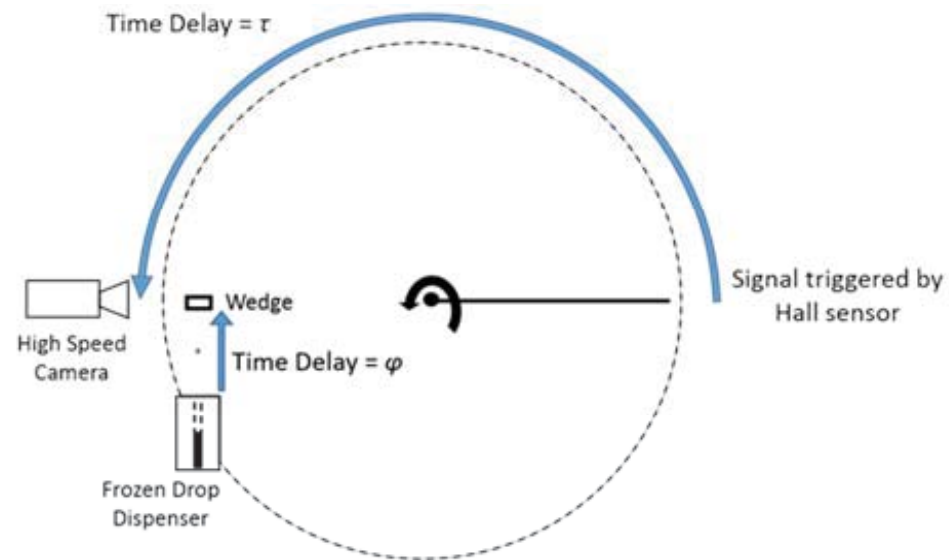
$$Launch\ Delay = \tau - \varphi$$

Test Matrix

- A total of 115 runs were completed including runs done to determine the time delays of the pressure gun and the camera

- Wedges of four different angles were used: 0^0, 30^0, 45^0 and 60^0

- The velocities of the wedge were 0, 15, 20, 40, 80 and 120 meters per seconds

- Particles were moving at velocities of 7 to 12 meters per second when they were impacted by the wedge

- The diameter of the particles varied from 1.5 to 3 millimeters.

- The main camera frame rates were 6100 and 6200 frames per second. A reduced number of runs were done at camera frame rates of 9528, 13002 and 21003 frames per second. Typical resolution was 27.5 pixels per millimeter

Low Velocity Data – Run 7

V_{wedge} = 0 m/sec; Vxparticle = 0 m/sec ;Vyparticle = -3.8 m/sec; Wedge Angle = 60º; Diameter = 2.8 millimeters

Camera Frame Rate = 6200 fps; Camera Resolution = 27.5 pixels/millimeter.

Velocities with respect to the wedge Vn = -3.3 m/sec; Vp = 1.9 m/sec

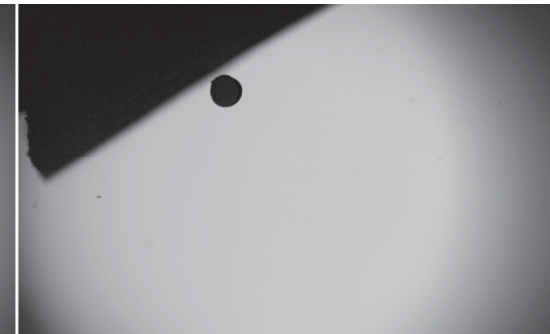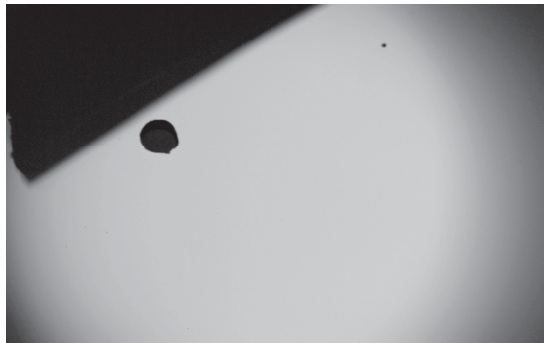| Frame 487	Frame 496	Frame 506

t = 0.0	1451.6	3064.5

microseconds

Low Velocity Data – Run 71

V_{wedge} = 0 m/sec; Vxparticle = 0.1m/sec ;Vyparticle = -5.6 m/sec; Wedge Angle 60°, Diameter = 3.1 millimeters;

Camera Frame Rate = 6200 fps; Camera Resolution = 27.5 pixels/millimeter.

Velocities with respect to the wedge Vn = -4.8 m/sec; Vp = 2.9 m/sec

Frame 330	Frame 334	Frame 358

t =   0.0   645.2   4516.1
microseconds

High Velocity Data - Run 85

V_{wedge} = 120 m/sec; Vx = 0.0 m/sec; Vyparticle = -9.0 m/sec; Wedge Angle 30º, Diameter = 2.9 millimeters;

Camera Frame Rate = 6200 fps; Camera Resolution = 27.5 pixels/millimeter.

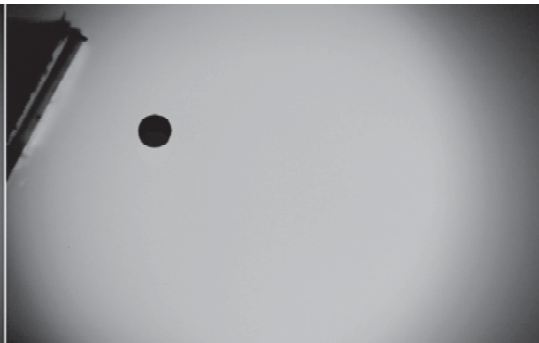Velocities with respect to the wedge Vn = -108.8 m/sec ; Vp = -52.4 m/sec

Frame 46　　　　　　　Frame 47　　　　　　　Frame 48

t =　　0.0　　　　　　　161.3　　　　　　　322.6
microseconds

Run 23 071613 – Ice Particle #2 Before Impact
## Overall Data Obtained about the Particle

Frame Number	time	tframe	x	y	x	y	Area1	Area2	Diameter	Pmtr	Ellipsemaj	Ellipsemino	Ellipseangle
								Area in	Equivalent		Ellipse	Ellipse	
	tracking	from first	Horiz. Disp.	Vert. Disp.	Horiz. Disp	Vert. Disp.	Area in pix	micrometers	Diameter	Perimeter	Major Axis	Minor Axis	Ellipse Angle
	microseconds	microseconds	pixels	pixels	micrometers	micrometers	pixels	micrometers^2	micrometers	pixels	pixels	pixels	degrees
28	0.00	4354.84	0.00	0.00	0.00	0.00	4954.00	6056530.88	2776.94	264.11	86.28	73.31	-10.82
29	161.29	4516.13	2.79	-58.84	-97.68	-2057.32	5117.00	6255807.13	2822.26	268.11	86.59	75.43	-1.50
30	322.58	4677.42	5.28	-117.19	-184.67	-4097.48	5259.00	6429409.75	2861.15	286.01	86.76	77.53	12.79
31	483.87	4838.71	7.79	-175.68	-272.40	-6142.48	5329.00	6514988.51	2880.13	273.52	87.18	77.98	21.13
32	645.16	5000.00	10.12	-233.47	-353.73	-8163.26	5390.00	6589564.28	2896.57	276.94	87.68	78.40	31.59
33	806.45	5161.29	12.63	-291.07	-441.59	-10177.28	5415.00	6620128.12	2903.28	277.52	88.36	78.18	41.90
34	967.74	5322.58	15.41	-348.47	-538.89	-12184.38	5422.00	6628686.00	2905.15	279.42	89.07	77.74	50.76
35	1129.03	5483.87	18.66	-405.63	-652.32	-14182.74	5418.00	6623795.78	2904.08	279.18	89.94	77.01	59.30
36	1290.32	5645.16	22.41	-462.84	-783.43	-16183.25	5298.00	6477089.34	2871.74	277.76	90.47	75.05	67.34

Run 23 071613 – Ice Particle #2 Before Impact
Vertical Velocity with respect to the Laboratory

t =   0.0   161.3   322.6   483.9   645.2   806.5   967.8   1129.0   1290.3
microseconds

Run 23 071613 Ice Particle #2 - Frames 28-36
Before Impact

$y = -12.584x$
$R^2 = 1$

Run 23 070913
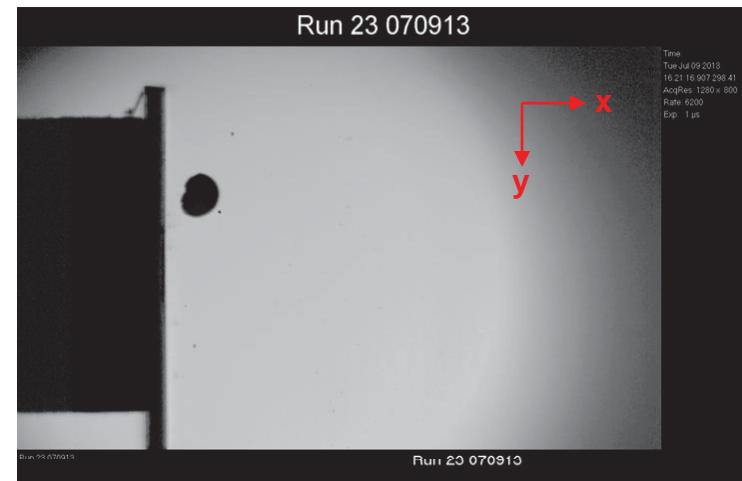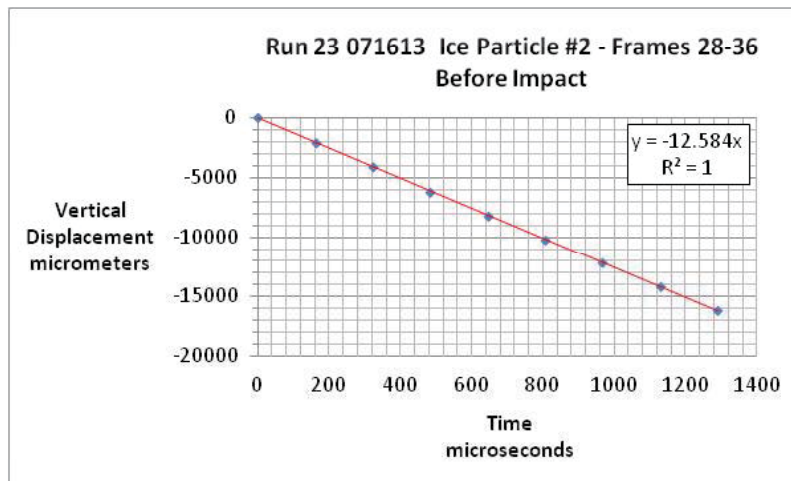
$$V_y = -12.6 m/\sec$$

Data Analysis Main Focus

- Studies by Guégan et al. and Pan and Render on the impact of hail-size ice particles showed very high velocities for the first ejected fragments during impact. The velocity of those first ejected fragments was higher than the approaching ice particle velocity before impact

- Scale difference between ice particles used in the experiment and hail stones used in past studies was 4 times or larger

- The main focus of the data analysis was to measure the velocity of the edge of the fragment cloud to determine if at the reduced size of the ice particles tested, the initial ejected fragments exhibited the same velocity behavior

- Additional general qualitative observations were recorded

High Velocity Data - Run 85

V_{wedge} = 120 m/sec; Vx = 0.0 m/sec; Vyparticle = -9.0 m/sec; Wedge Angle 30º, Diameter = 2.9 millimeters;

Camera Frame Rate = 6200 fps; Camera Resolution = 27.5 pixels/millimeter.

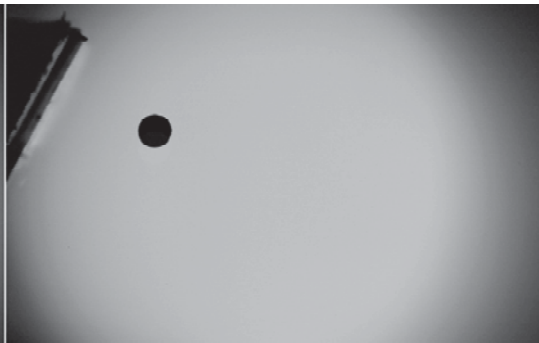Velocities with respect to the wedge Vn = -108.8 m/sec ; Vp = -52.4 m/sec

Frame 46	Frame 47	Frame 48

t =   0.0   161.3   322.6

microseconds

Data Analysis

Cloud Velocity Measurement Methodology

Input Parameters

(xi, yi), (xf, yf), $(x1, y1)$, $(x2, y2)$, (xd, yd), (xu, yu), R, α, res, fmr

$$\vec{V}_{xy} = u\vec{i} + v\vec{j} \qquad u = \frac{(xf - xi)*fmr}{1000*resolution} \qquad v = \frac{(yf - yi)*fmr}{1000*resolution}$$

$$\vec{V}_{np} = (V_n\vec{n} + V_p\vec{p}) \qquad V_n = (v*\sin\alpha + u*\cos\alpha - |W_{wedge}|*\cos\alpha)\vec{n}$$

$$V_p = (u*\sin\alpha - v*\cos\alpha - |W_{wedge}|*\sin\alpha)\vec{p}$$

(xc, yc), L

$t = L/(abs(V_n))$, $\qquad s = V_p * t$,

$$Ximp = xc + s*\sin(\alpha)$$
$$Yimp = yc - s*\cos(\alpha)$$

$$V_{cloud-up} = \frac{\sqrt{(xu-ximp)^2+(yu-yimp)^2}-R}{(1/fmr)-t}$$

$$V_{cloud-down} = \frac{\sqrt{(xd-ximp)^2+(yd-yimp)^2}-R}{(1/fmr)-t}$$
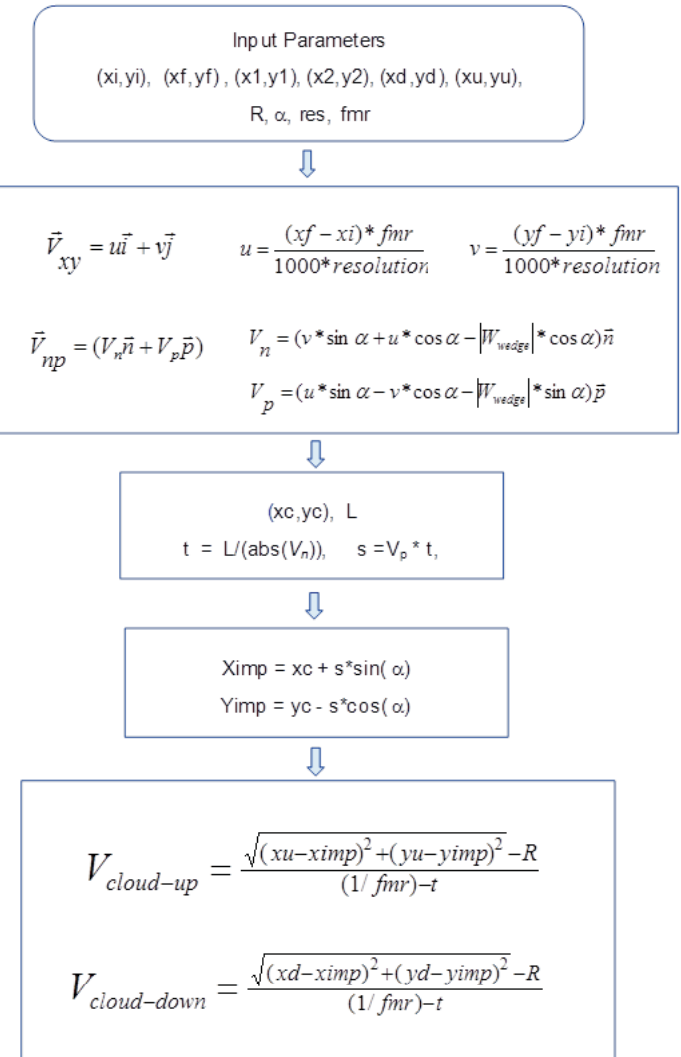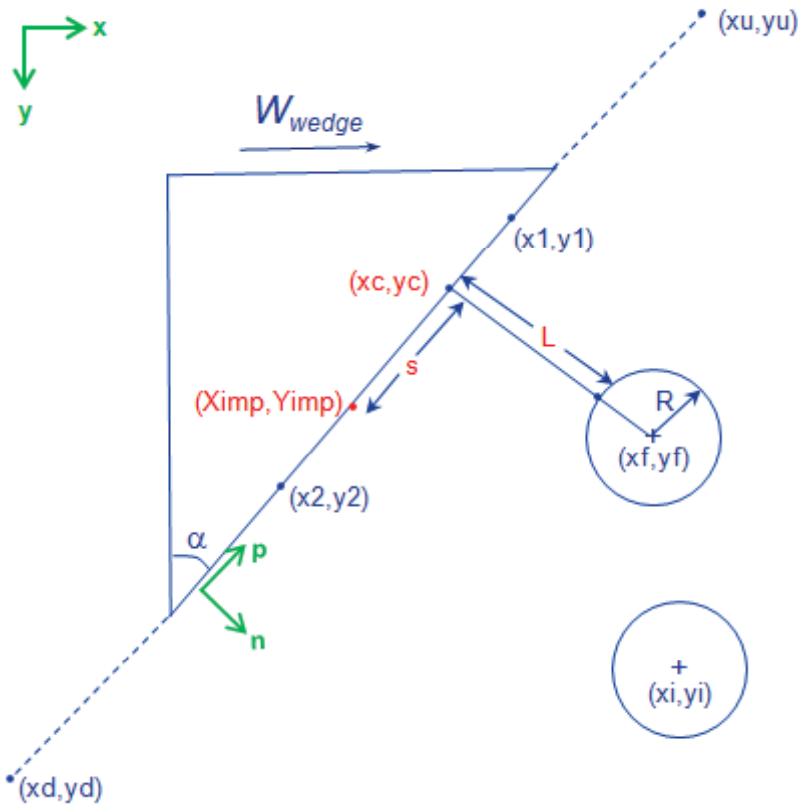
Results - Run 85

V_{wedge} = 120 m/sec; Vx = 0.0 m/sec; Vyparticle = -9.0 m/sec; Wedge Angle 30°, Diameter = 2.9 millimeters;
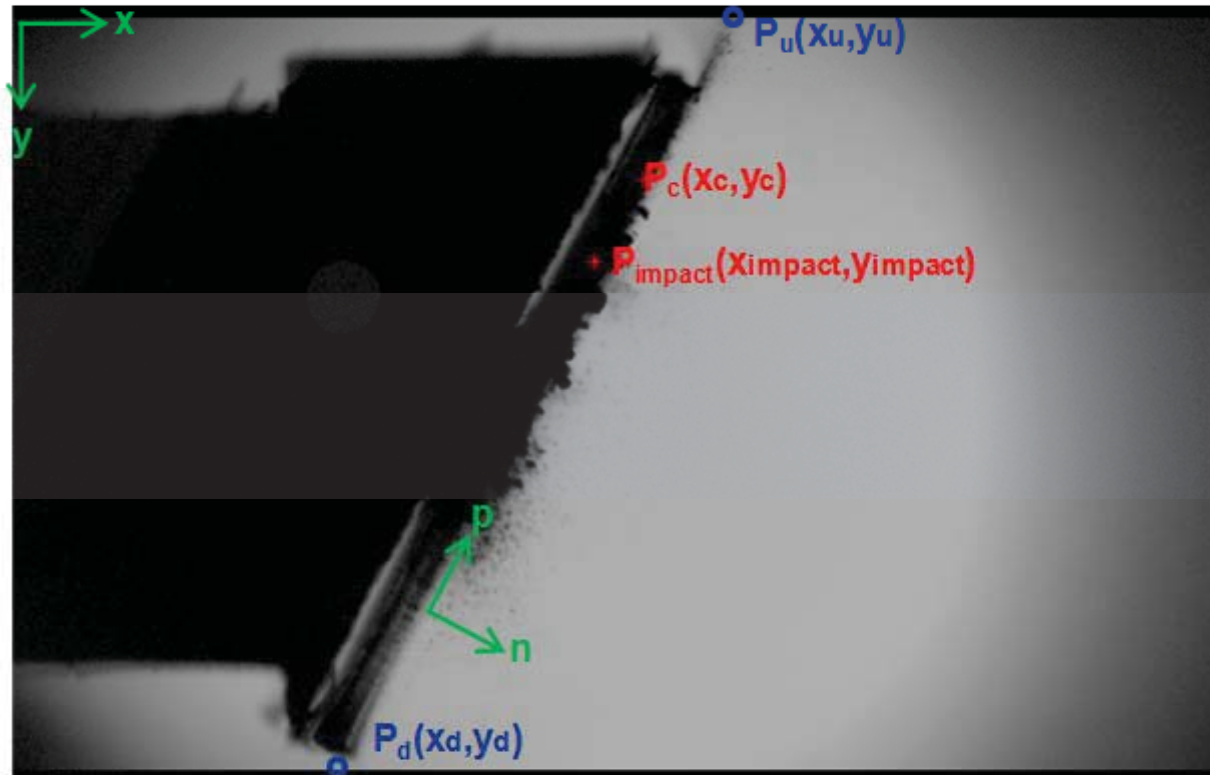
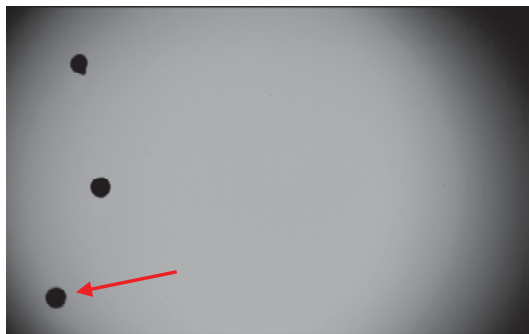| ximpact	yimpact	Cloud Velocity Down	Cloud Velocity Up	Wedge Velocity
Pixels	Pixels	m/sec	m/sec	m/sec
82.2	259.0	-240.2	117.8	120.4

Results

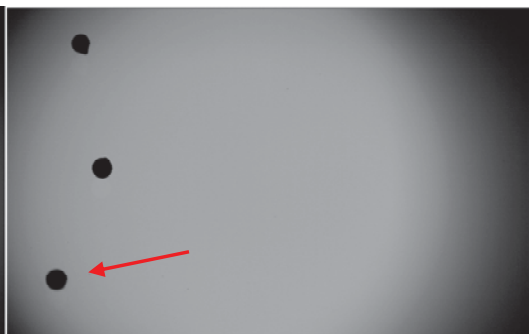## Selecting the Edge Points of the Cloud

Results - Run 96

V_{wedge} = 120 m/sec; Vyparticle = -10.3 m/sec; Wedge Angle 0º, Diameter = 1.7 millimeters;

Frame 44 Frame 45 Frame 46

t =   0.0   163.9   327.9
microseconds

Results - Run 96

V_{wedge} = 120 m/sec; Vyparticle = -10.3 m/sec; Wedge Angle 0°, Diameter = 1.7 millimeters
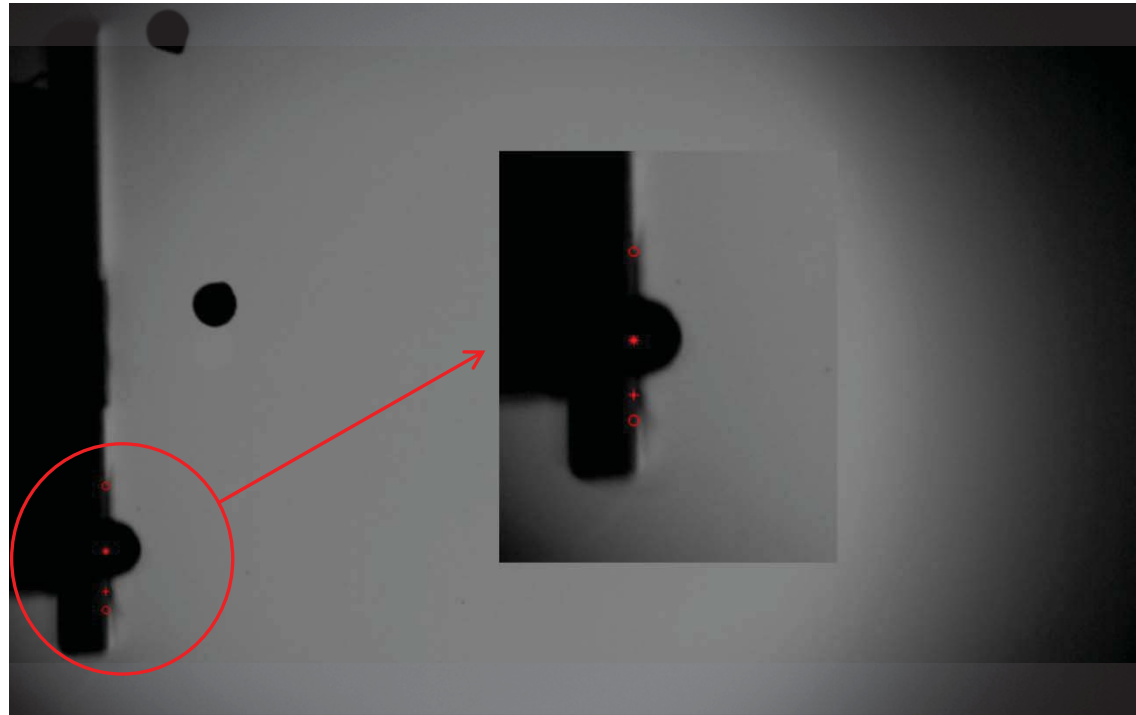
ximpact	yimpact	Cloud Velocity Down	Cloud Velocity Up	Wedge Velocity
Pixels	Pixels	m/sec	m/sec	m/sec
-430.0	617.9	-326.3	388.1	120.2

Additional General Observations

- Fragment size was found to decrease with the impact kinetic energy. This can be expected because the higher the impact energy, the more fracture cracks are created in the particle

- Guégan et al. and Pan and Render, when studying impact of hailstones at high velocities, observed a very shallow angle at which the particle fragments move in a direction perpendicular to the impact surface. Angles of less than 2° were observed. Particle fragments bounce very little; they spread over the surface

- To verify this with the smaller size ice particles used in the present experiment, the distance of fragment rebound was measured normal to the wedge surface in the first post-impact image. At the lower velocities the fragments can rebound a large distance from the wedge surface. As the velocity is increased, the rebound distance decreases and at 120 m/sec it was measured to be less than 6 millimeters. This agrees with what was observed by Guégan et al. and Pan and Render

Conclusions

- A rotating wedge and an ice particle shot from a pressure gun can be timed so that an impact on the target can be obtained with some degree of repeatability and captured with high speed imaging. The experimental configuration allows the study of ice particle impacts on a moving surface

- The data showed that the velocities of the first ejected fragments that formed the edge of the cloud were higher than the approaching ice particle velocity before impact. This result agrees with work done by researchers studying the impact of hailstones on flat plate targets

- At the higher velocity tested, 120 meters per second, the fragments after impact tended to have a low bounce normal to the wedge, compared to the motion of the fragments along the surface of the wedge. This also agrees with previous observations from studies on hailstone impacts on a flat surface

- The results of the work presented here will help in the design of future experiments of ice particle impacts on a moving surface. The experiments are needed to understand the physics involved in the impact of ice crystals on moving elements in turbofan engines which is one of the current main areas of engine icing studies

END OF PRESENTATION