Thermographic Phosphor Measurements of Shock-Shock Interactions on a Swept Cylinder

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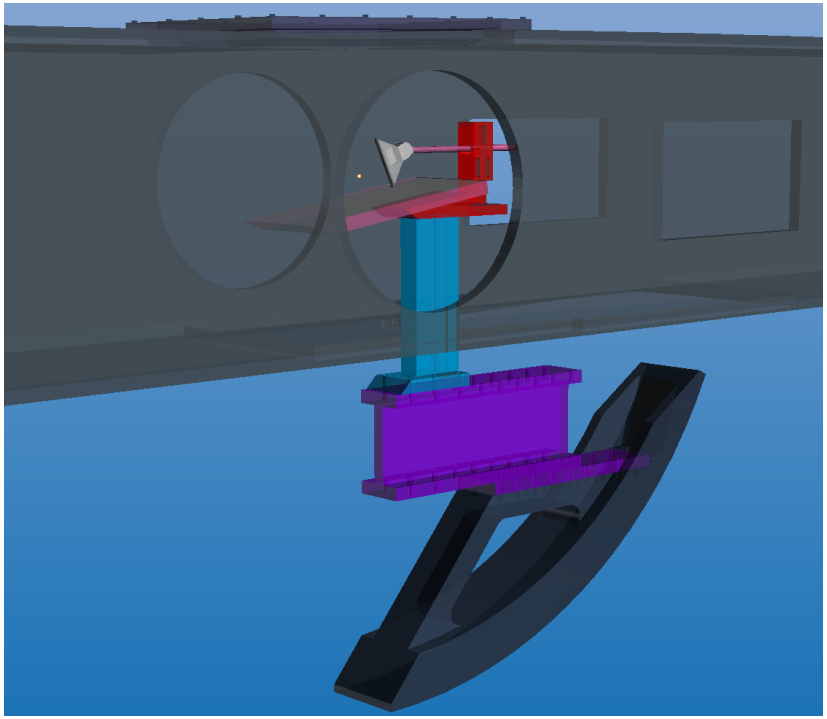
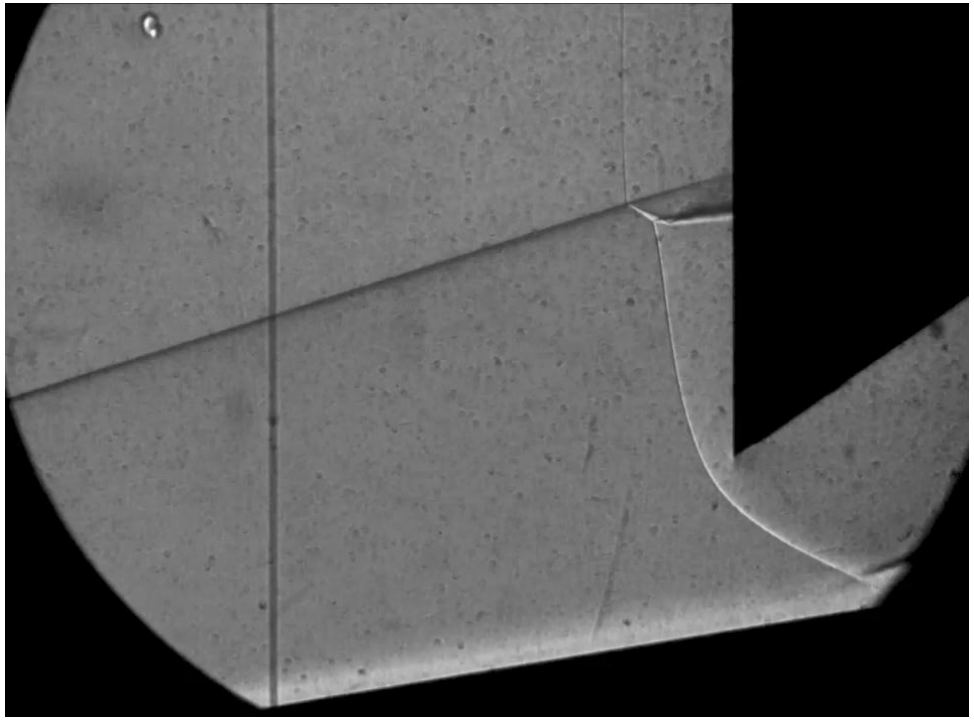




Thermal & Fluids Analysis Workshop (TFAWS 2013)
July 29-August 2, 2013, Kennedy Space Center (KSC), FL

Presentation Outline

Introduction

The main purpose of this study is to experimentally investigate shock-shock interactions that can affect the surface heating of supersonic and hypersonic flight vehicles

Goals

- Characterize shock-shock interaction patterns and heating with increased resolution
- Analyze the heat transfer using one-dimensional and multi-dimensional techniques

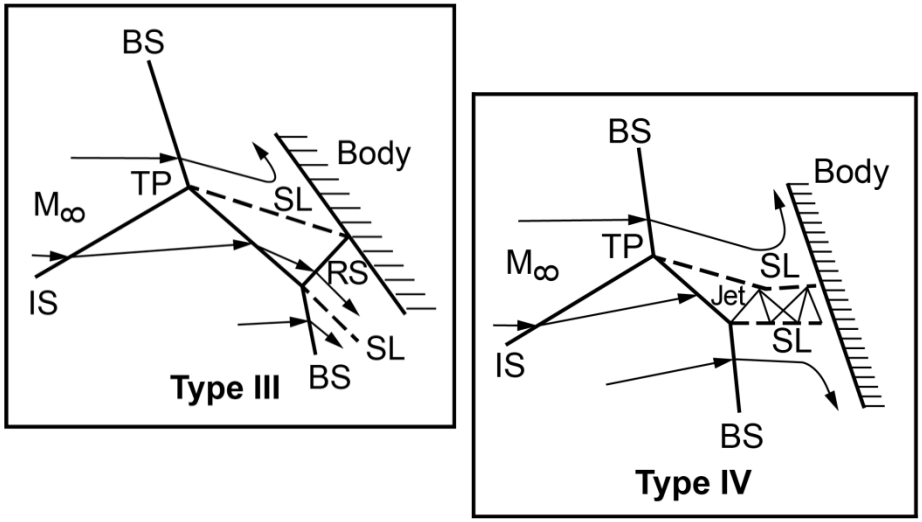
Study Impact

- First published results investigating peak heating augmentation due to shock-shock interactions with global imaging techniques and multi-dimensional thermal analyses
- Contributes to the knowledge of 3D hypersonic shock-on-strut interactions using high-speed zoom schlieren and oil-flow techniques

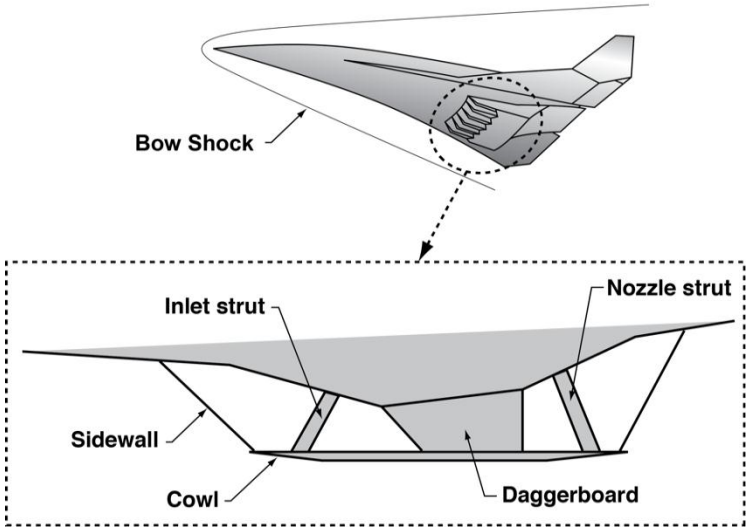
Historical Perspective

Type III and IV Shock-Shock Interactions

(Barry Edney, ARI of Sweden, 1968)

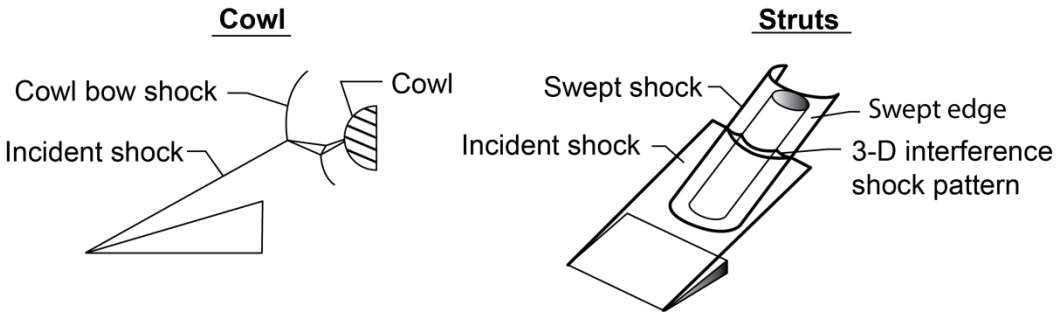


Shock Interaction on Hypersonic Flight Vehicles



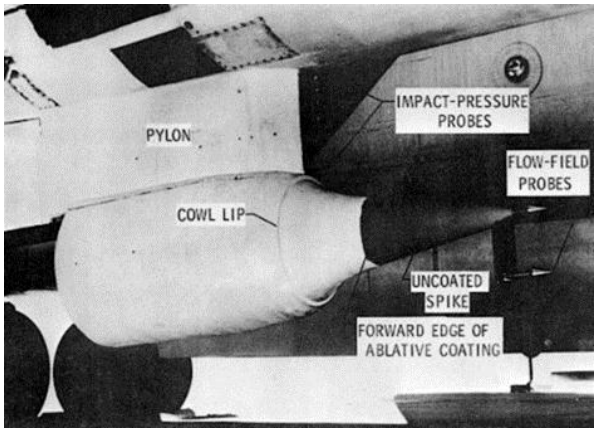
3D shock-on-fin (strut) cases were investigated in this study

Experimental simulation



Historical Perspective

X-15 damage during Mach 6.7 hypersonic flight (October 1967)



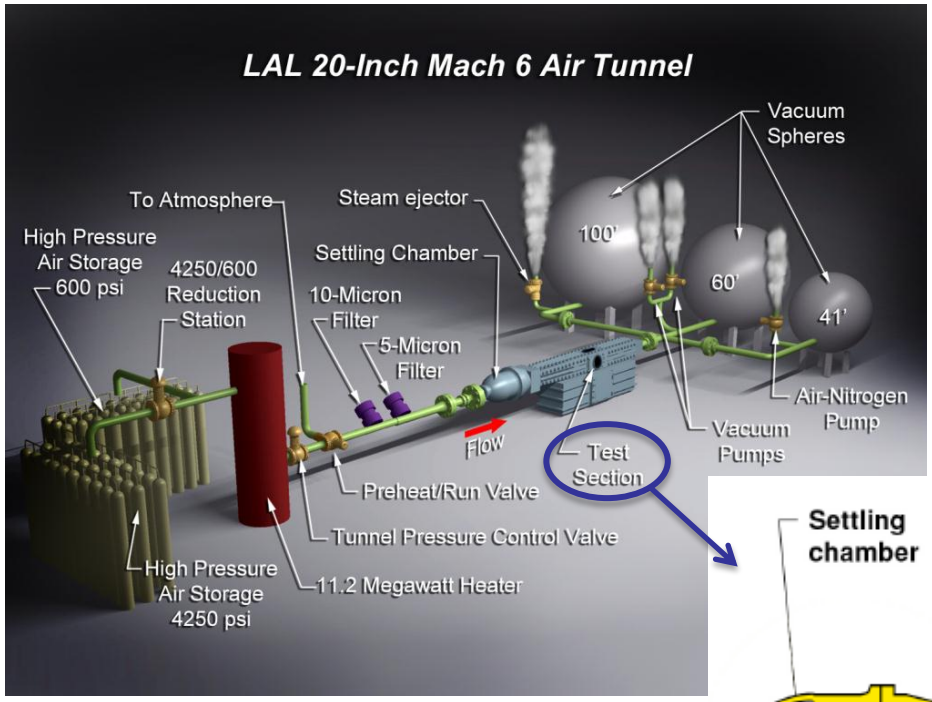
http://www.hq.nasa.gov/office/pao/History/x15lect/structur.html

Damaged dummy ramjet

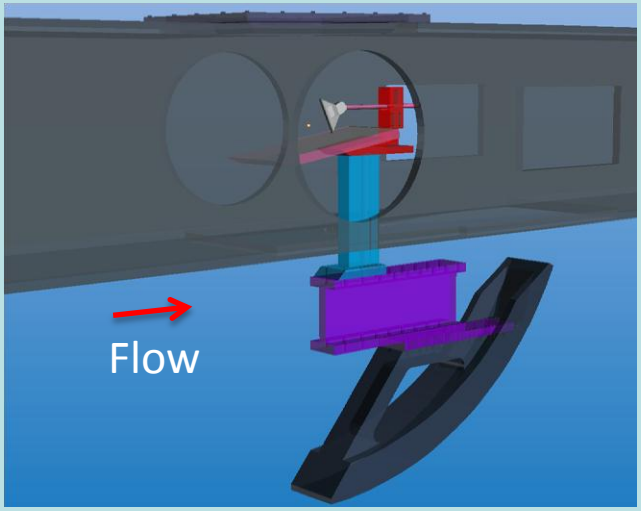
Damaged pylon

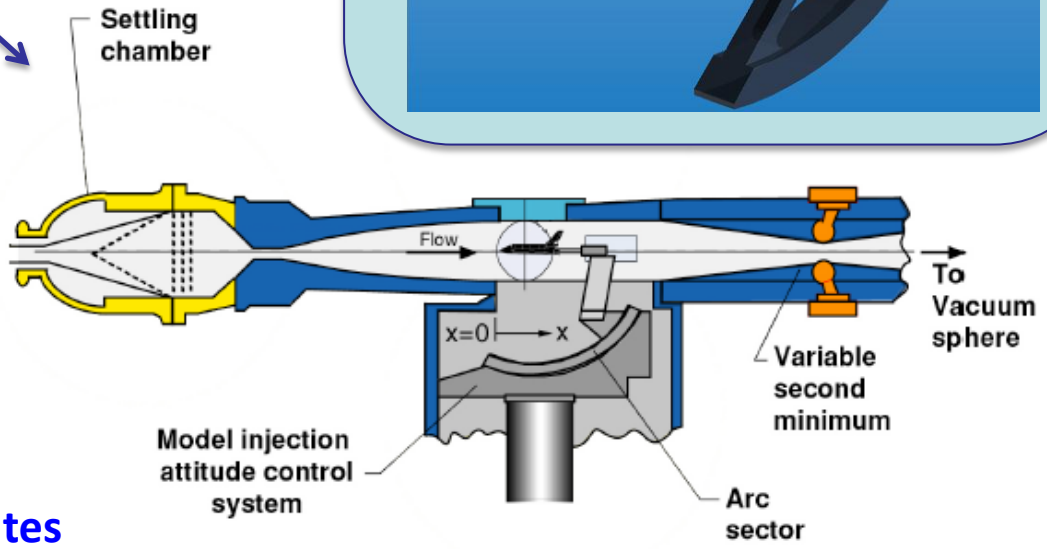
Experimental Facility

Conventional blow-down tunnel with rectangular cross-section



Graphic rendering of the present model in the test section:





Nominal Tunnel Conditions:

- Mach 6, Re: 0.5-8.0 x10^6/ft
- $T_{t,1}$: 410-475˚ F
- $P_{t,1}$: 30-475 psia
- Test section: 20.5” x 20.0”
- Run duration: Up to a few minutes

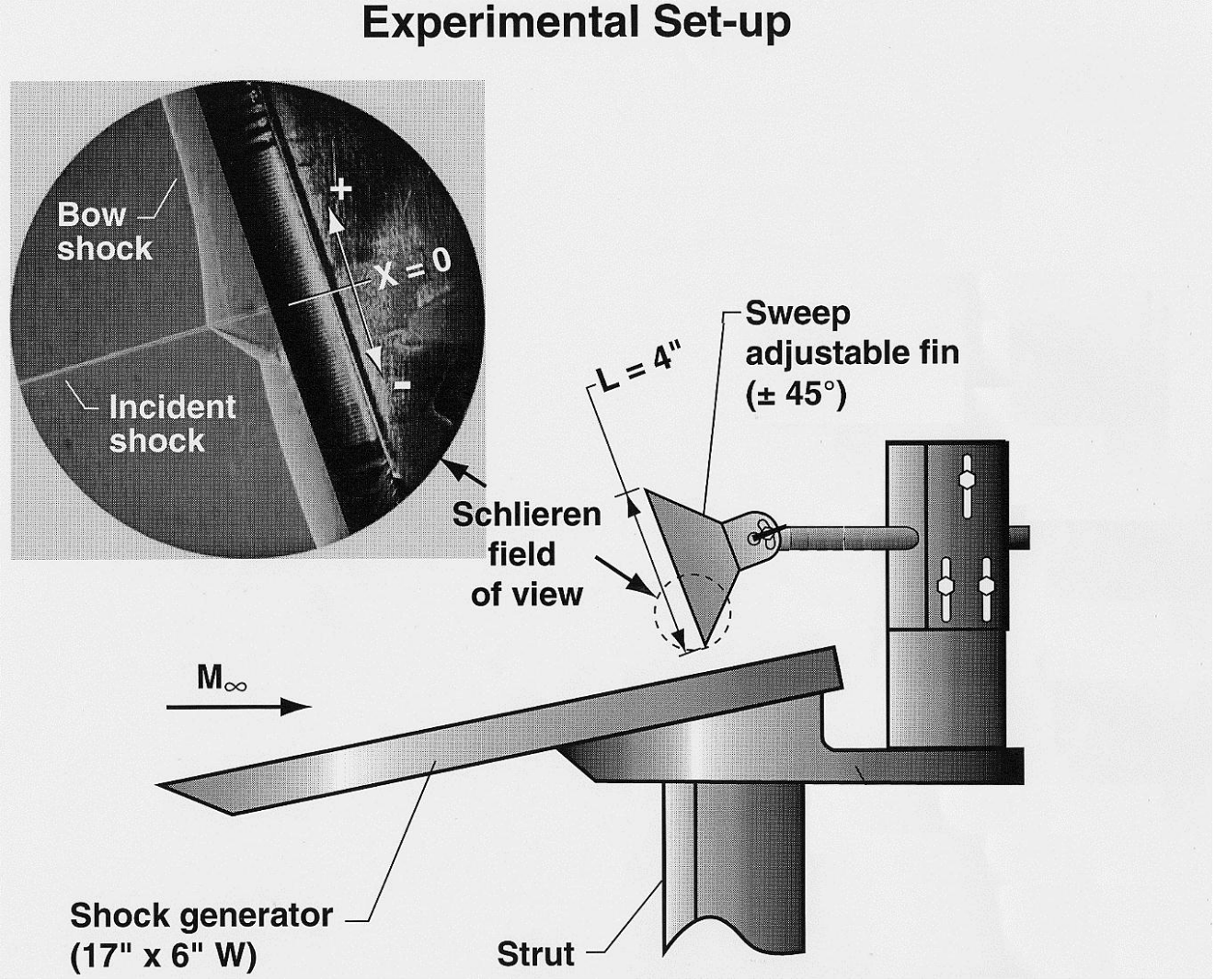
Experimental Approach

- Design and build test articles with cylindrical leading edges
- Utilize the 20-Inch Mach 6 Air Tunnel to simulate shock-shock interactions expected in hypersonic flight
- Analyze the flow patterns above (schlieren) and at (oil flow) the test article surface
- Develop 1D semi-infinite code based on a legacy program to analyze the heat transfer to the test article
- Develop 1D and 2D finite-volume codes to analyze the heat transfer to the test article

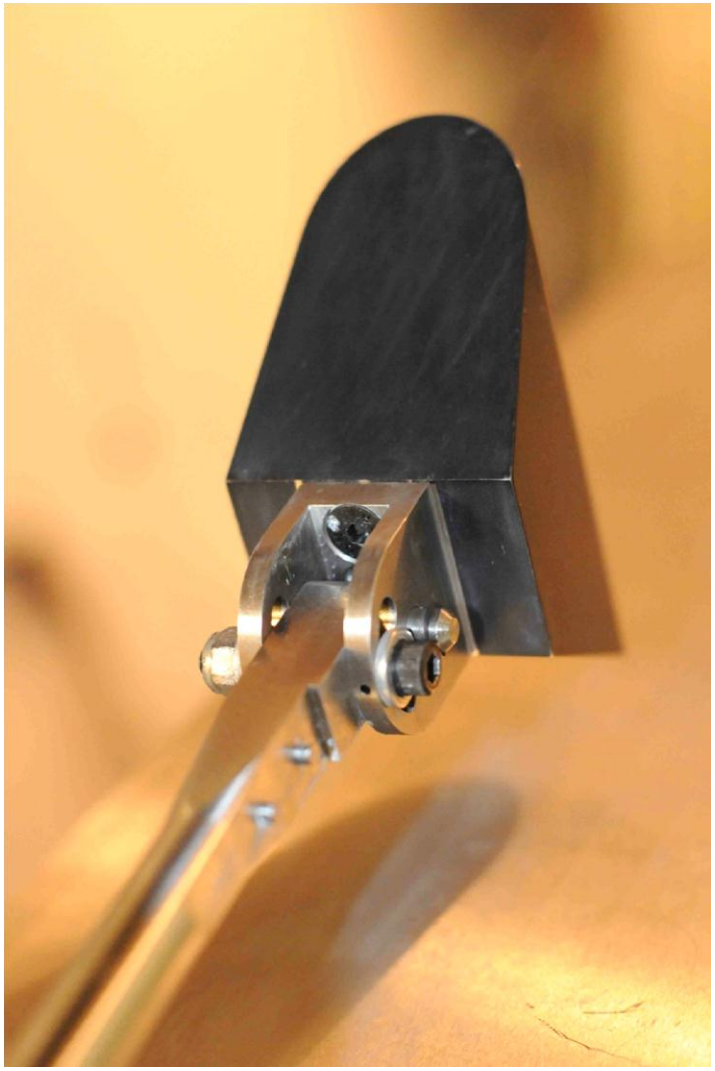
Test 6976	–	Exploratory study to test custom zoom schlieren system	**March 2012**
Test 6983 Phase 1	–	Conducted oil-flow visualization test with metal models and obtained high-speed zoom schlieren data	**August 2012**
Test 6983 Phase 2	–	Performed phosphor thermography tests with fused silica models, and improved high-speed zoom schlieren	**October 2012**

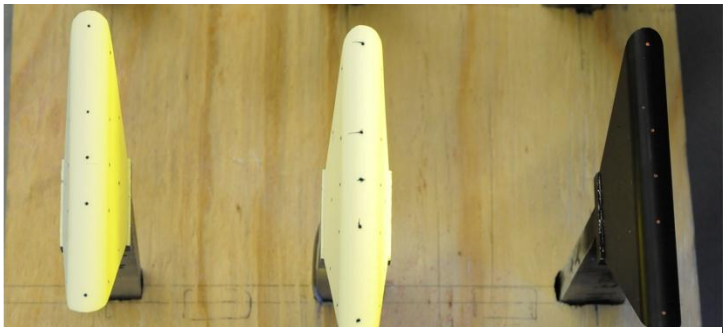
Test Set-up

Previous shock-on-strut experiment (see Berry & Nowak, 1997):

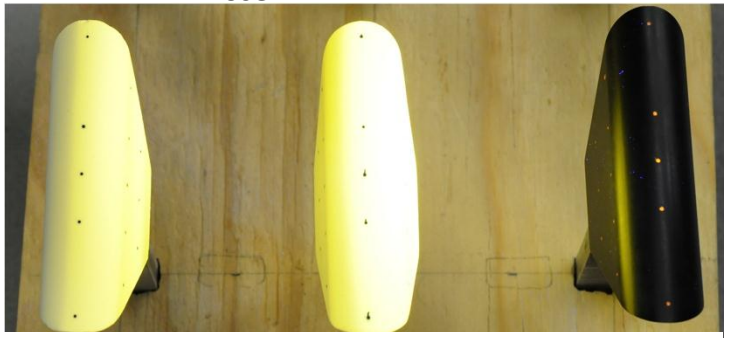


Test Set-up

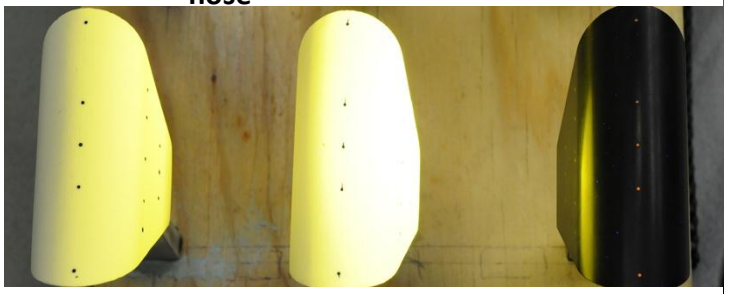




r_{nose} = 0.25 inches



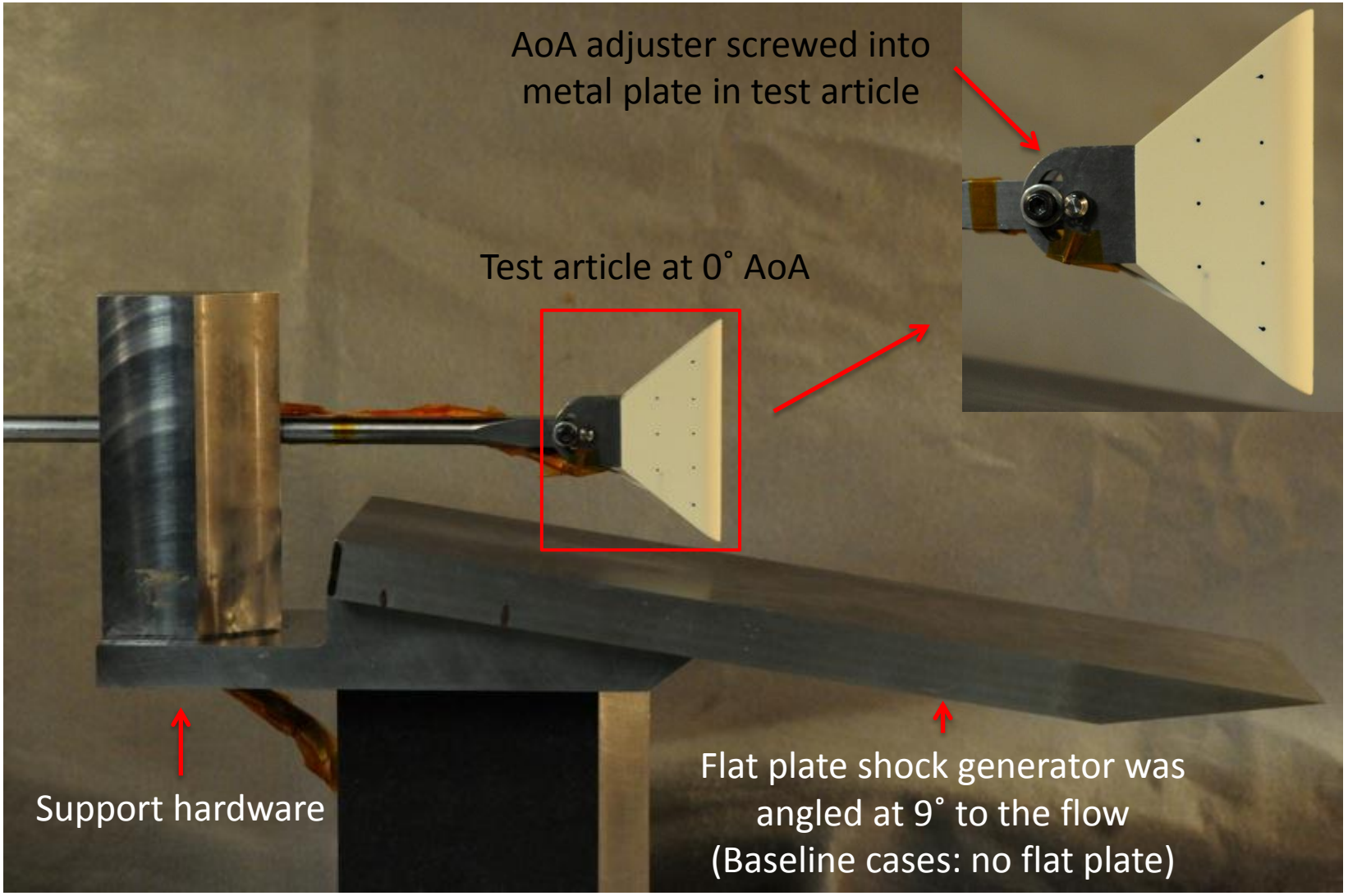
r_{nose} = 0.50 inches



r_{nose} = 0.75 inches

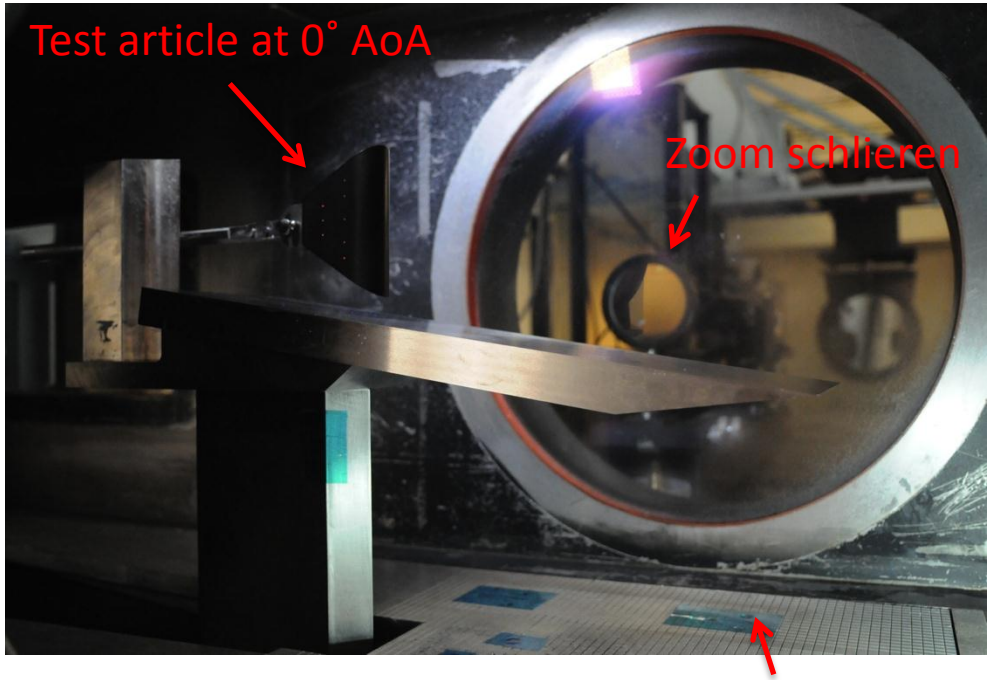
Fused Silica **Metal**

Test Set-up


AoA adjuster screwed into metal plate in test article
Test article at 0˚ AoA
Support hardware
Flat plate shock generator was angled at 9˚ to the flow (Baseline cases: no flat plate)

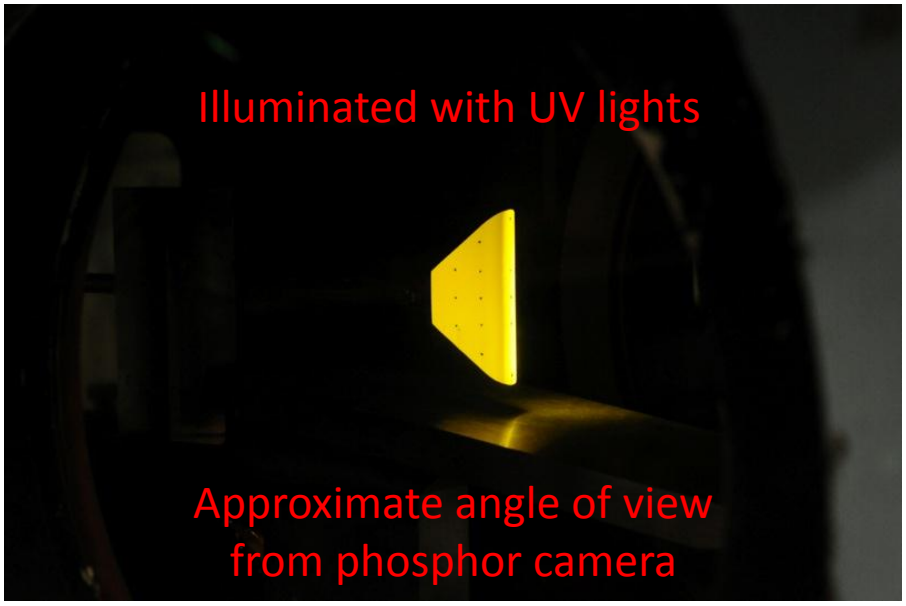
Test Set-up

Test 6983: Oil Flow



Test articles were inserted into the tunnel test section in about 1.5s and each run lasted 3-10 seconds

Test 6983: Phosphor Thermography

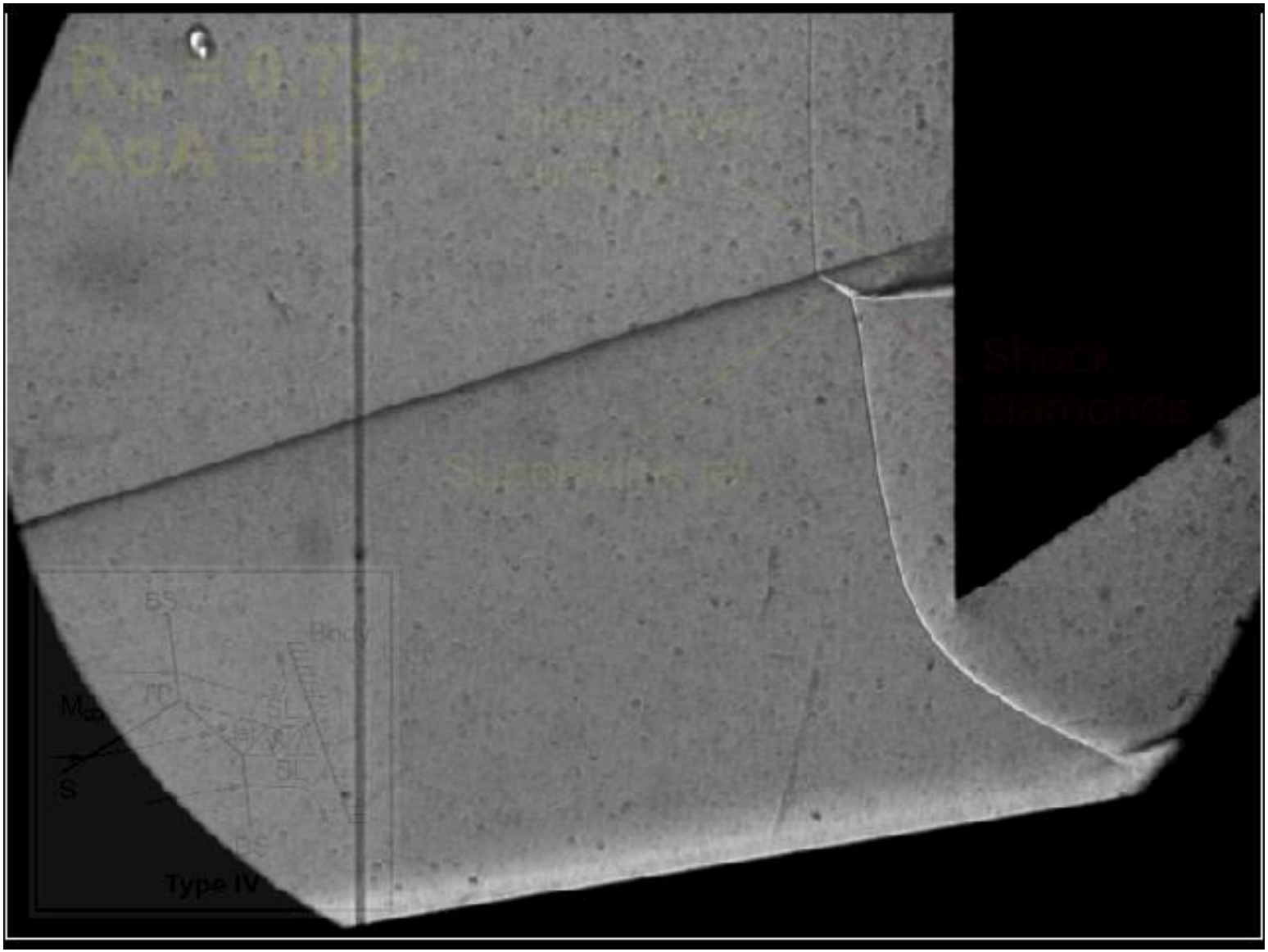


Test Matrix

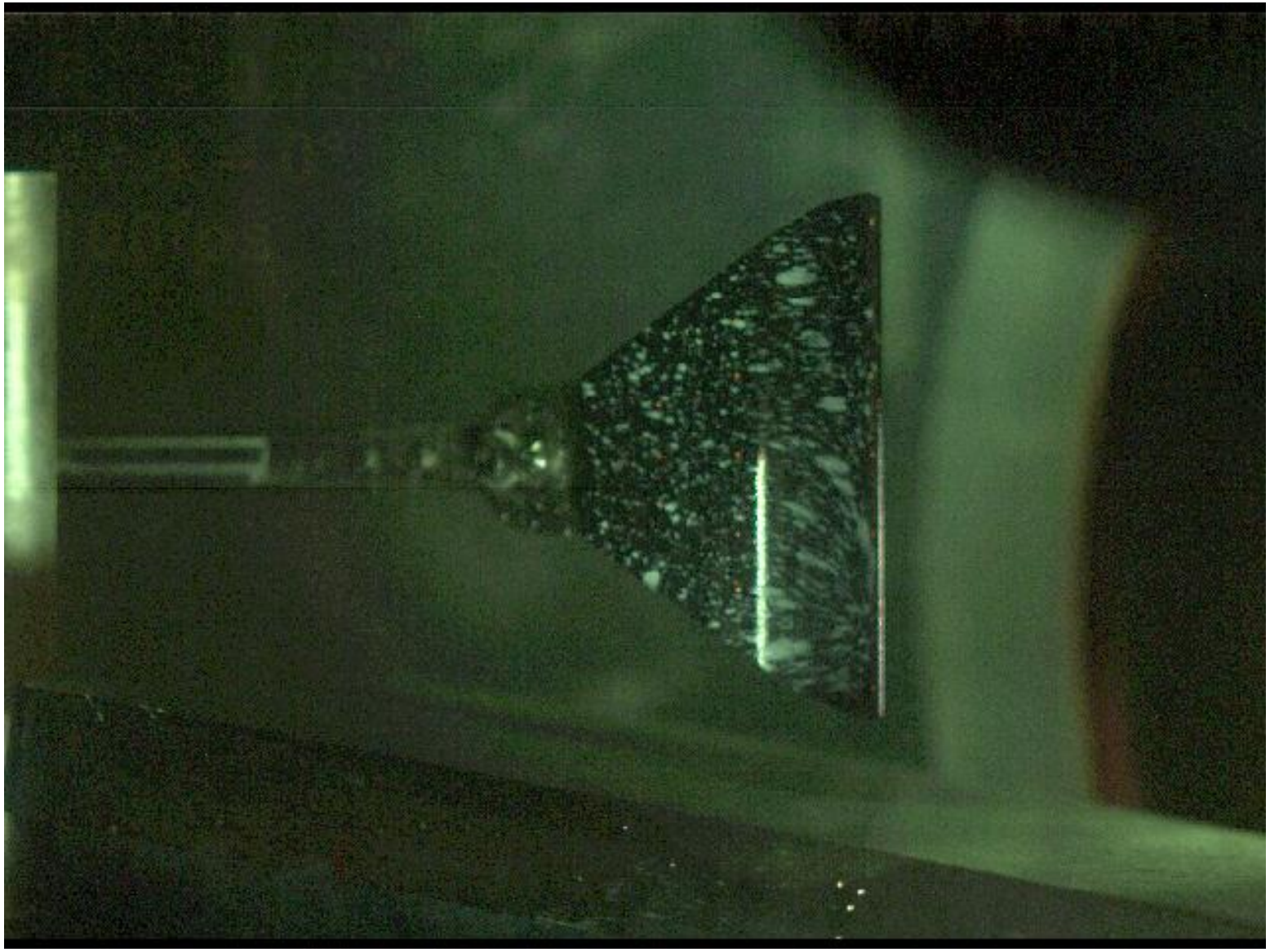
Test Article and Support Hardware Configurations for Test 6976 and Test 6983							
Test	Test Article			S.G. Angle	Type of Data Acquired		Re #, ft^{-1} x10^{-6}
	Type	Nose Diameter	AoA		Schlieren	Other	
6976	Macor®, Upilex®	0.5"	0°	6°, 9°	30 fps	Thin film	2.1
6983-1	Metal	0.5”, 1.0”, 1.5”	-15°	9°	1000-1600 fps	Oil flow	2.1
6983-2	Fused Silica	0.5”, 1.0”, 1.5”	-25°	9°	7900-28000 fps	Phosphor	1.1, 2.1, 4.1

Averaged Flow Conditions for 20-Inch Mach 6 Air Tunnel							
Test	M_∞	$P_{t,1}$, psia	$T_{t,1}$, °R	Re_∞, ft^{-1} x10^{-6}	ρ_∞, 10^{-4}slug/ft^3	T_∞, °R	V_∞, ft/s
6983	5.90	60.5	875.1	1.1	0.33	110.3	3035
6976	5.96	126.4	894.7	2.1	0.64	110.7	3073
6983	5.96	125.5	898.5	2.1	0.63	111.3	3082
	6.00	252.2	901.6	4.1	1.23	110.5	3087

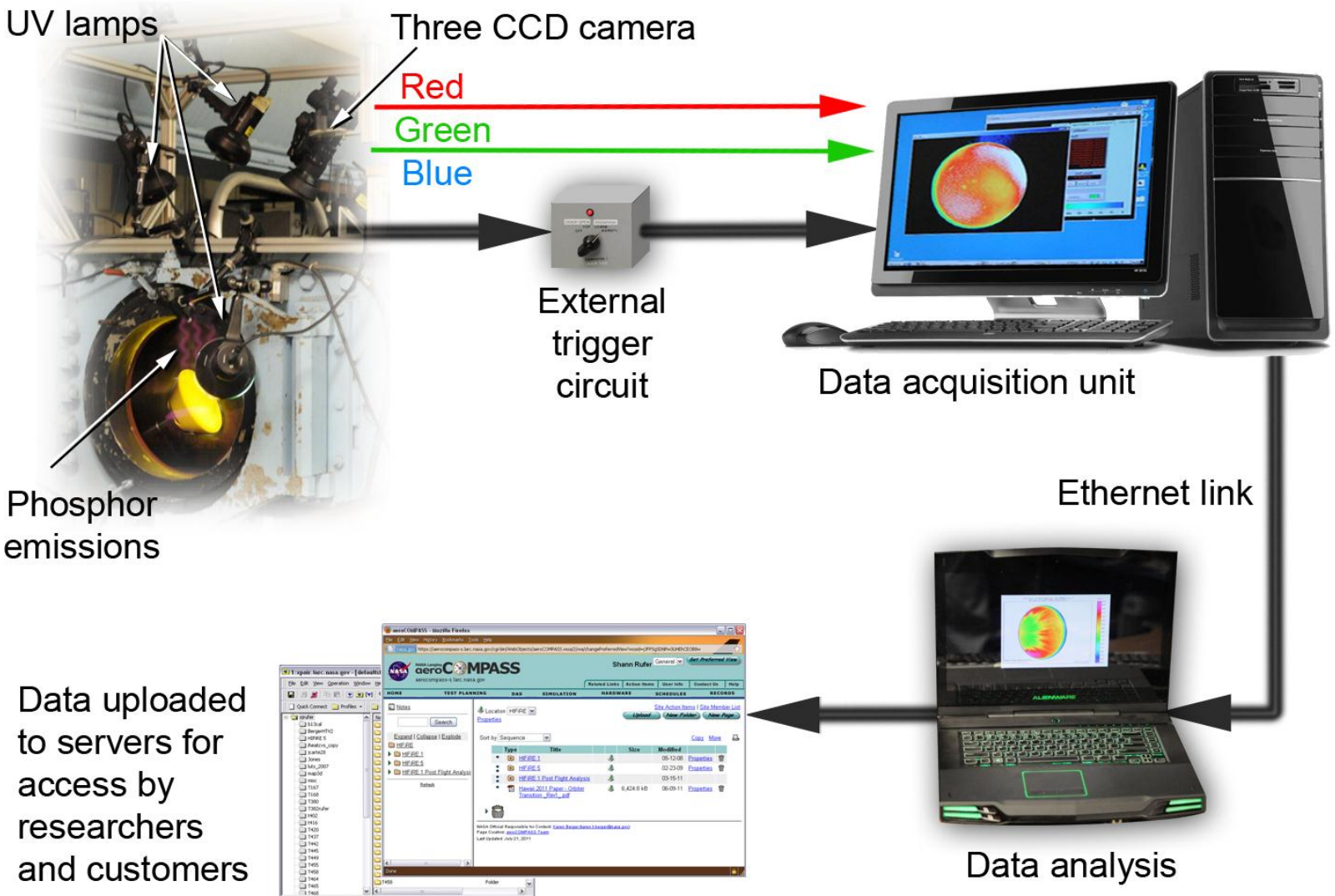
Experimental Zoom Schlieren



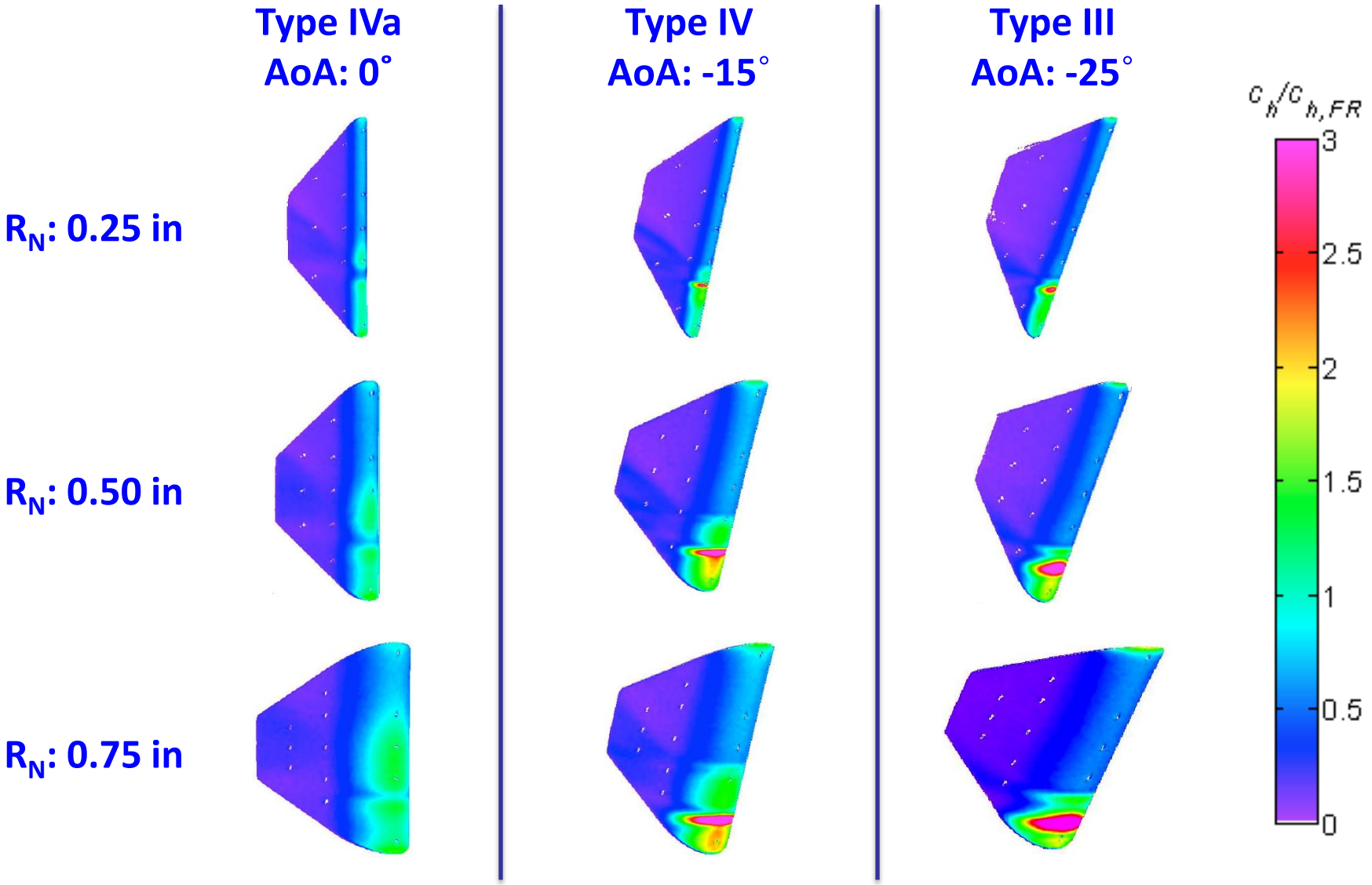
Oil Flow Tests



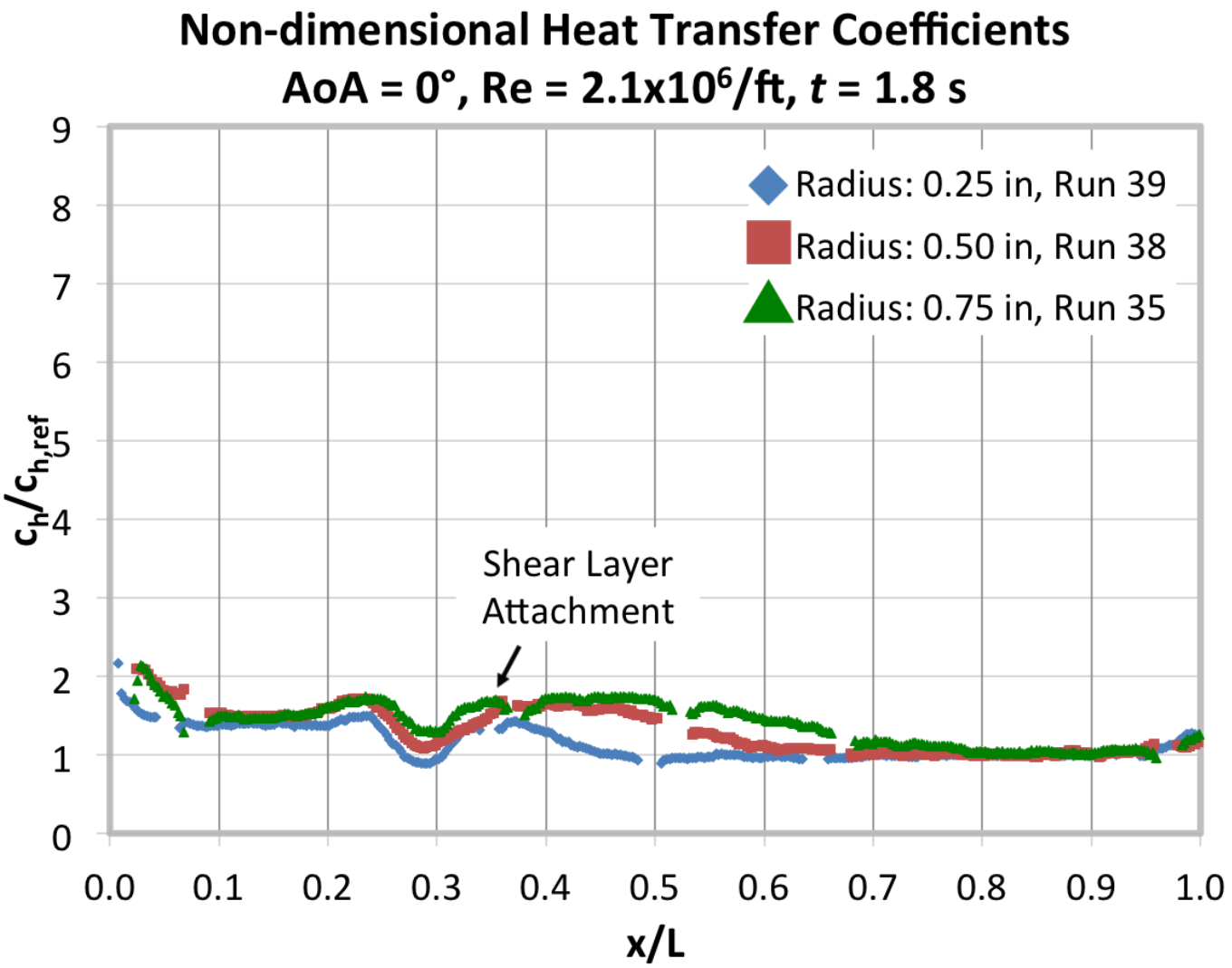
Phosphor Thermography



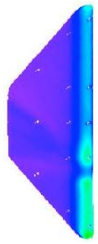
1D Global Heating Contour Maps



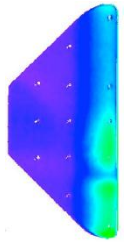
Heat Transfer Data



Type IVa
AoA: 0°



Run 39



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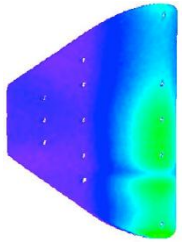
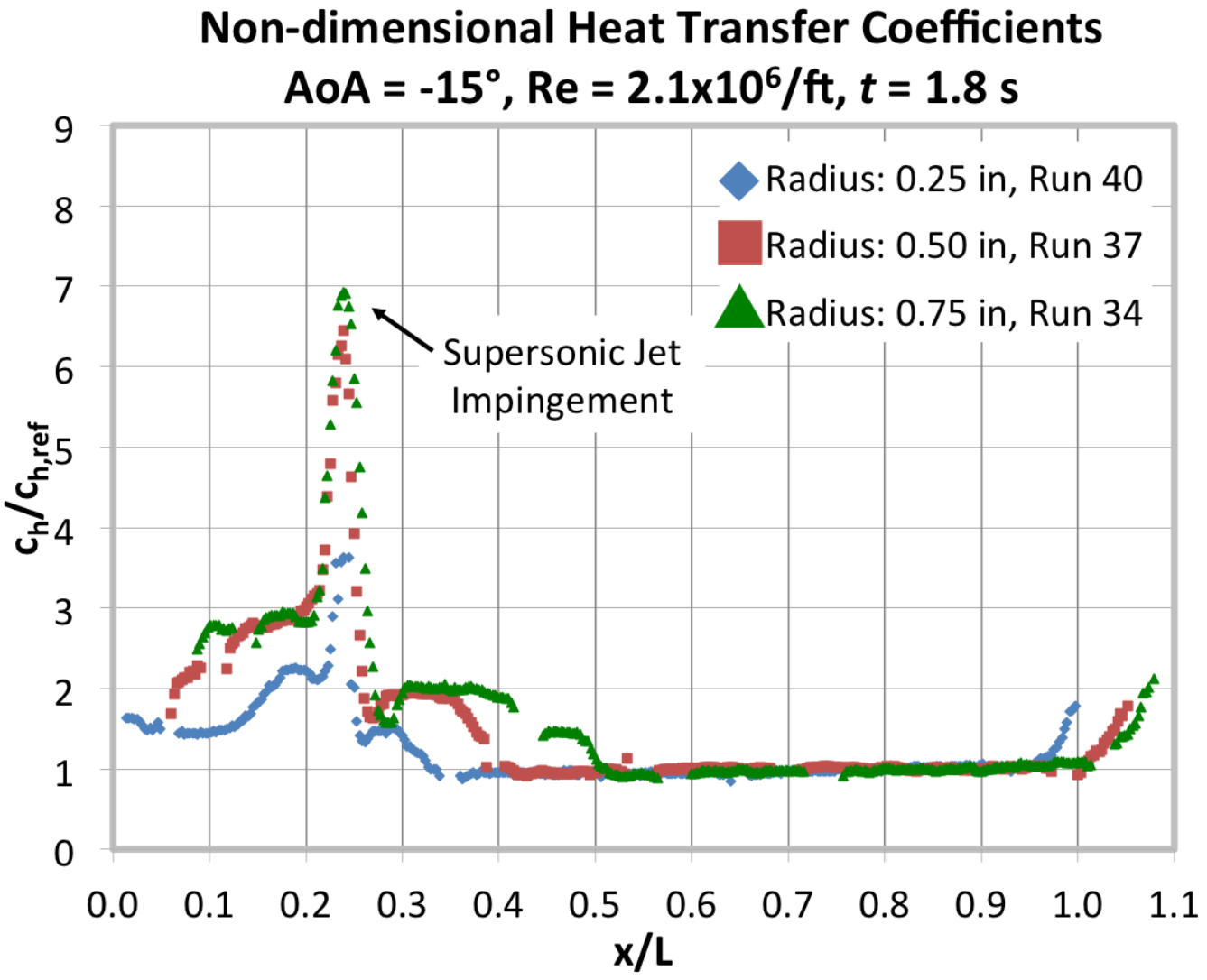


Run 35

Heat Transfer Data



Type IV
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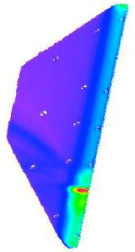

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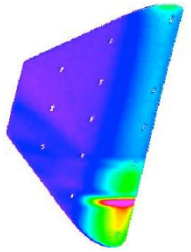

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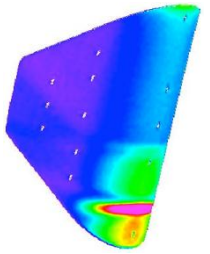

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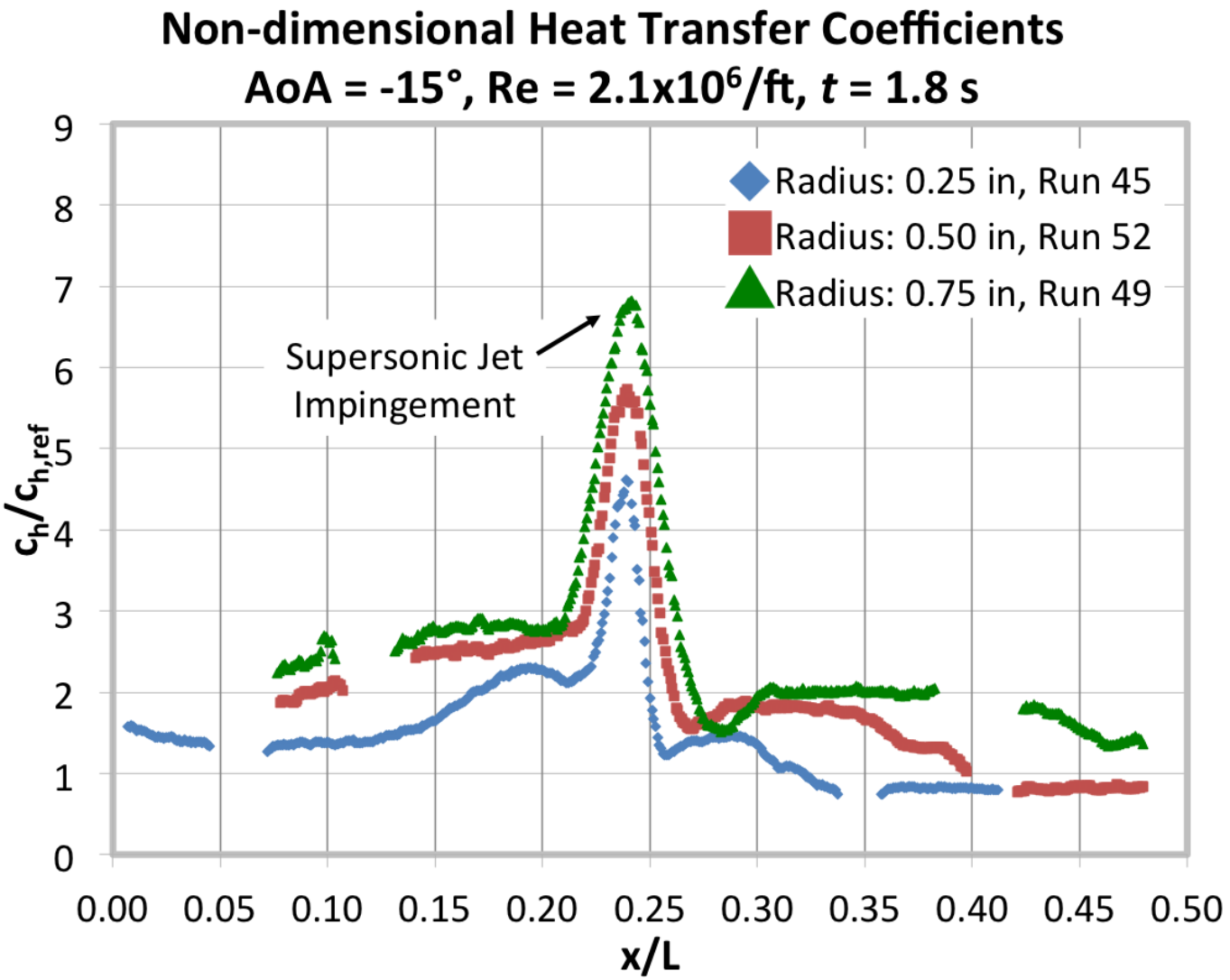
Heat Transfer Data



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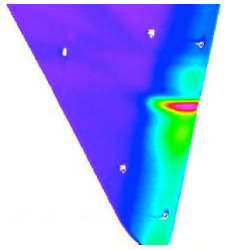

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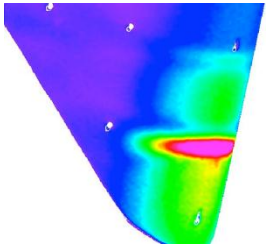

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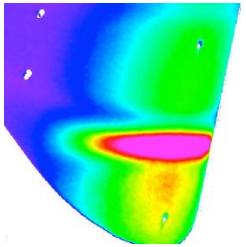

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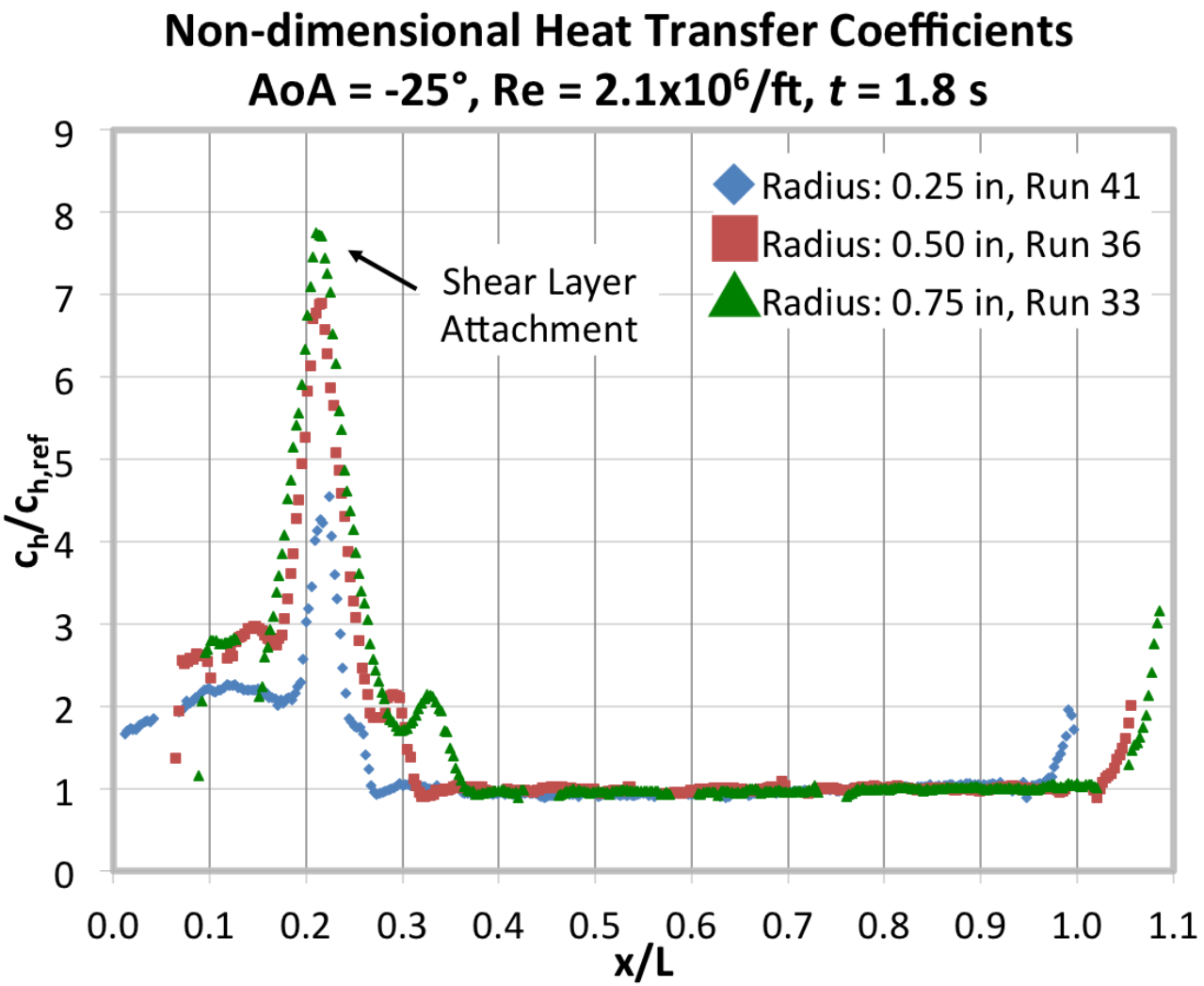

Type III
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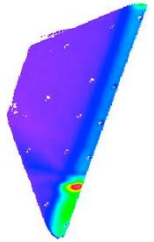

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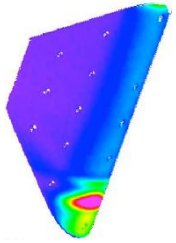

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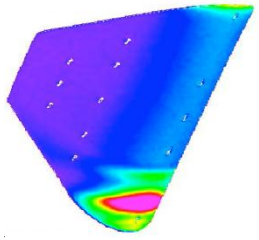

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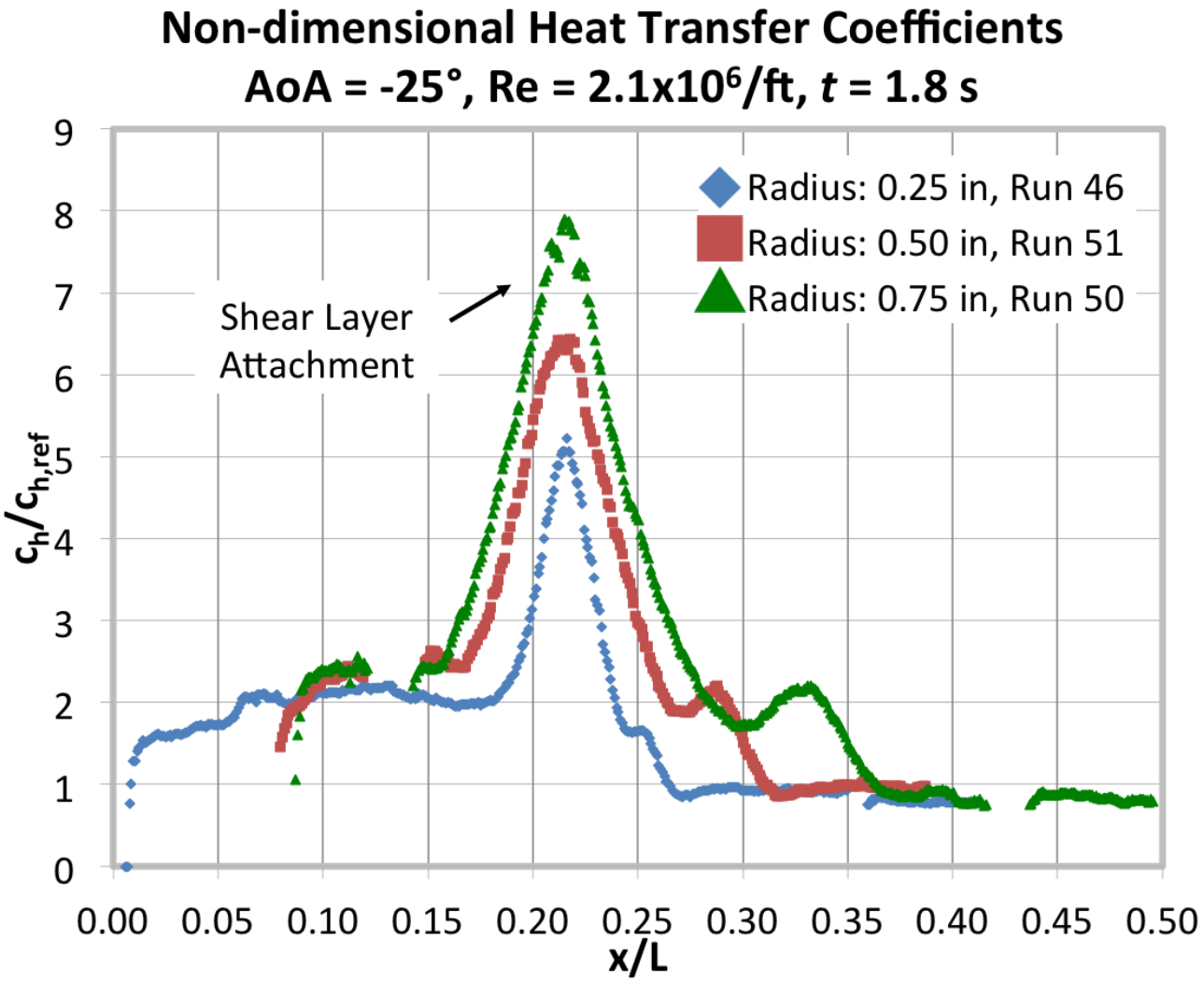

Type III
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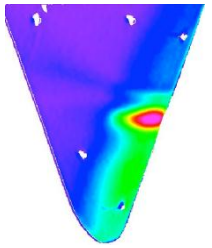

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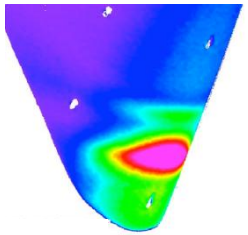

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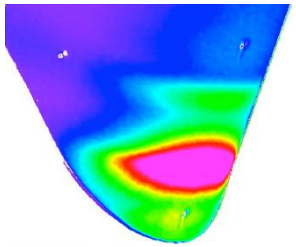
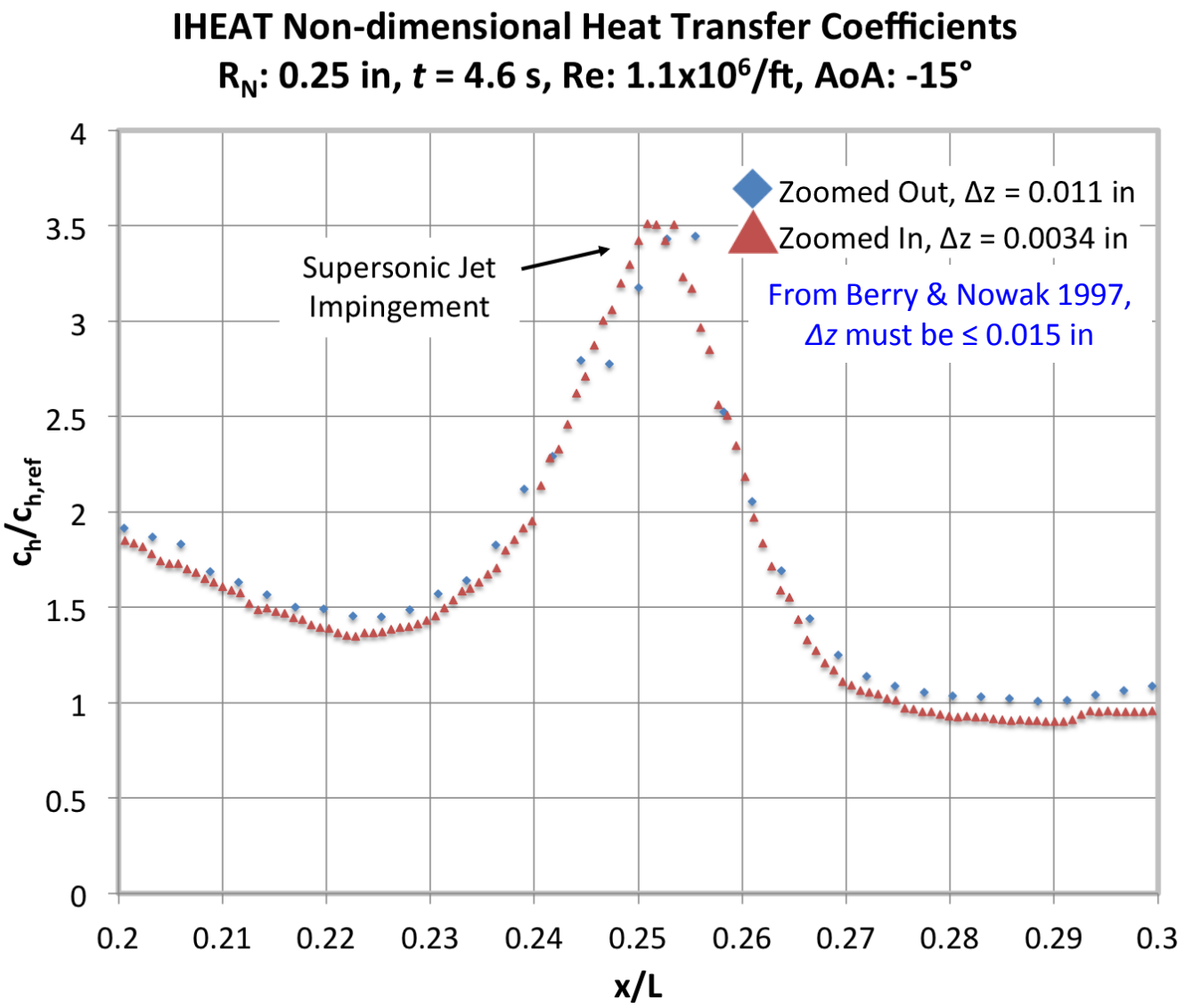


Run 50

Spatial Resolution



Type IV
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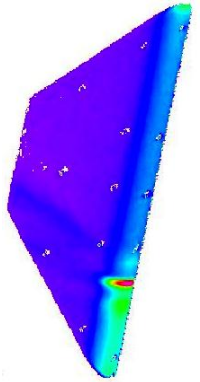

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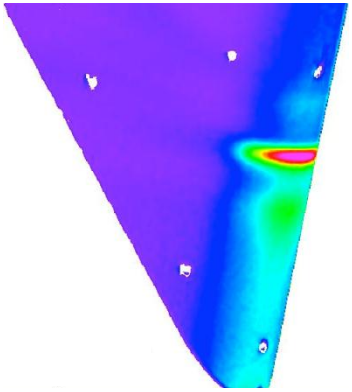


Run 44

Heat Transfer Analyses

1D IHEAT Code:

- Semi-infinite conduction
- Convection boundary condition (BC)

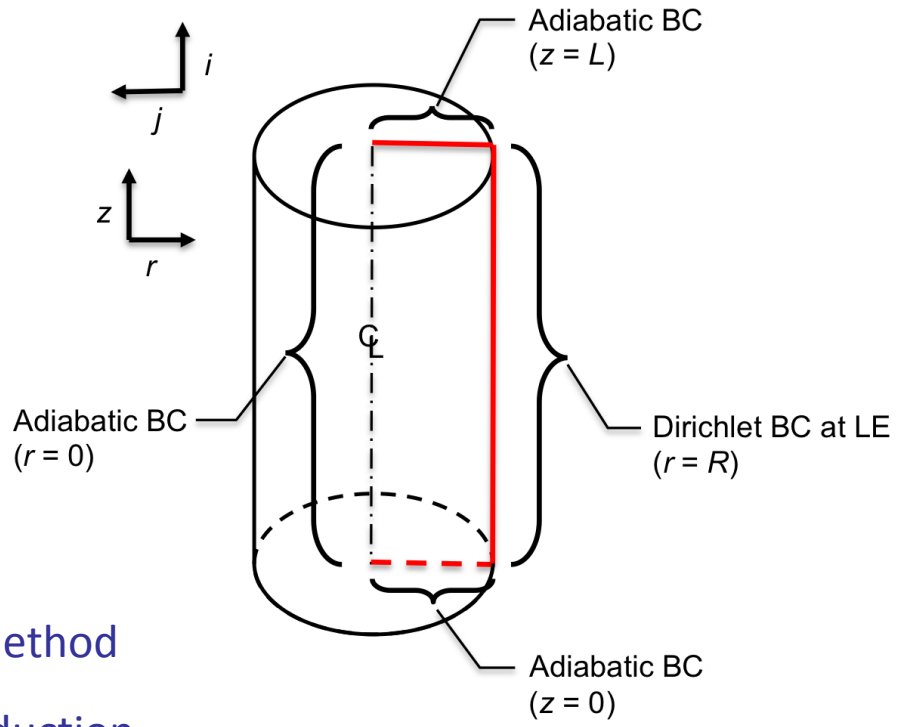
1D Finite-Volume Code:

- Direct Crank-Nicolson method
- Neglects curvature, radial conduction only
- Unconditionally stable, grid converged

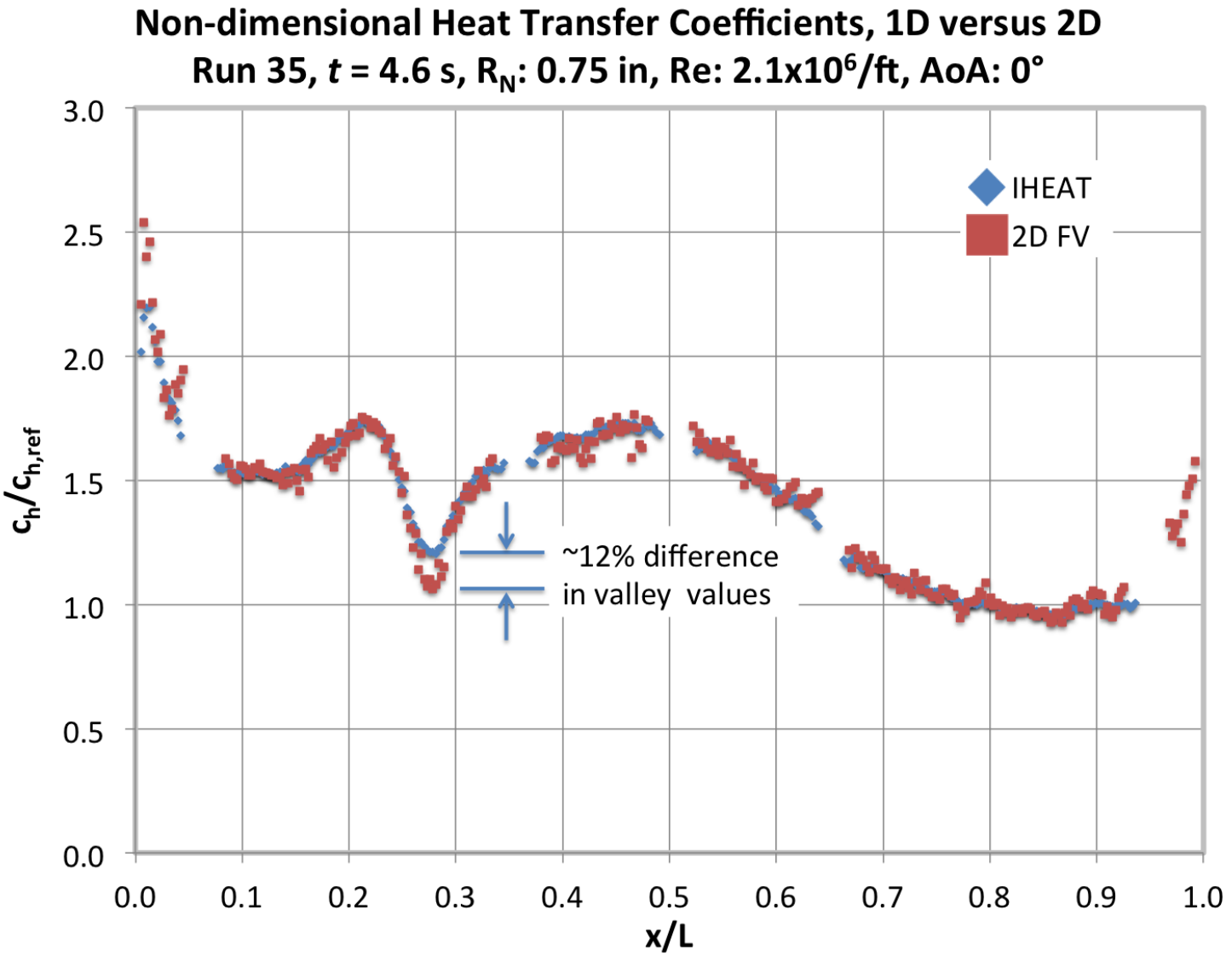
2D Finite-Volume Code:

- Direct Alternating Direction Implicit (ADI) method
- Cylindrical geometry, radial and lateral conduction
- Unconditionally stable, grid converged

Boundary conditions for finite-volume codes



1D versus 2D Heat Transfer



Type IVa
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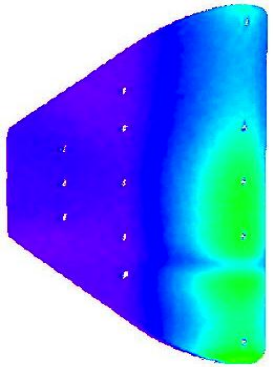
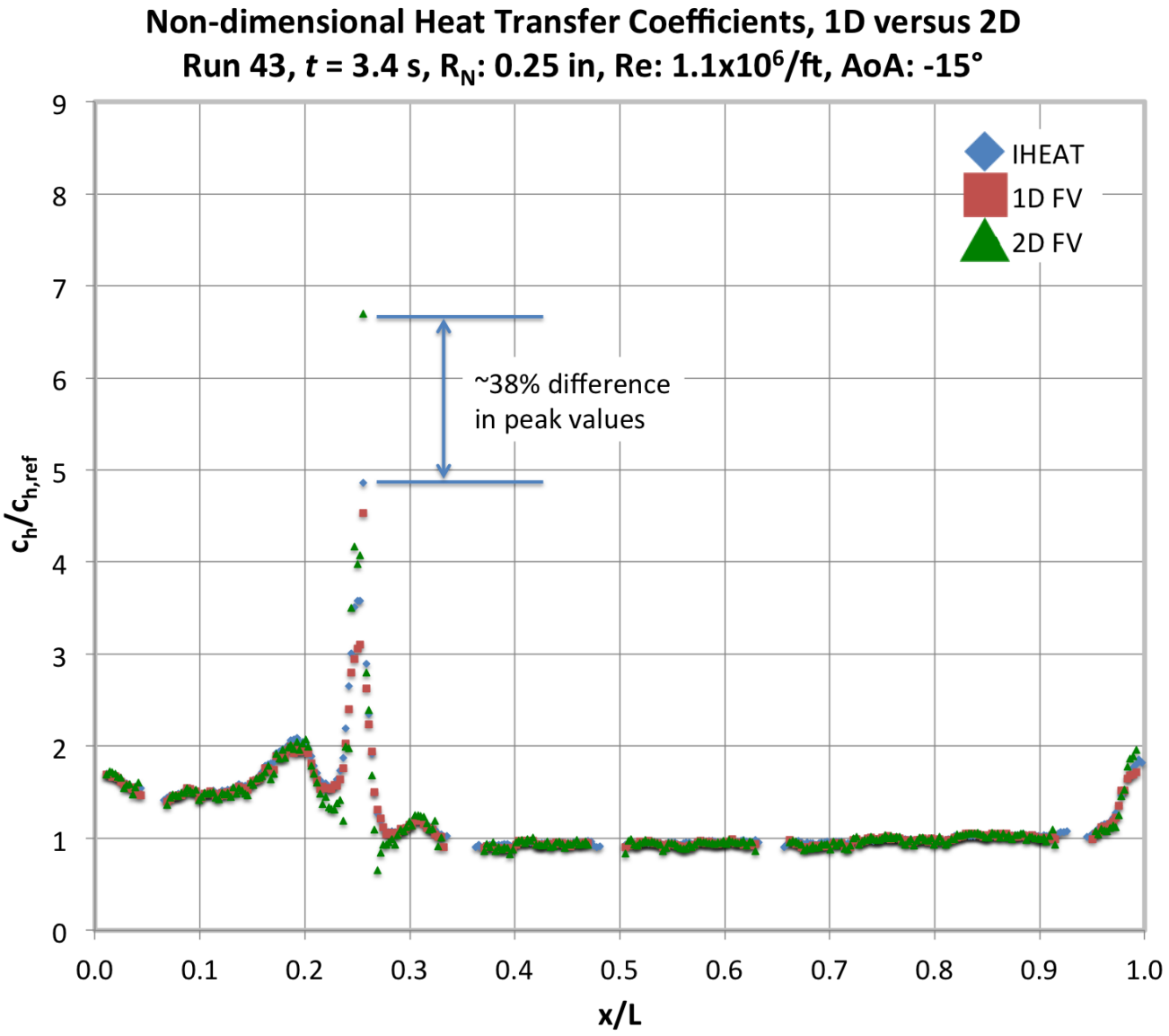
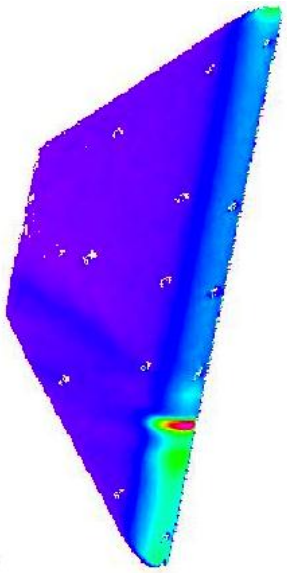


Run 35

1D versus 2D Heat Transfer

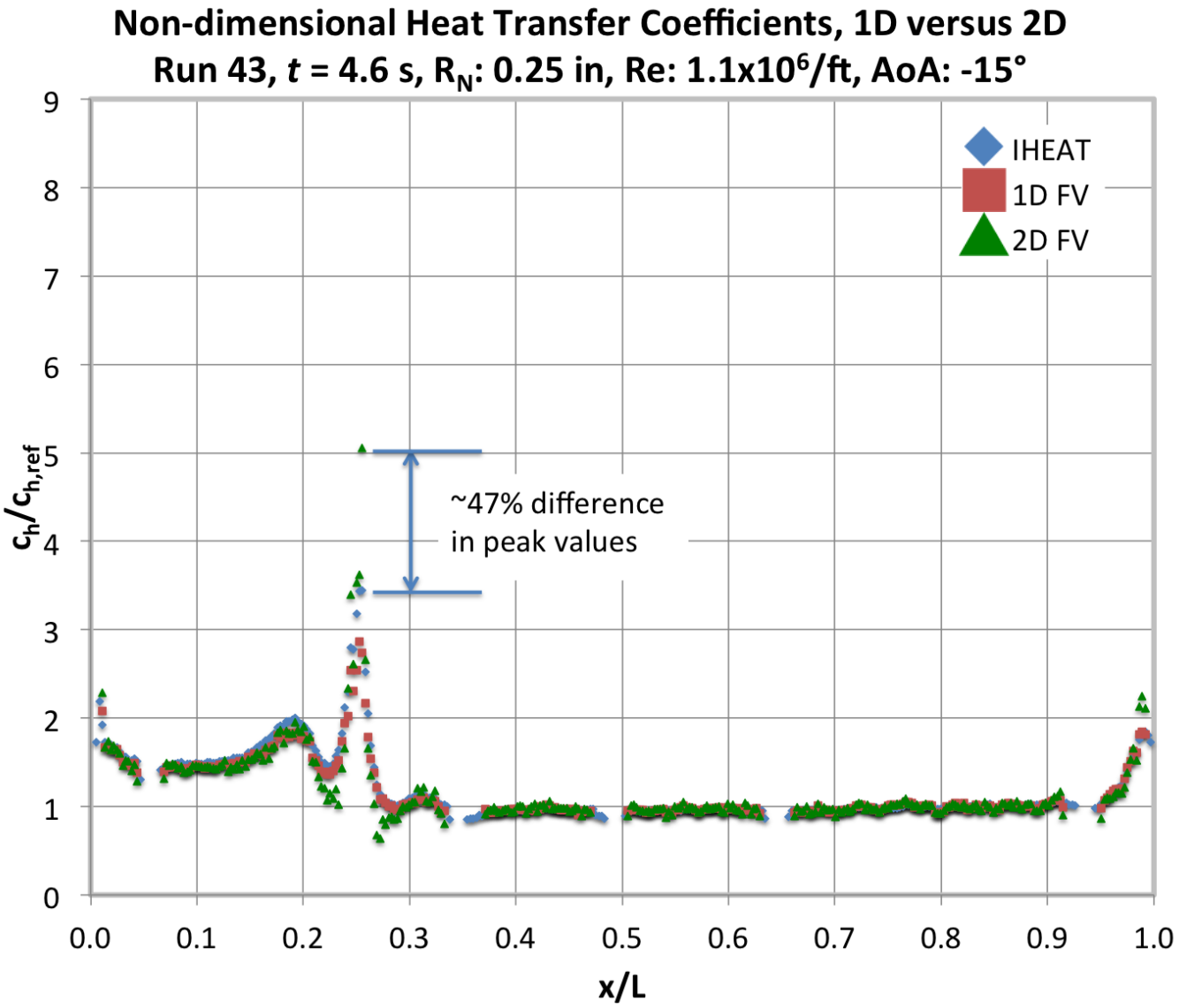


Type IV
AoA: -15°

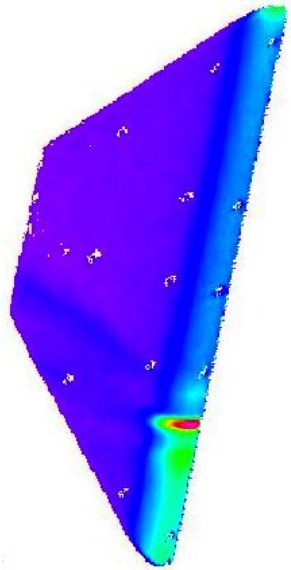


Run 43

1D versus 2D Heat Transfer



Type IV
AoA: -15°

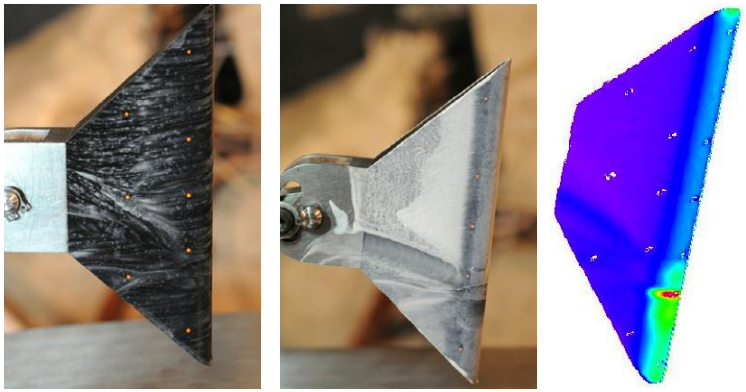


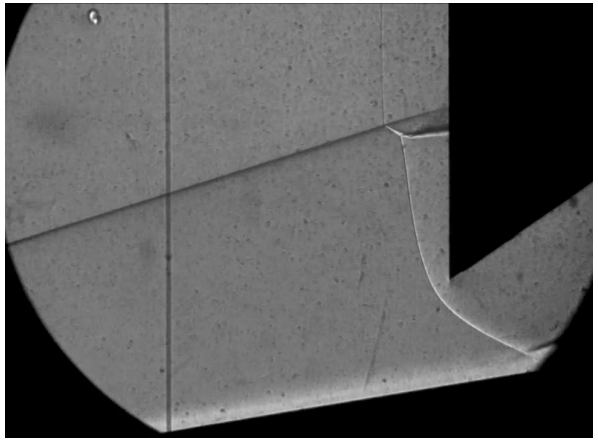
Run 43

Conclusions

- Of the cases considered, the smallest leading-edge radius produced the worst case dimensional peak heat transfer augmentation
  - Type III interaction for AoA = -25˚
  - Type IV interaction for AoA = -15˚
- All the shock-shock interaction cases behave similarly for the three test article geometries
- Oil flow and zoom schlieren results show the main effects of shock-shock interactions are confined to specific regions on the test article
- Multi-dimensional heat transfer analyses that account for lateral conduction are required if sharp temperature gradients exist
- A spatial resolution of 0.015 in is sufficient to capture the peak heat transfer due to a Type III or Type IV shock-shock interaction

First global thermal imaging study to improve the understanding of 3D shock-on-strut interactions





Thank you! Questions?

Back-up Slides

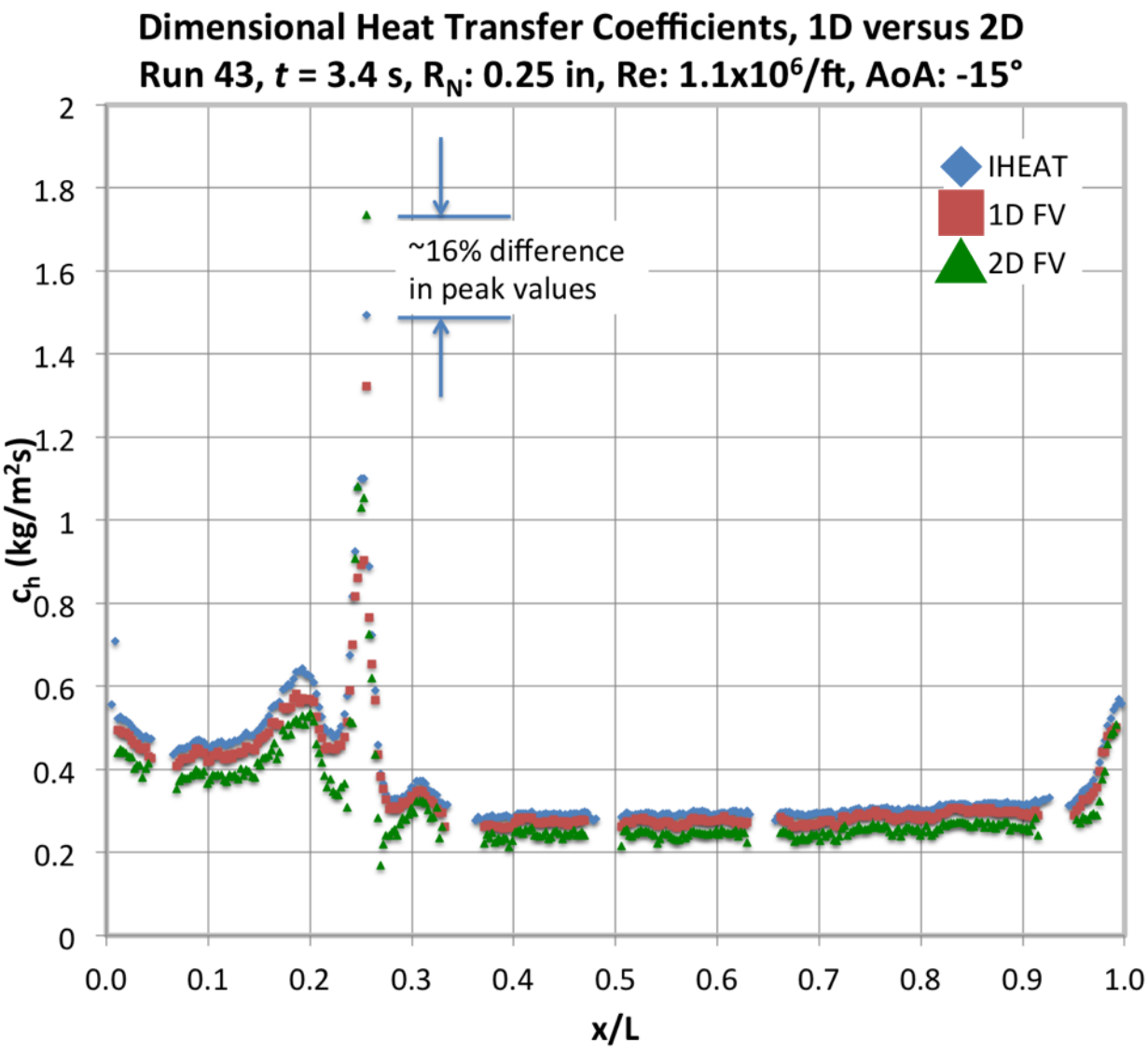
Future Work

- Obtain global temperature data later in wind tunnel runs with similar test articles and either
  - A higher temperature phosphor system
  - An IR system (with at least 640x480 resolution)
- Improve the 2D FV code
  - Include additional geometries
  - Finish debugging the Douglas-Gunn method
- Develop a 3D Douglas-Gunn FV code to use in IHEAT
  - Implement a 3D mapping algorithm to correlate the temperature data in the 2D image to the 3D CAD geometry of the test article
  - Test the 3D code using the shock-shock interaction data to compare to the 1D and 2D results

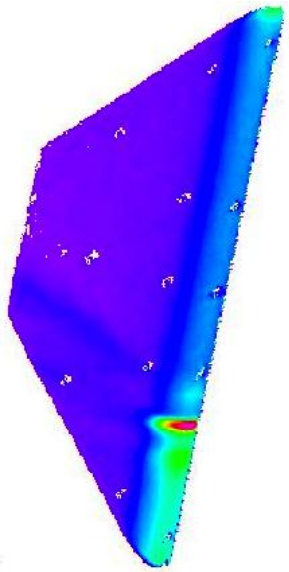
Future Work

- If higher temperature data can be obtained, consider the following additional cases
  - Higher Reynolds numbers (4 x10^6/ft, 8 x10^6/ft) using high-speed zoom schlieren to capture the unsteady flow features
  - Consider the effects of using a 12° SG angle
  - Test at the 31-Inch Mach 10 tunnel where the test articles heat up even more quickly so a 2D analysis may be more critical
  - Move the fins down closer to the shock generator plate to investigate the effects of shock-BL interactions in addition to the characterized shock-shock interactions
- Compare the 1D and 2D results for a zoomed-in case, properly converting the results to non-dimensional data

Heat Transfer Data

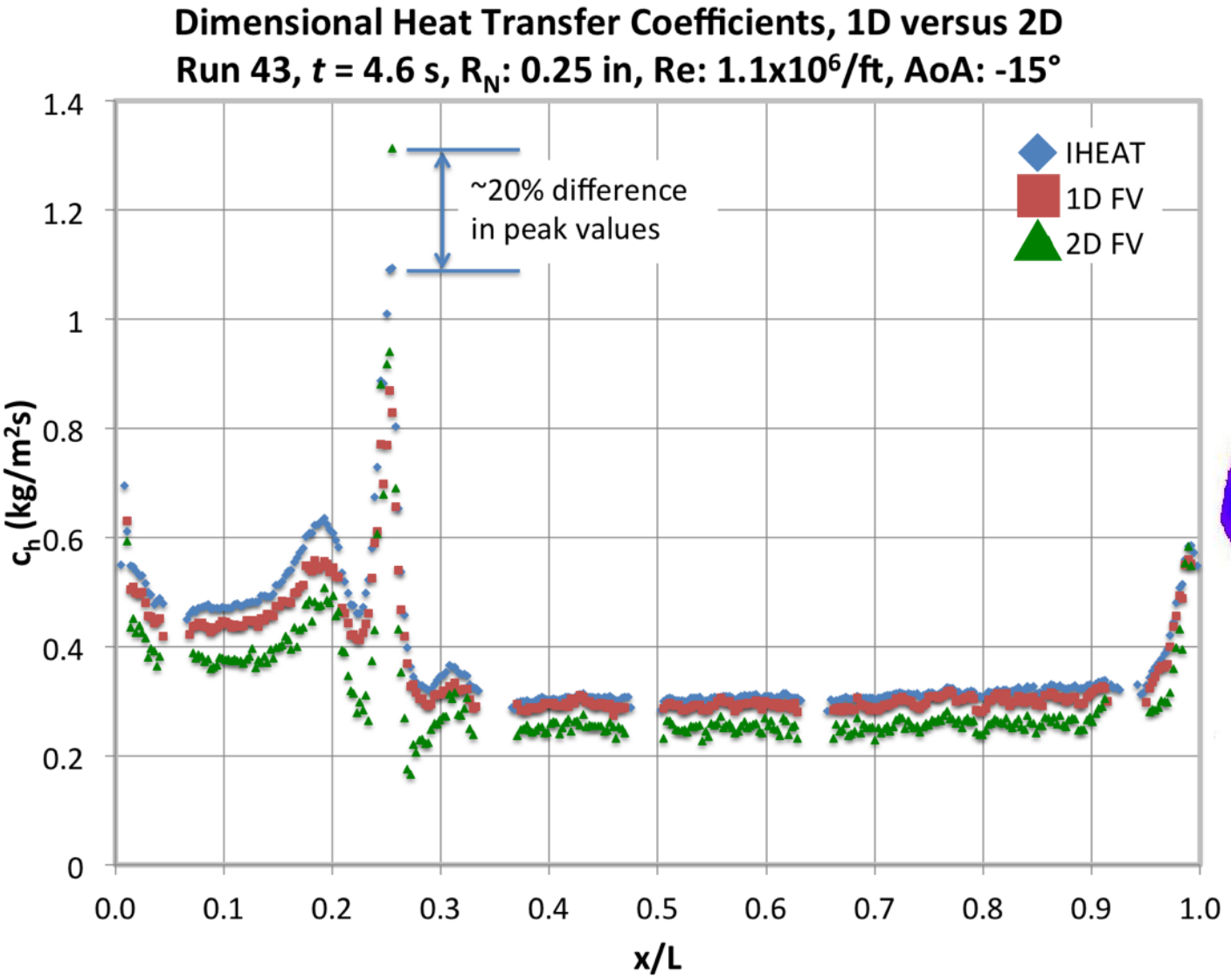


Type IV

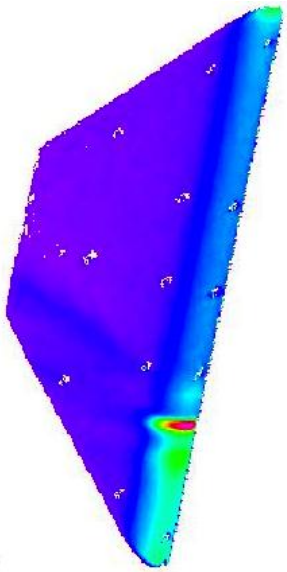


Run 43

Heat Transfer Data



Type IV



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