Direct Skin Friction Measurements in High-Speed Flow Environments

International Test and Evaluation Association (ITEA)
22nd Test and Training Instrumentation Workshop
15-17 May 2018 – Las Vegas, Nevada

Veteran-Owned Small Business (VOSB)
400 Sugar Camp Circle, Suite 302
Dayton, OH 45409
www.AhmicAero.com

Ryan J. Meritt, *Ph.D.*
President, Ahmic Aerospace LLC
Email: ryan@AhmicAero.com
Phone: 937-272-5880

Application of Skin Friction Sensors

PERFORMANCE

- Direct measure of vehicle's energy efficiency
  - range/speed/payload/maneuverability
- Design tool
  - reduce performance uncertainties
  - flight analysis & optimization

VALIDATION

- Establish an experimental database
  - challenge CFD standards
  - essential for correlating techniques

CONTROL

- Input device for flow control
  - sensitive, real-time signal
  - provide actuator control authority

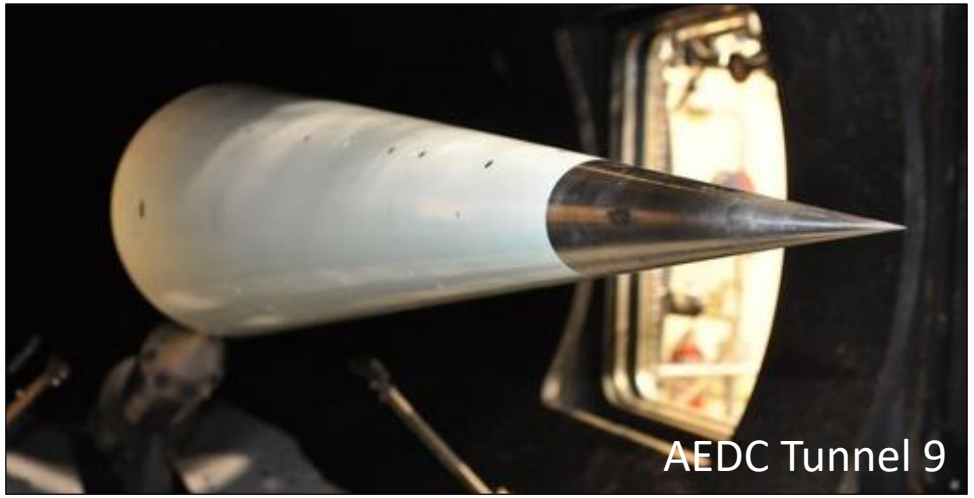
HTV-3X Blackswift

X-51A WaveRider

Overview

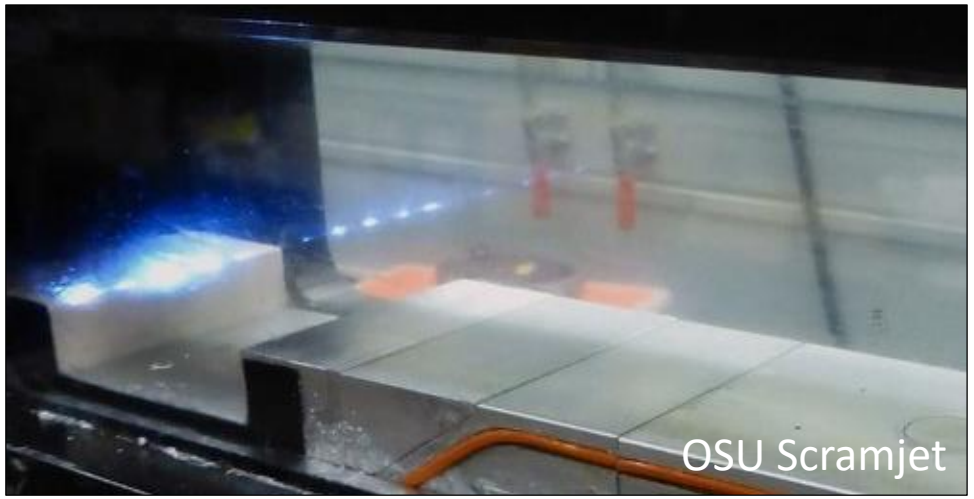
1) Hypervelocity Re-Entry Vehicle

- AEDC Tunnel 9 and CUBRC LENS I
- Two-Component (2D) skin friction sensor
- Measurements along a 3D curved Surface
- Measure upwash angle (ϵ)
- Detect boundary layer transition (BLT)



2) Scramjet Engine Testing

- OSU ARC and AFRL RC-18, -19, -22
- Detect boundary layer separation
- Measure reverse flow
- Detect & measure shock patterns

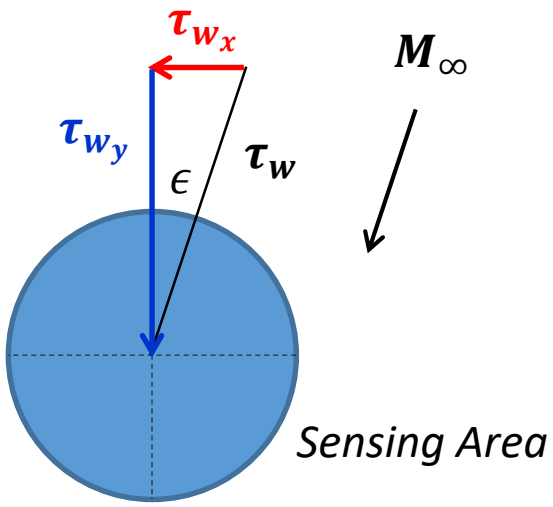


AEDC Tunnel 9

Program Objectives

1) Measure wall shear (τ_w) & skin friction (C_f)
2) Detect boundary layer transition (BLT)
3) Measure upwash angle (ϵ)

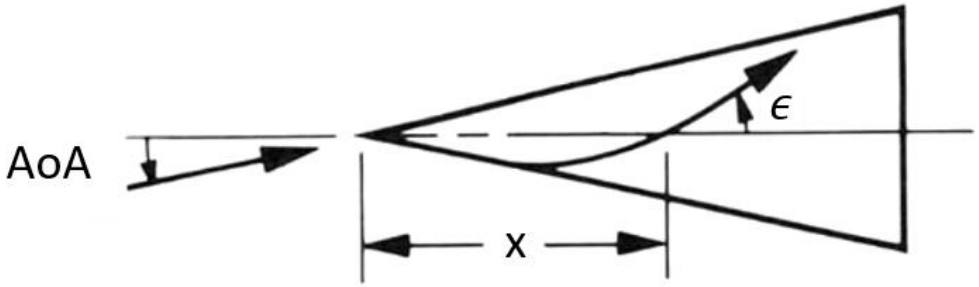
- Demonstrate new two-component (2D) skin friction sensor
- Perform at Mach 14, on pitching cone model (20 deg/s)
- Comparative CFD estimations



Two-Component Wall Shear (τ_w)

Relevant Programs

- AEDC Tunnel 9 (2014):
  - Mach 10
  - 1x 1D C*f* Sensor
- CUBRC LENS I (2017):
  - Mach 10 & 14
  - 3x 2D C*f* Sensors
  - Compare to Tunnel 9



Upwash Angle (ϵ)

AEDC Tunnel 9

Tunnel 9 Facility

- Program: Center of Testing Excellence (CoTE)
- Location: Silver Spring, MD
- Nozzles: Mach 7, 8, 10, and 14
- Unit Re: 0.18 - 159 $\times 10^6$/m (0.05 - 48.4 $\times 10^6$/ft)
- Test Section: 1.52 m (5 ft) diameter, 3.66 m (12 ft) long

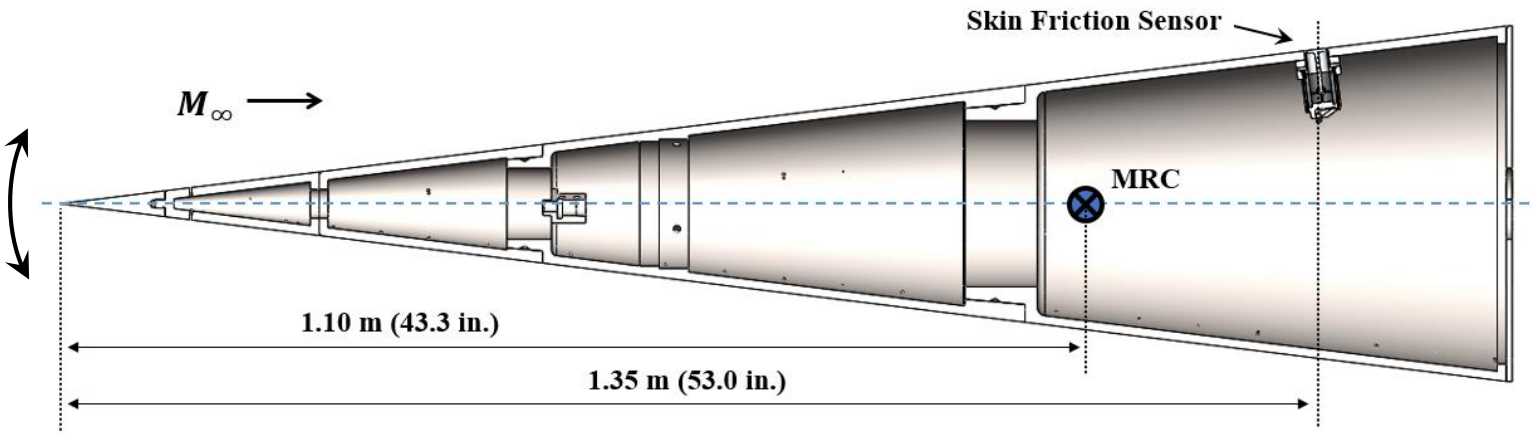
2016 Program Conditions

Test Conditions	Re/m (E6/m)	AoA (deg)	P_0 (MPa)	T_0 (K)	h_0 (MJ/kg)	M_∞ -	P_∞ (Pa)	T_∞ (K)	ρ_∞ (kg/m^3)	U_∞ (m/s)
C1	12.1	0 to 10	124.6	1,685	2.0	14.4	263.1	45.7	1.94E-02	1,974
C2	7.2	0 to 10	72.7	1,697	2.0	14.0	174.1	47.8	1.23E-02	1,984
C3	3.6	0 to 10	30.2	1,567	1.8	13.6	82.0	45.1	6.12E-03	1,990
C4	2.6	0 to 10	20.7	1,551	1.8	13.5	58.9	45.2	4.39E-03	1,972
C5	1.7	0	14.2	1,603	1.8	13.3	81.4	47.9	5.96E-03	1,867

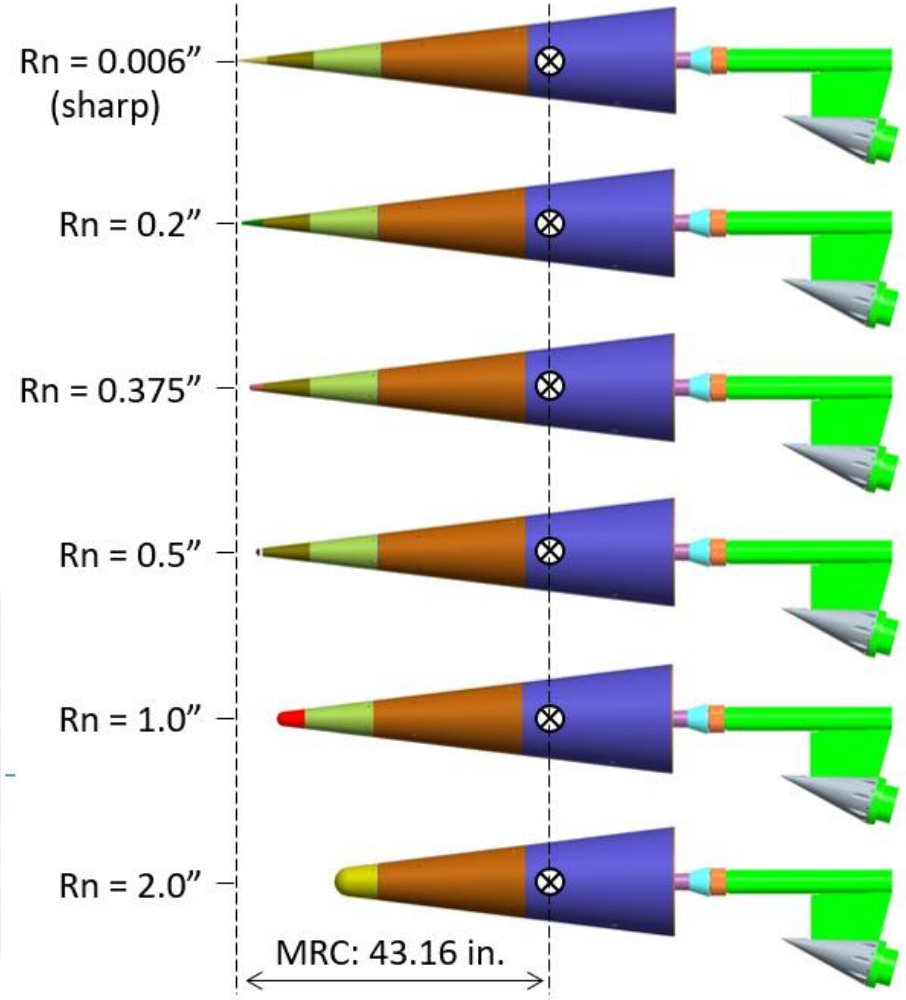
Test Configuration

Cone Specifications

- 7-deg half-angle
- Stainless Steel (15-5 PH)
- Cone length = 155.6 cm (61.27 in.)
- Moment reference center (MRC) @ x = 43.3 in.
- Skin friction sensors @ x = 53.0 in.
- Only sharp nose-tip cone configuration is discussed

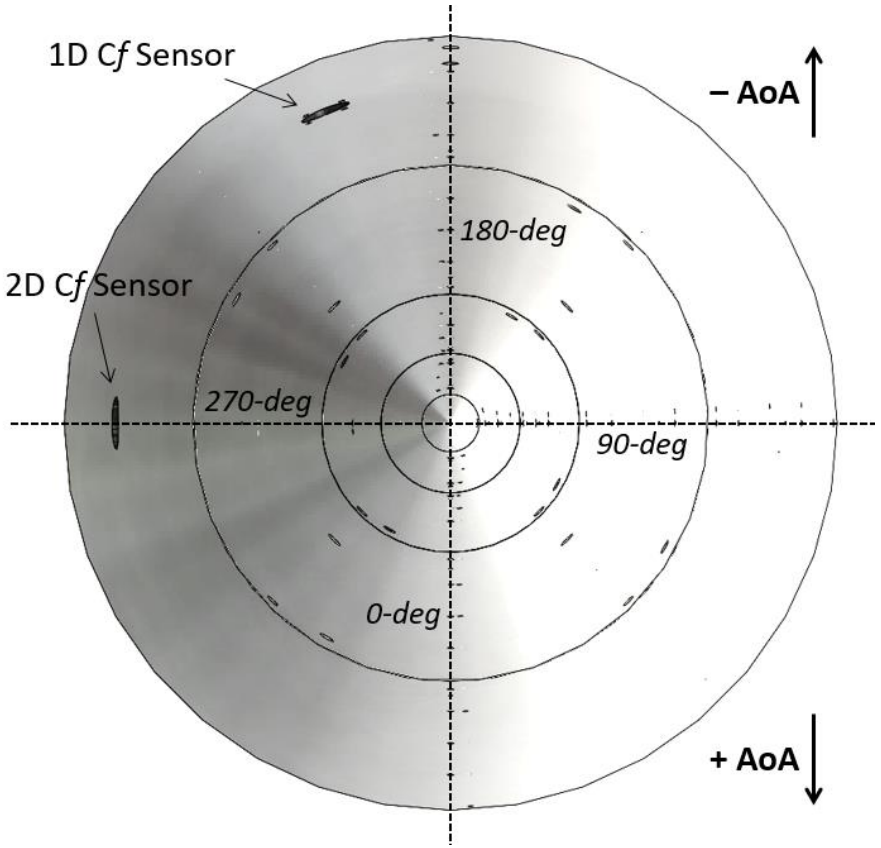


Location of Cf Sensor in Cone Model

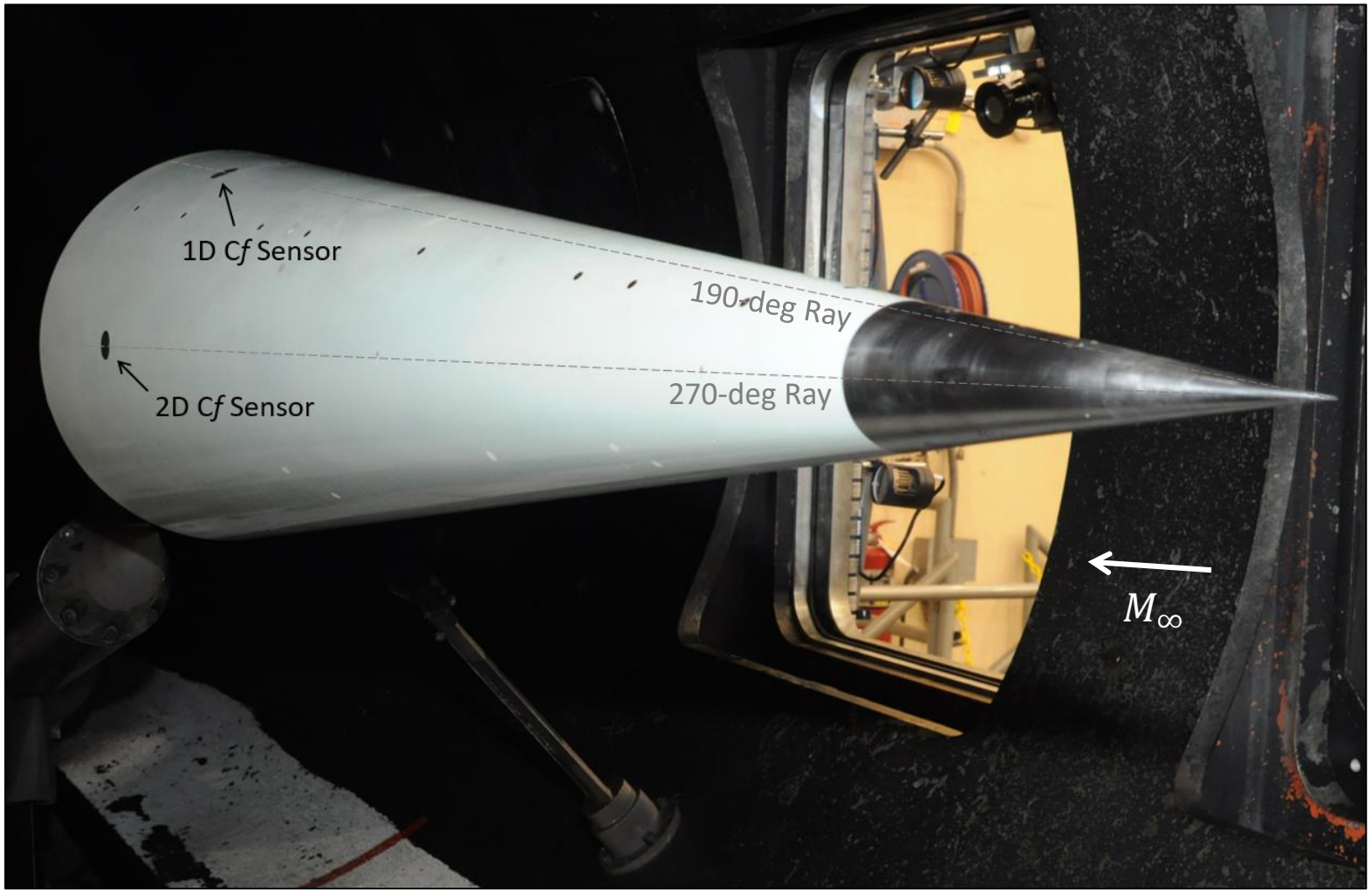


Tunnel 9 Cone Model Configurations

Test Configuration

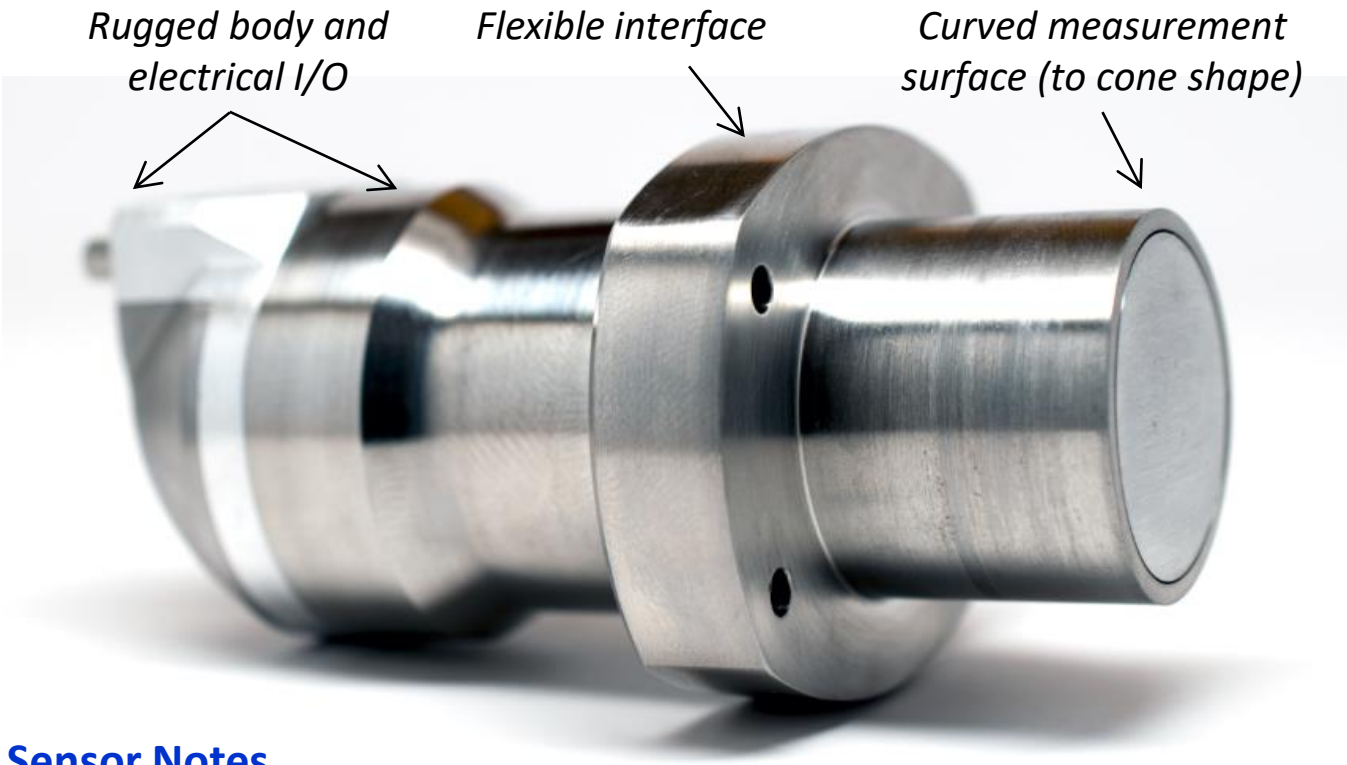


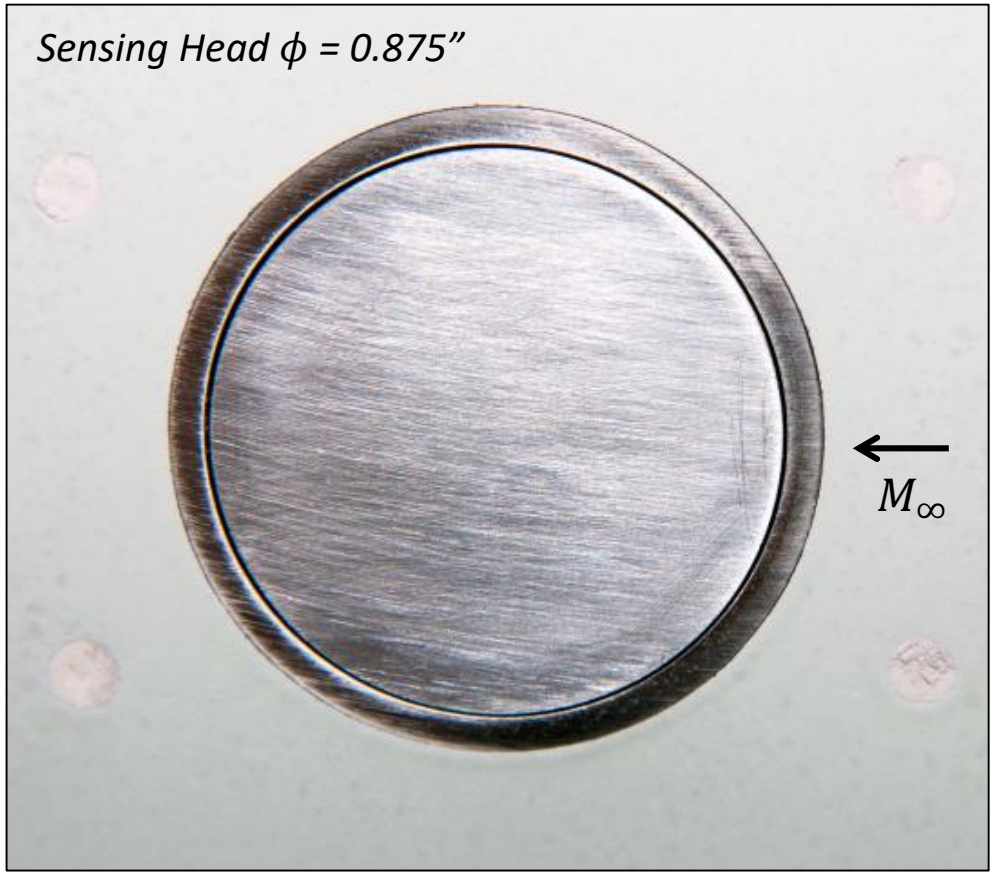
Downstream View of Cone



Photograph of Sharp Nose Cone and Skin Friction Sensors

Skin Friction Sensor



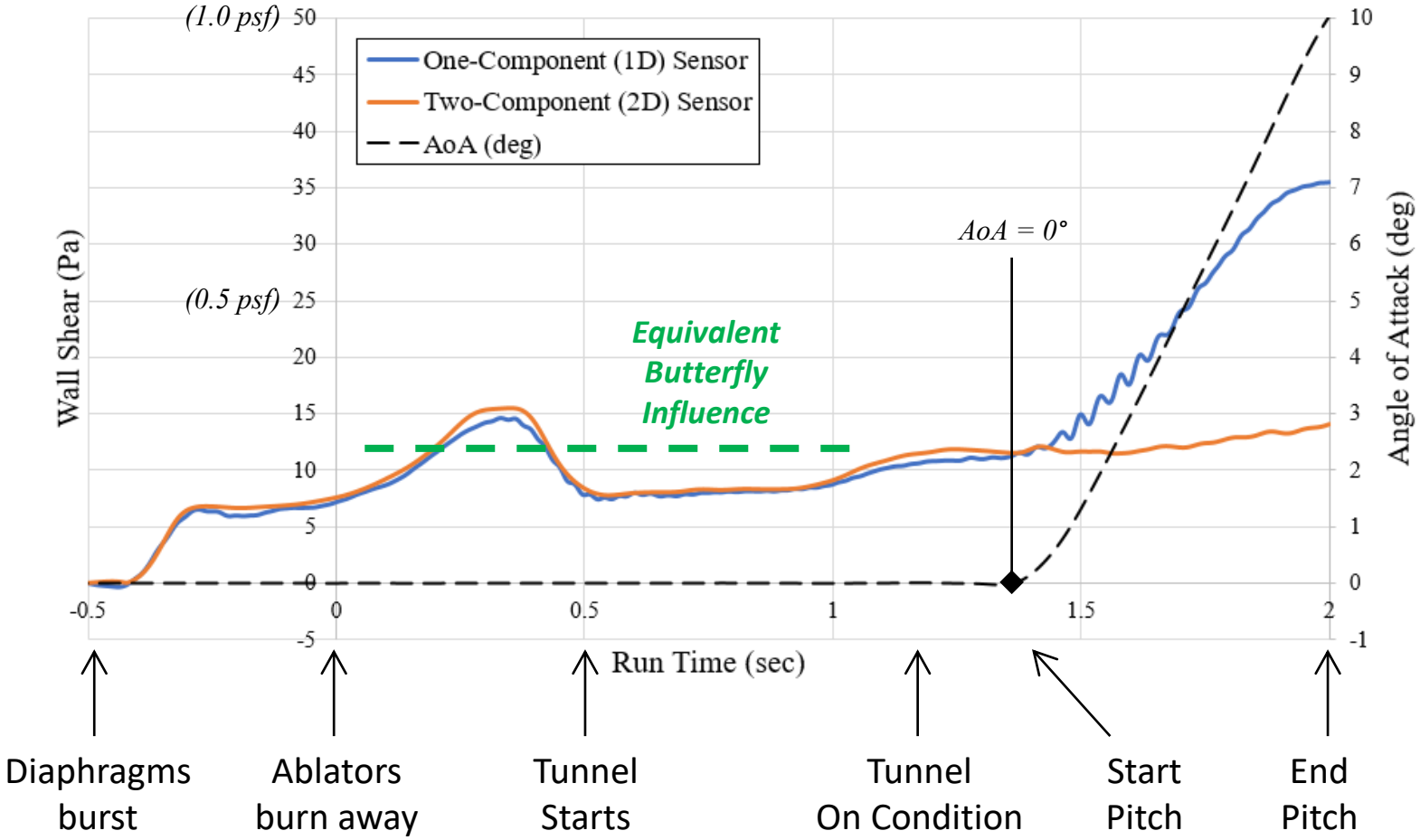


Integrated Sensor in Cone Surface

Sensor Notes

- Increases sensitivity, measurements < 1 Pa (0.02 psf)
- Uncertainty: ±9.7% of the C*f* measurement at U95
- NIST traceable calibrations
- Seamlessly integration into native Tunnel 9 DAQ

Wall Shear Measurements



Standard Test Run – Condition C5

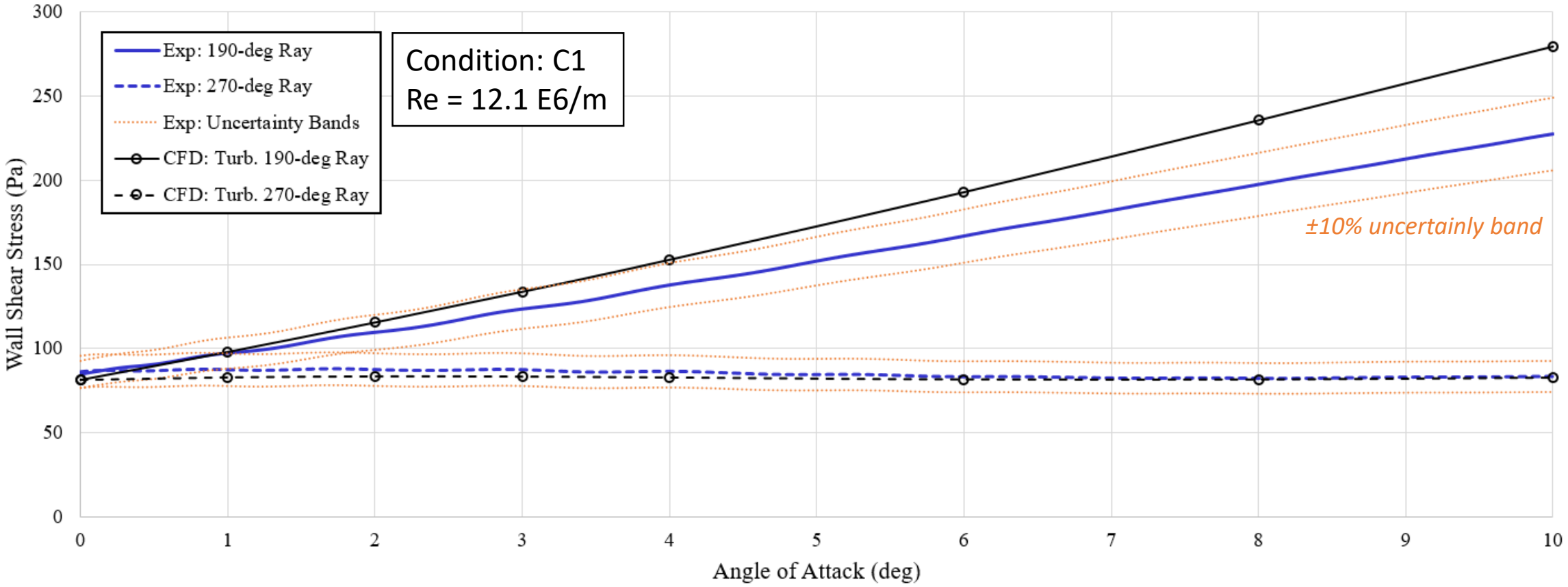
Measurement Sensitivity

Butterfly Mass ≈ 0.5 g (0.018 oz)

Equivalent wall shear ≈ 12.6 Pa (0.26 psf)

for element ϕ = 22.2 mm (0.875 in.)

Wall Shear Measurements



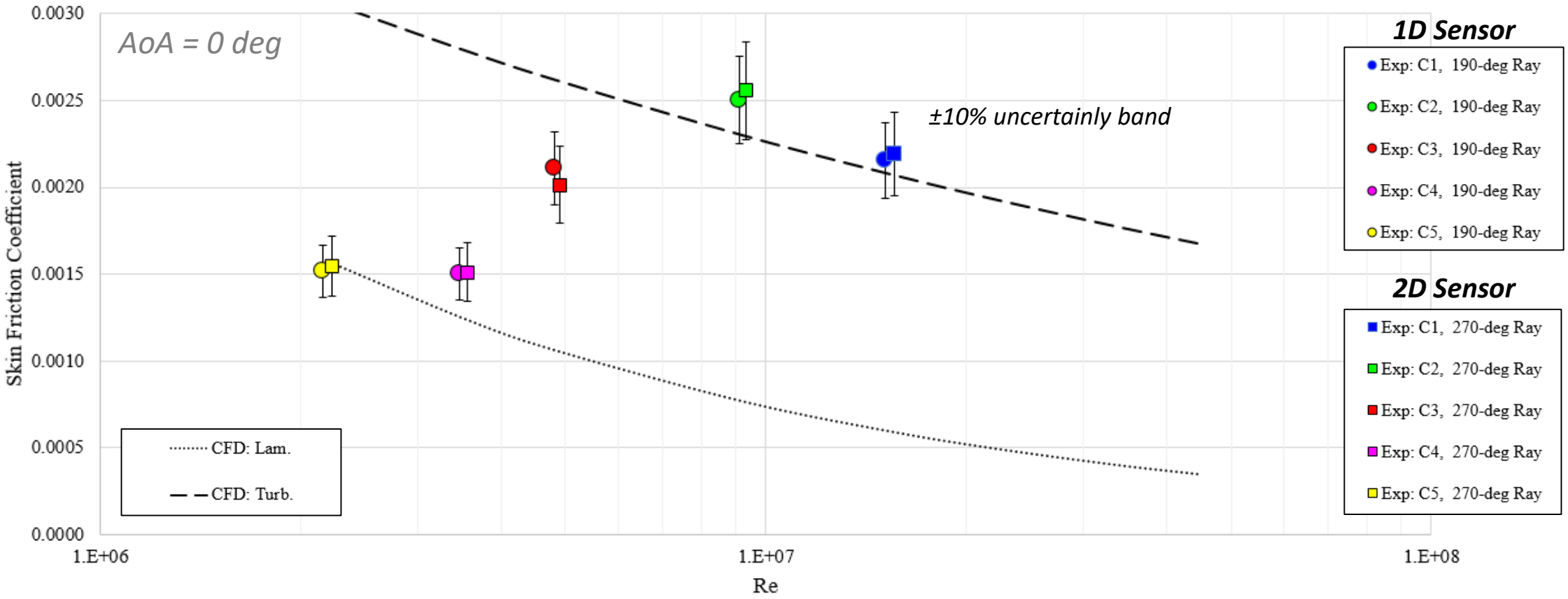
Example Conditions C1

- 1D sensor (190-deg ray) experimental data
- 2D sensor (270-deg ray)) experimental data
- Turbulent CFD predictions

At AoA = 0 deg

- 1D sensor: τ_w = 84.7 Pa (1.77 psf)
- 2D sensor: τ_w = 86.1 Pa (1.80 psf); difference of 1.6%
- CFD: τ_w = 81.3 Pa (1.70 psf), difference of 4-6%

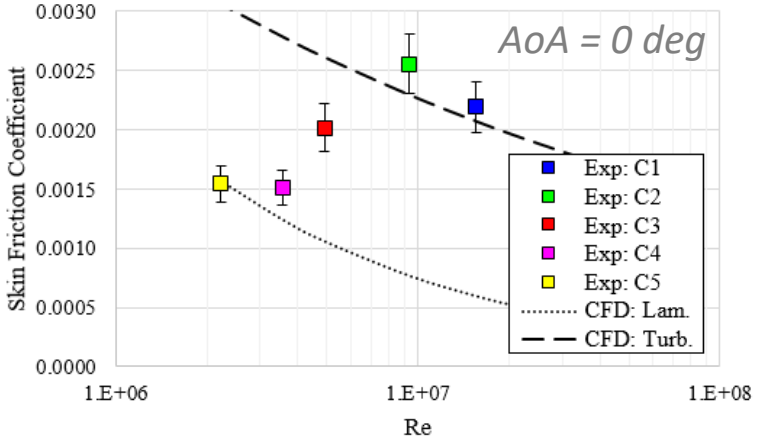
Boundary Layer Transition @ AoA = 0-deg

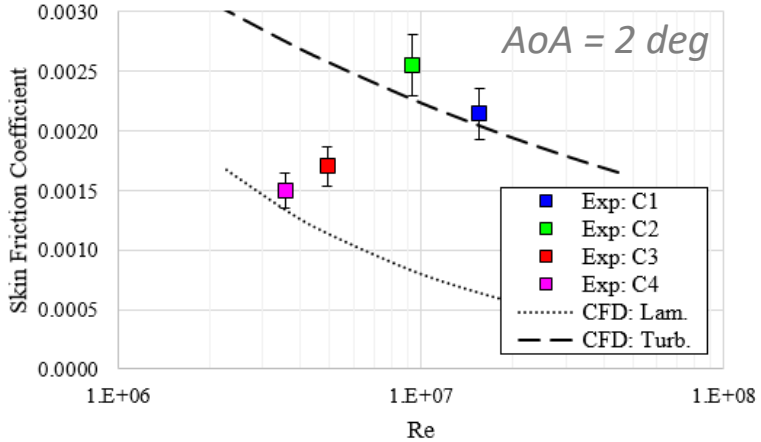


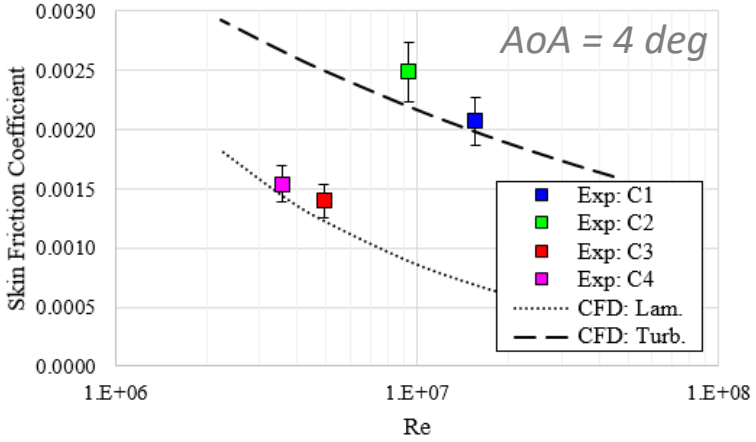
Comparison @ 0-deg AoA

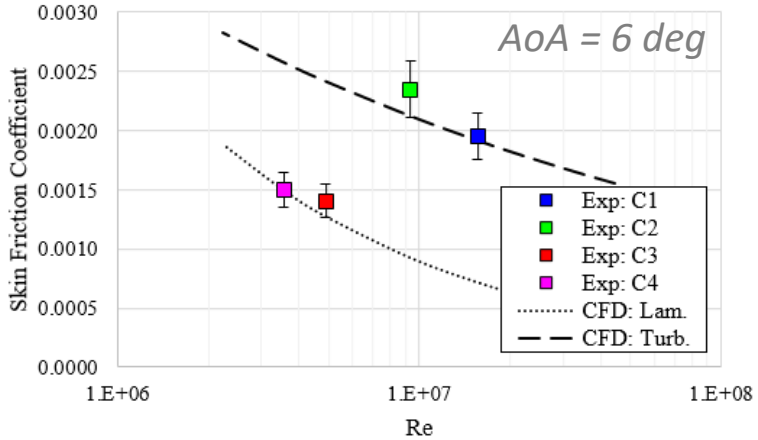
- 1D sensor (190-deg ray) skin friction
- 2D sensor (270-deg ray) skin friction
- 1D & 2D measurements in good agreement at 0-deg AoA

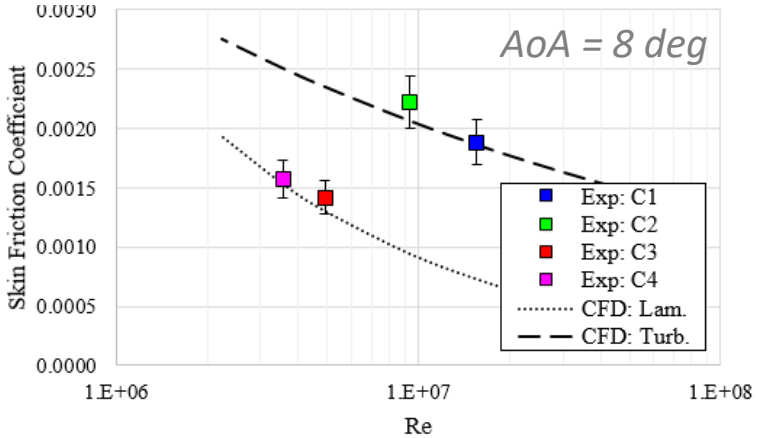
BLT: 2D Sensor vs Angle-of-Attack

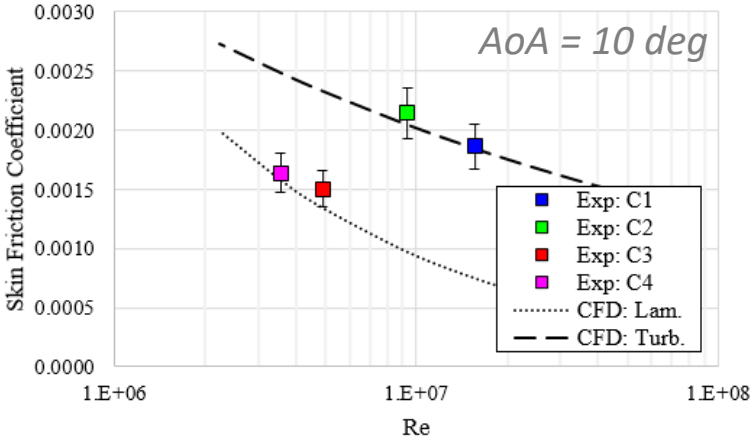












C1 & C2: Turbulent
C3: Transitional to Laminar @ ~7-8° AoA
C4: Transitional to Laminar @ ~3-4° AoA
C5: Laminar @ ~0° AoA

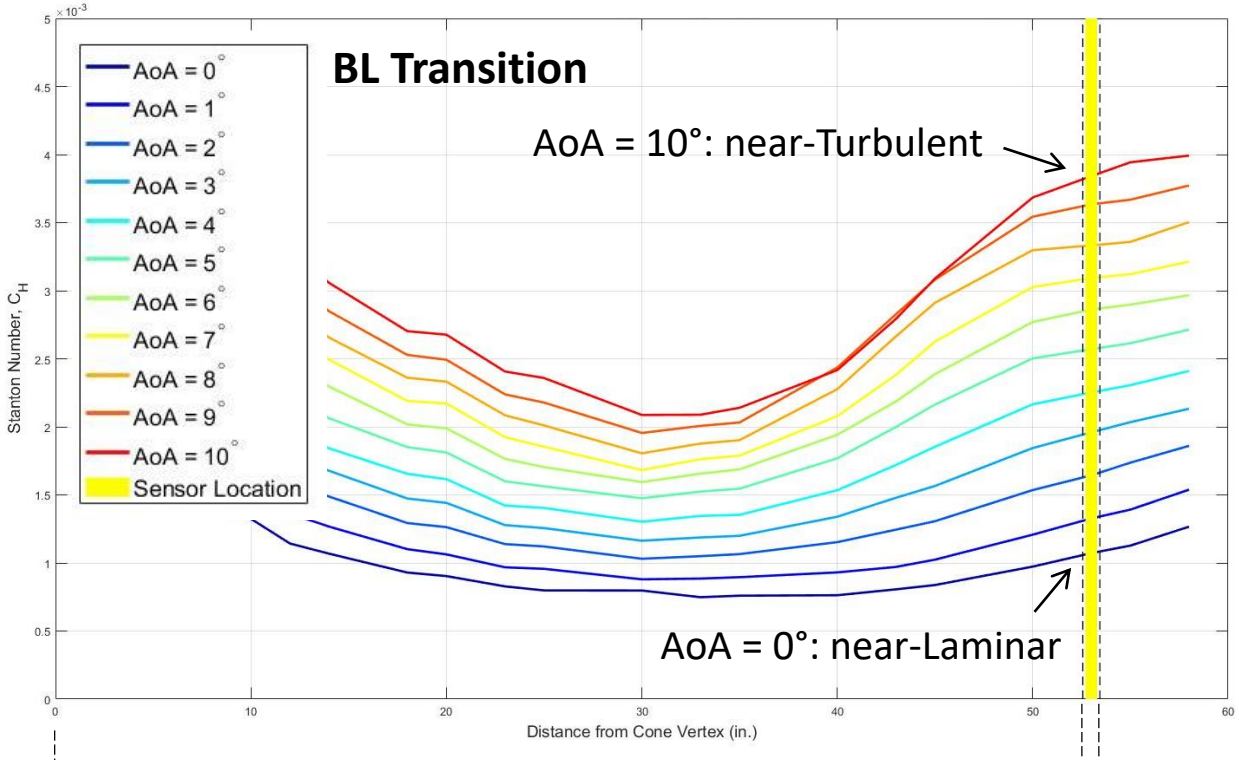
Notes

- C_f range: 0.0014 to 0.0026
- Good agreement (within 10%) of CFD
- Evidence of transitional overshoot (~10%) to turbulent BL

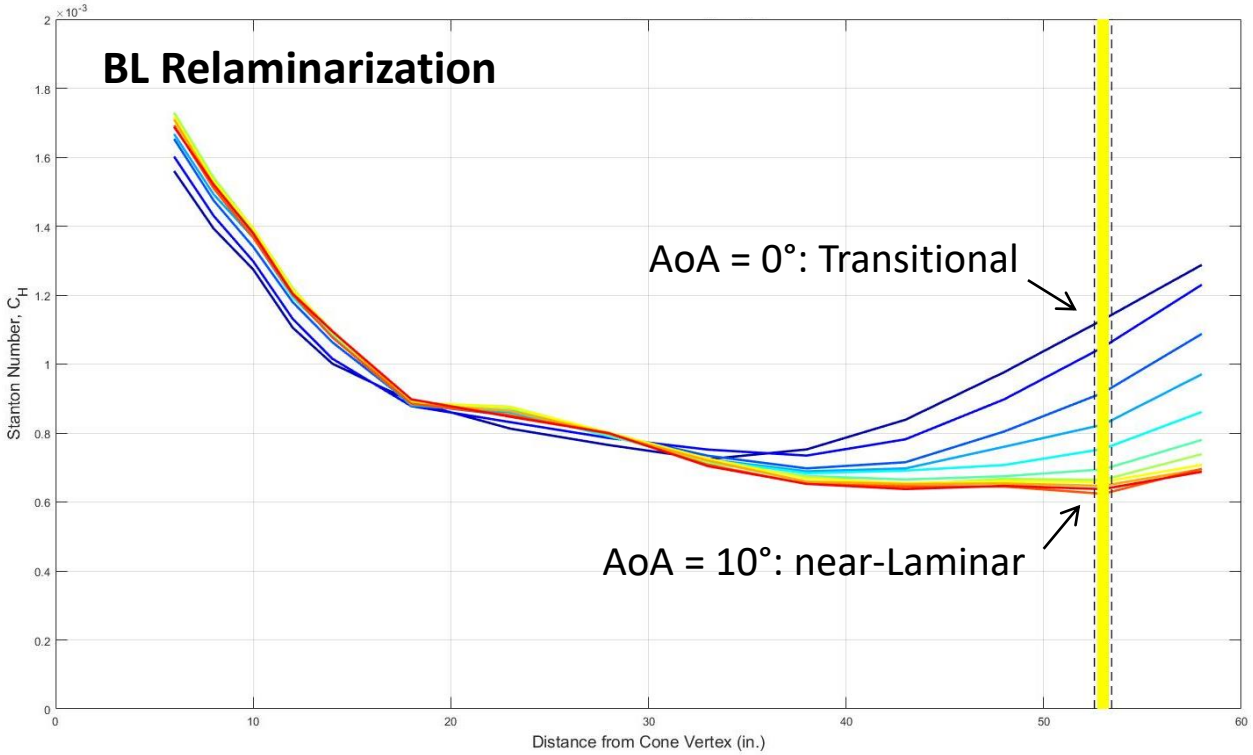
Stanton Number Example

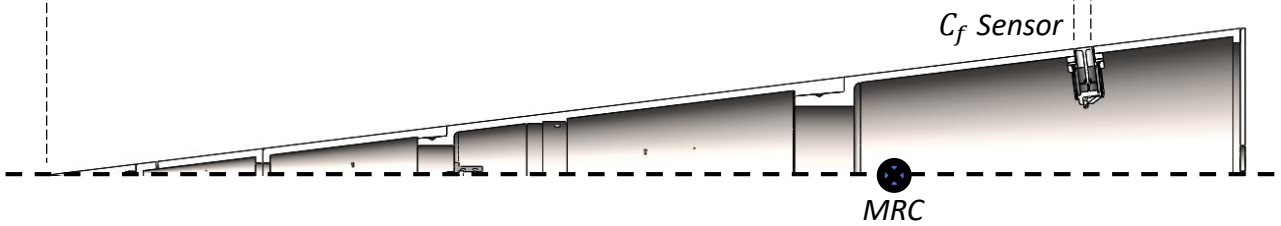
Condition: C3
Re = 3.6 E6/m

1D Sensor (190-deg Ray)



2D Sensor (270-deg Ray)

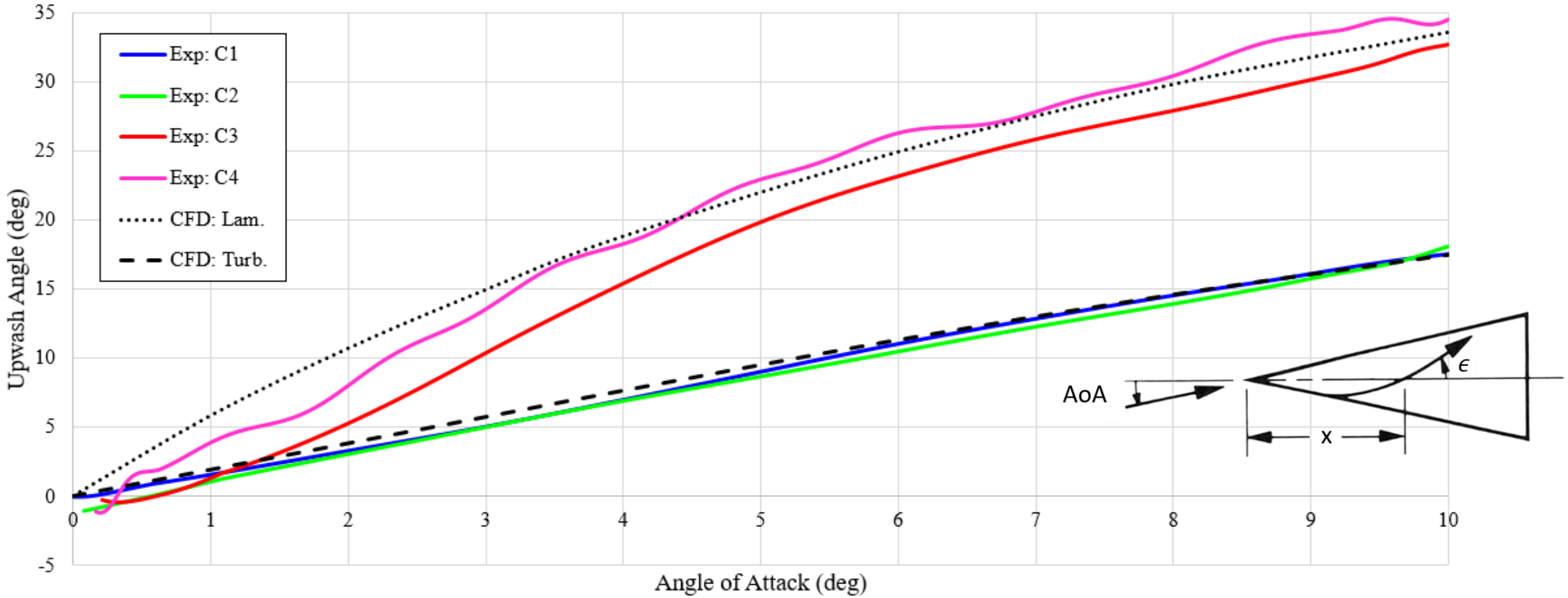




Notes

- Stanton number established from local heat transfer data
- Measured with 66x coaxial thermocouples

Upwash Angle (ϵ)



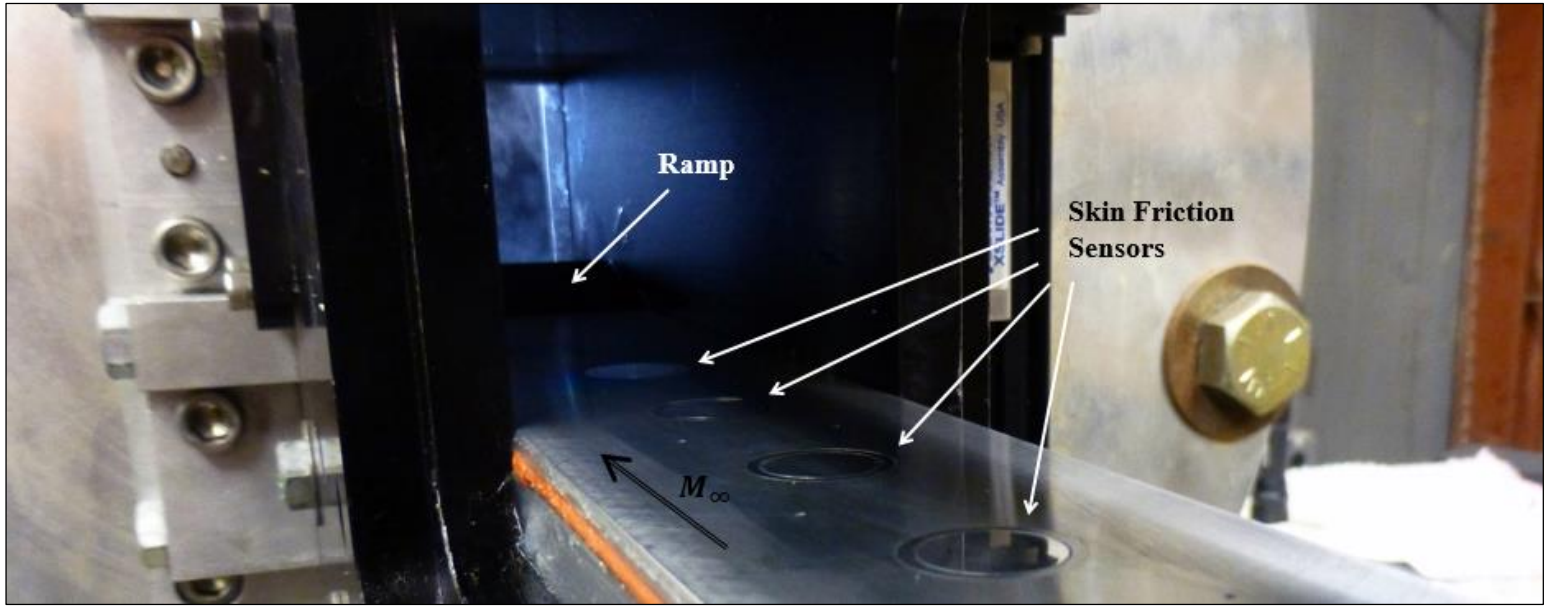
C1 & C2: Turbulent
C3: Transitional to Laminar @ ~7-8° AoA
C4: Transitional to Laminar @ ~3-4° AoA

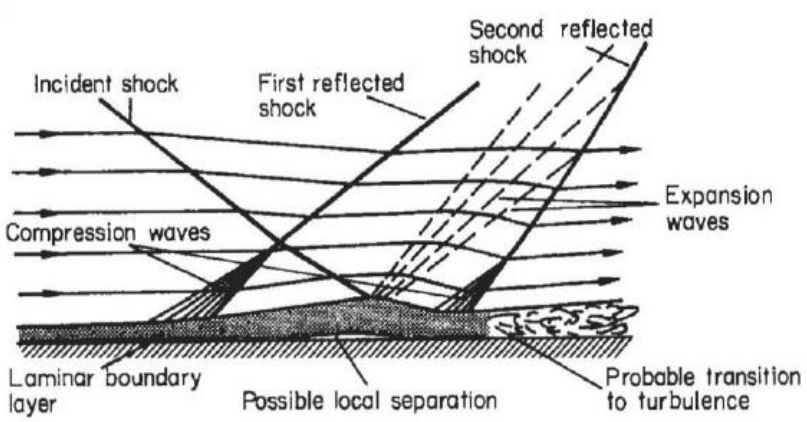
- 2.0x - 2.2x decrease in ϵ between laminar and turbulent BL
- Due to the larger shearing stress, smaller 3D effects can be expected for turbulent layers
- To the authors' knowledge, no such comparisons have been done for turbulent flow conditions before, since the experimental measurement capability did not yet exist

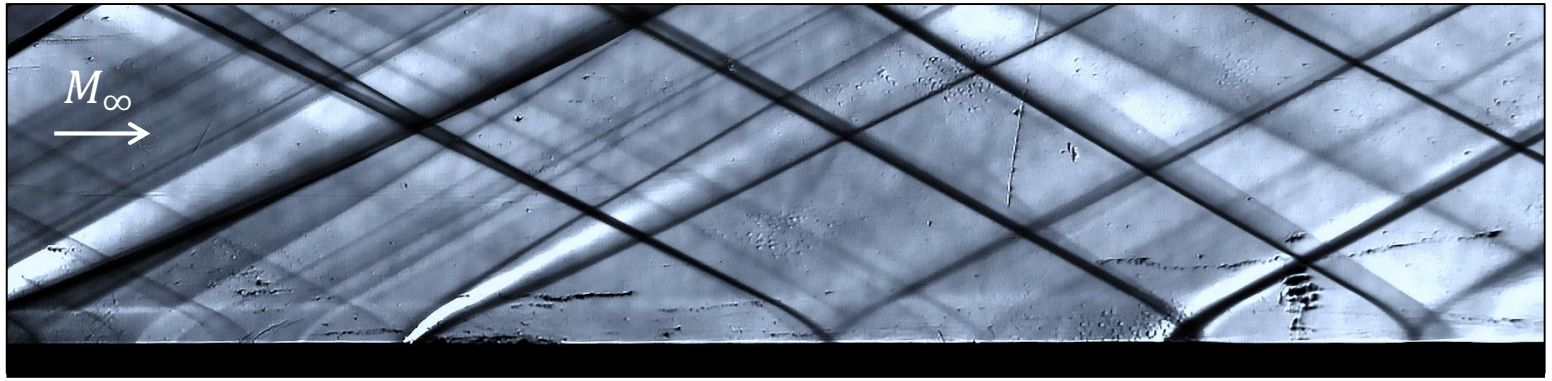
Scramjet Applications

OSU ARC Supersonic Tunnel

- Location: The Ohio State University
- Flow: 2” x 2” CS, continuous flow
- Nozzle: Mach 2.2
- Pressure: P0 = 58.2 psia
- Temperature: T0 = 60 °F
- Reynolds: Re/ft = 12.9 E6/ft
- Ramp: 0% to 32% blockage





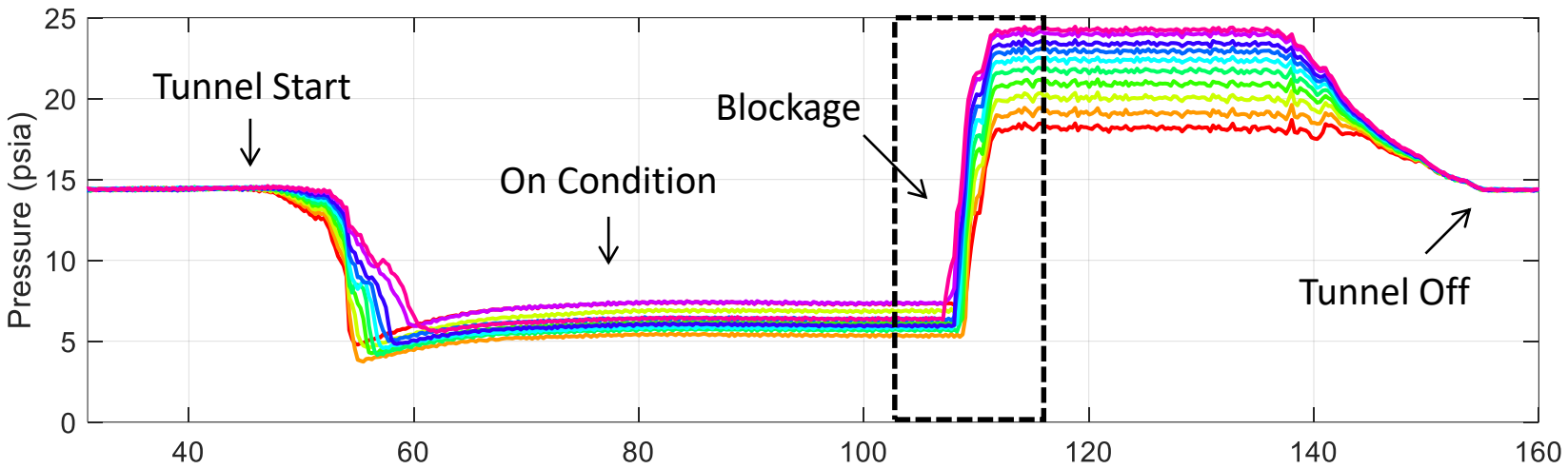


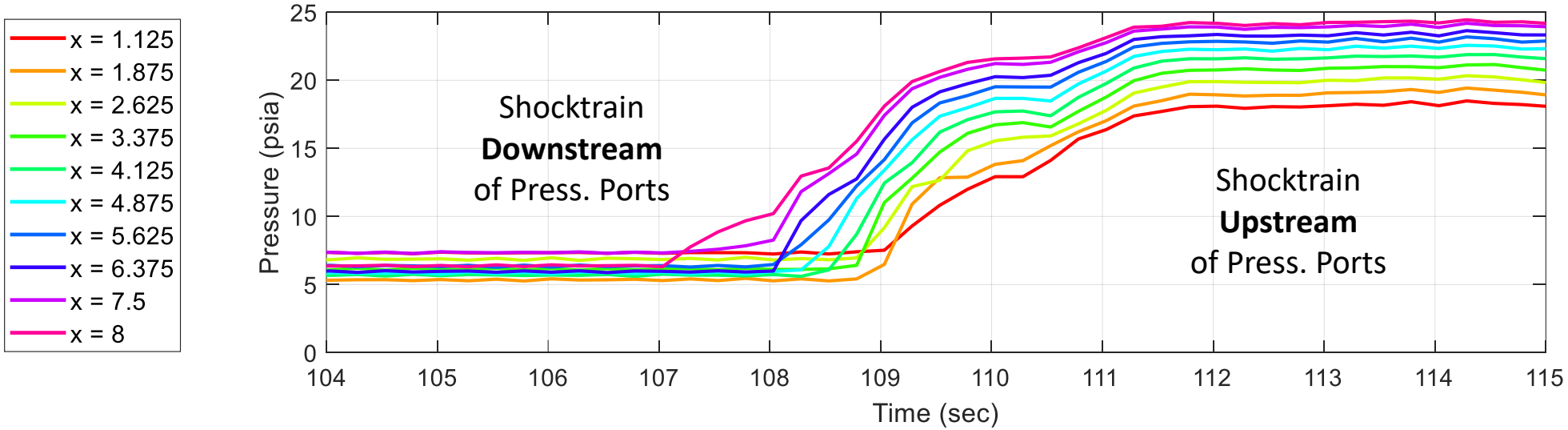
Enclosed Test Environment for Skin Friction Sensors (Shadowgraph)

Scramjet Applications

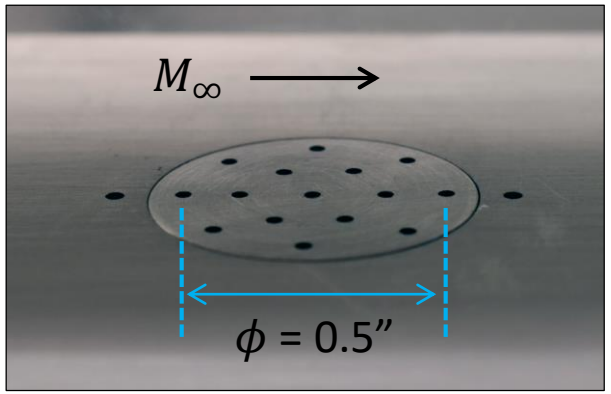
Wall Static Ports

- Standard approach to tracking shocktrain movement
- Conducted with pressure taps (Scanivalve unit) + Kulites
- Objective: Identify shocktrain location, velocity, magnitude, pressure gradient

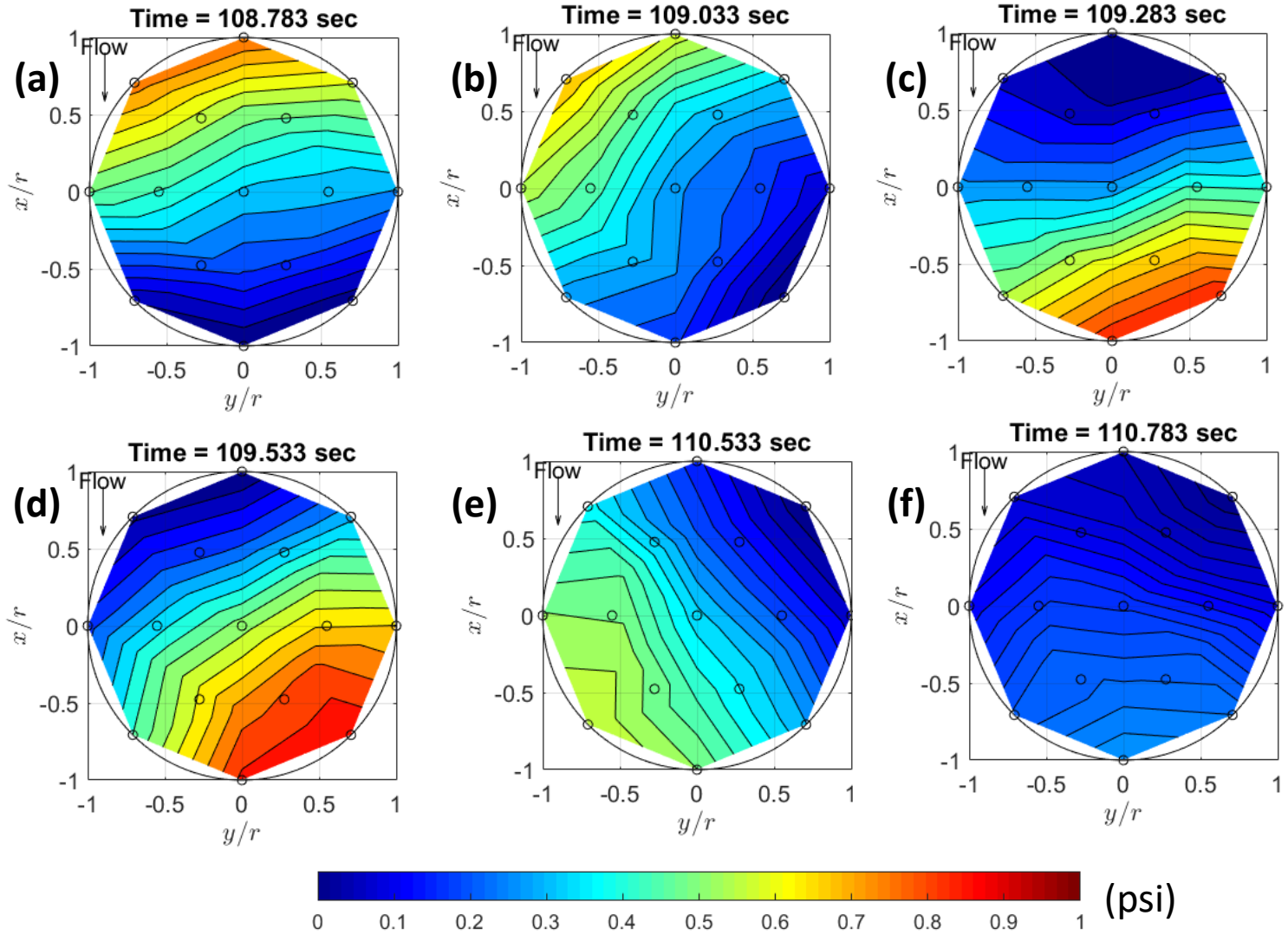




Shockwave/Boundary Layer Interaction (SBLI)



Pressure Plug: 15x Ports



<u>Favorable pressure gradient</u>

- Negative gradient: $\frac{dP}{dx} < 0$
- Plots (a) & (b)

<u>Adverse adverse pressure gradient</u>

- Positive gradient $\frac{dP}{dx} > 0$
- Plots (c) & (d)

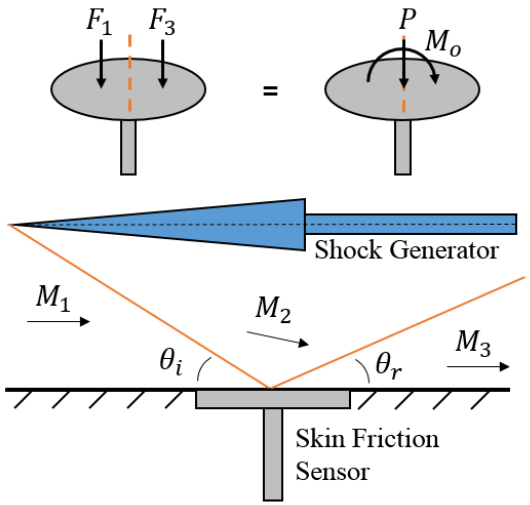
SBLI Challenges

Skin Friction Sensor Challenges

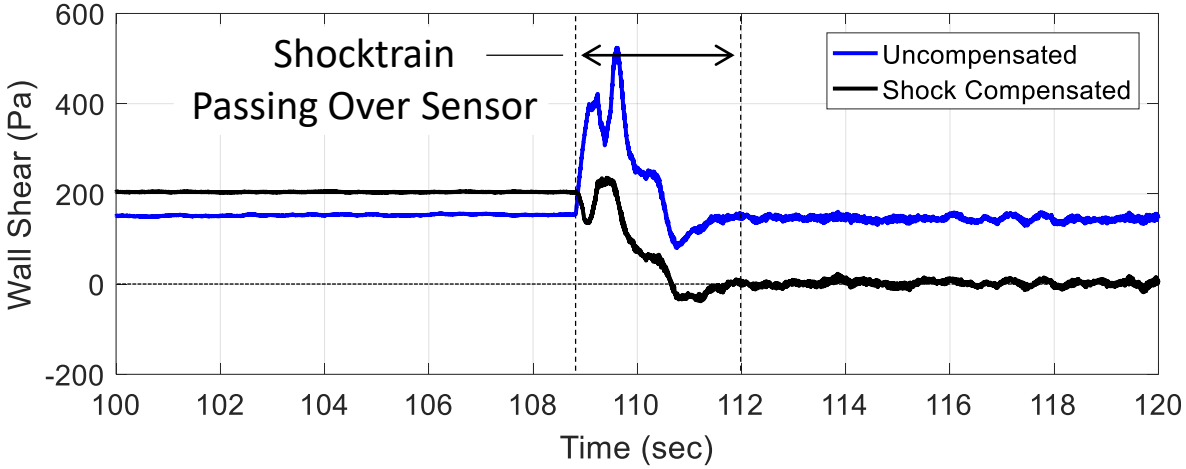
- Shock patterns very common in enclosed facilities
- Shockwaves & pressure gradients can result in an error source of over 100% of the wall shear measurement

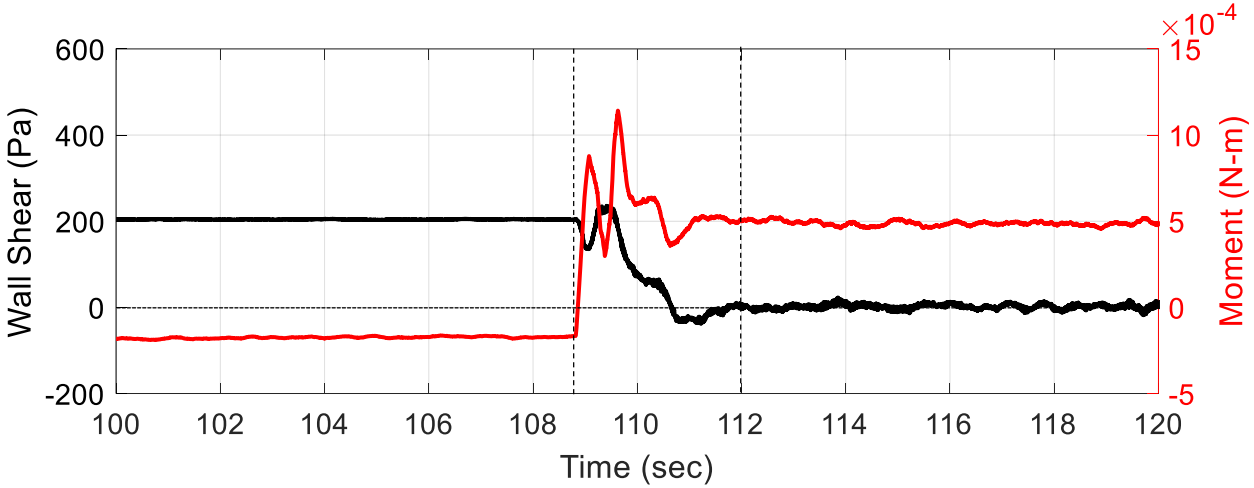
Two Solutions

1) **Shock-Compensation (SC)**: decouple shock-influence
2) **Immune (I)**: isolate shock-influence

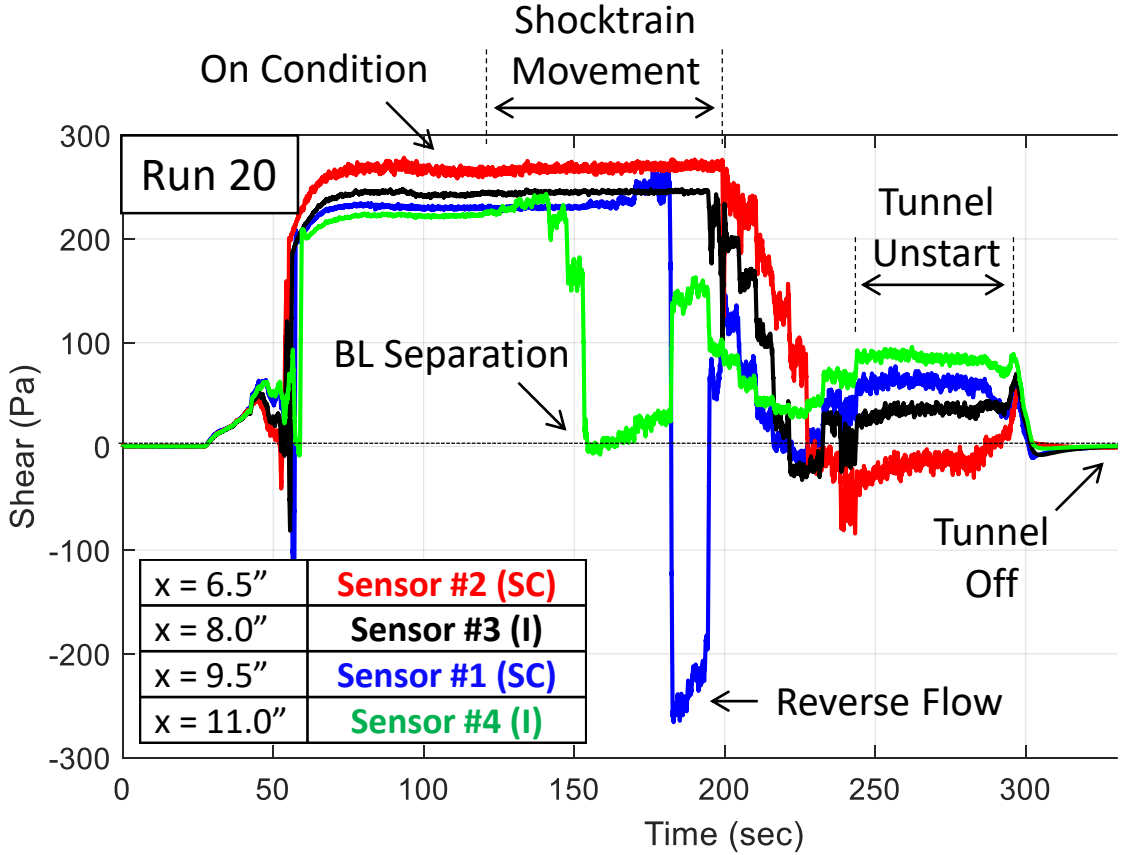


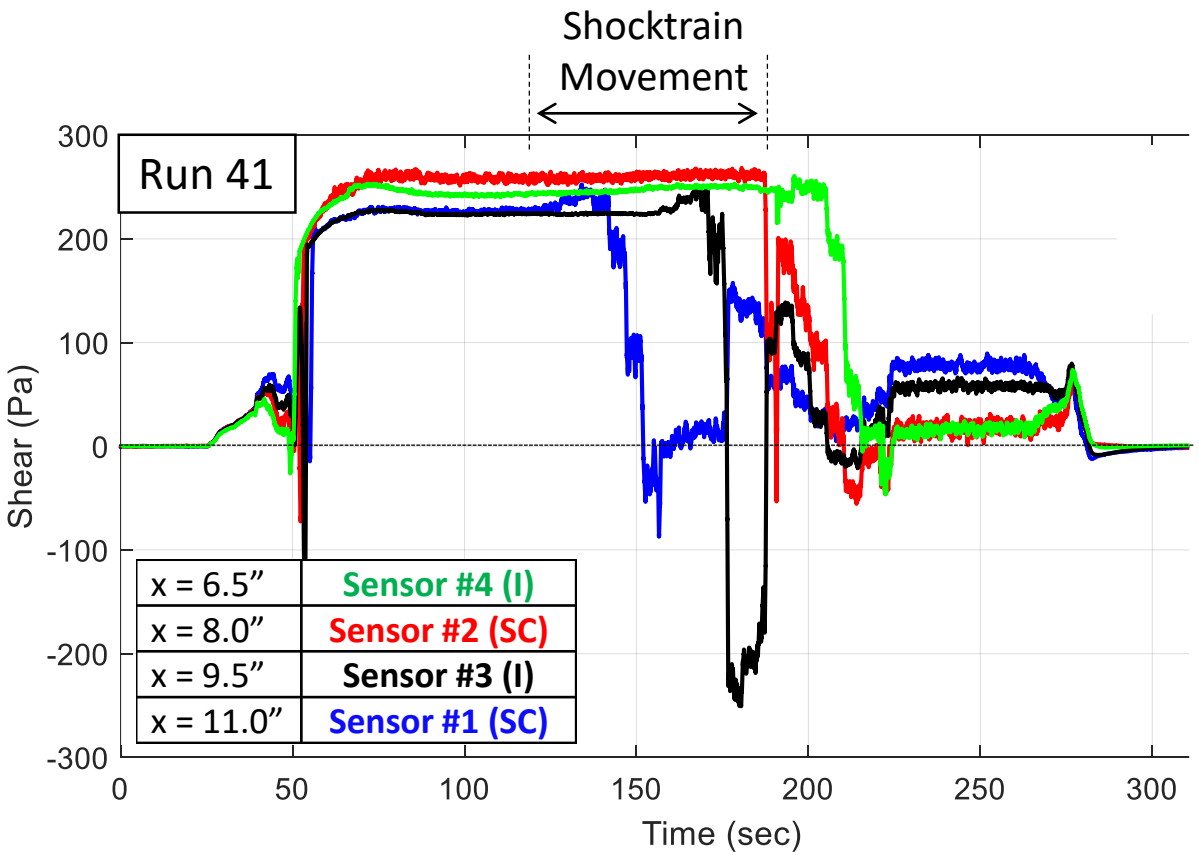
2-D Shock Impingement Diagram





SBLI Challenges





- Measurement agreement is independent of sensor location & sensor design (SC vs I)
- Sensors capable of measuring boundary layer separation & reverse flow features

* Shocktrain stepped forward every 10 sec

Engine Control System

Advantages of Skin Friction Sensors

- Match capabilities of pressure taps: identify shocktrain location, velocity, magnitude, pressure gradient
- Plus:
  - Measure wall shear / skin friction
  - Infer heat flux (Reynolds Analogy)
  - Measure shock moment: impingement & shock strength
  - Measure directional component: cross flow & reverse flow
  - Detect BL interaction & separation
  - Only one sensor is required (equivalent to matrix of taps)

Active Control Device

- Program objective:
  - develop a closed-loop engine control system (i.e., sensors, actuators, and algorithms)
  - manage critical flow transients & prevent engine unstart
  - skin friction sensor is the active input device

Other Scramjet Applications

Program Objectives

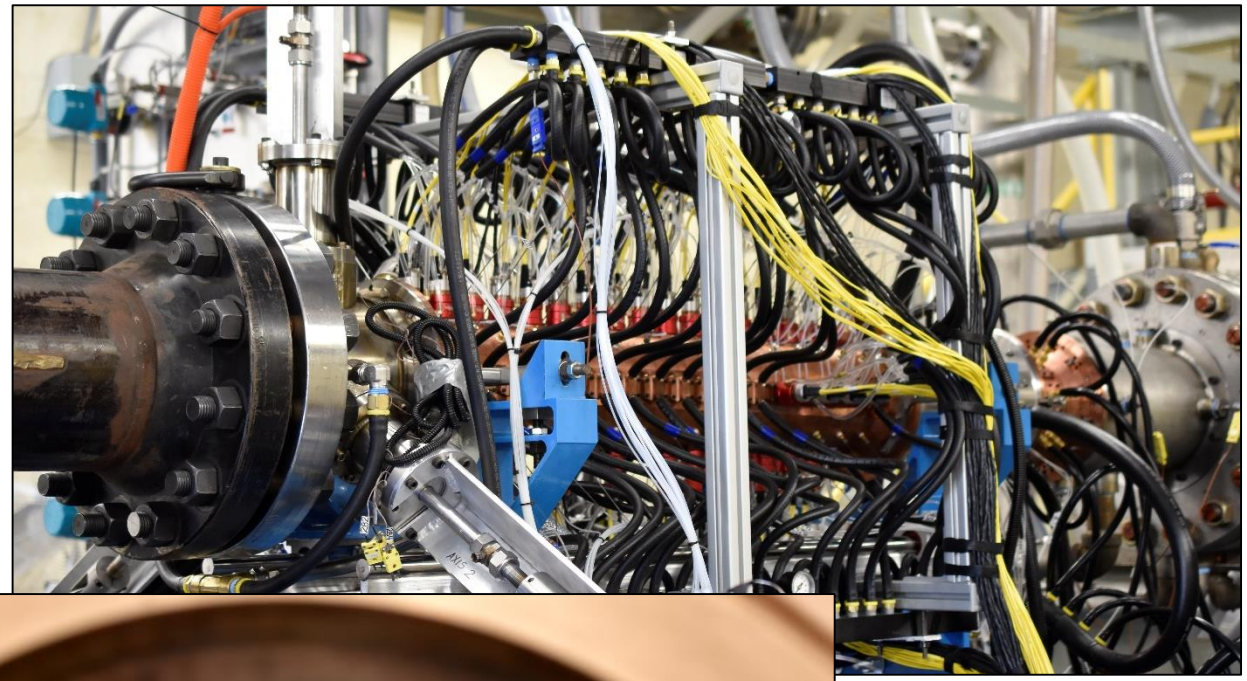
- Map skin friction in test section
- Identify distortion patterns
- Comparative CFD study

Other Scramjet Tests:

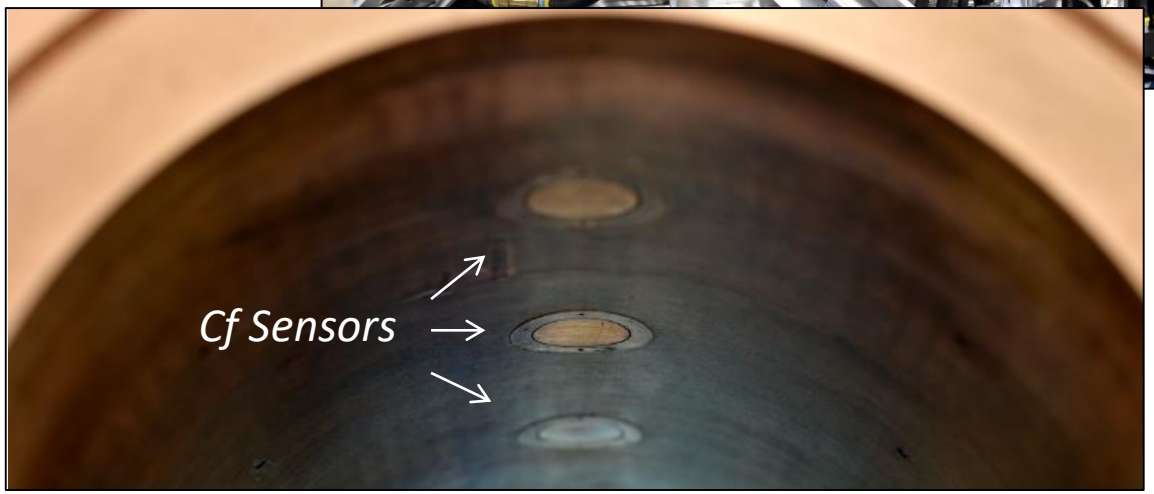
- *AFRL RC-19*
- *AFRL RC-18*
- *ATK GASL*
- *Academia*

Skin Friction Sensors

- Fabrication
  - Fabricated & tested 36x *Cf* sensors
  - Total of 68x *Cf* sensors planned (late 2017)
- Sensor Features
  - Shock-compensation
  - Water-cooled sensing head
  - Curved (concave) surface
- High-Enthalpy Testing
  - Mach 2.6, T0 = 2,000 °R, P0 = 200 psia
  - Temperatures: T_{aw} = 1,875+ ° R
  - Run durations: 30+ min at a time



AFRL Scramjet Research Cell 22



Curved Wall Test Section

Questions

Ryan J. Meritt, Ph.D.
Ahmic Aerospace LLC
400 Sugar Camp Circle
Dayton, OH 45409
Office: 937-272-5880
ryan@AhmicAero.com
www.AhmicAero.com