Direct Skin Friction Measurements in High-Speed Flow Environments

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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
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 (\(\epsilon\))
   - 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 ($\tau_w$) & skin friction ($C_f$)
2) Detect boundary layer transition (BLT)
3) Measure upwash angle ($\epsilon$)

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

**Relevant Programs**

- **AEDC Tunnel 9 (2014):**
  - Mach 10
  - 1x 1D Cf Sensor

- **CUBRC LENS I (2017):**
  - Mach 10 & 14
  - 3x 2D Cf Sensors
  - Compare to Tunnel 9
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 ×10⁶/m (0.05 - 48.4 ×10⁶/ft)
- Test Section: 1.52 m (5 ft) diameter, 3.66 m (12 ft) long

**2016 Program Conditions**

<table>
<thead>
<tr>
<th>Test</th>
<th>Re/m (E6/m)</th>
<th>AoA (deg)</th>
<th>P₀ (MPa)</th>
<th>T₀ (K)</th>
<th>h₀ (MJ/kg)</th>
<th>M∞</th>
<th>P∞ (Pa)</th>
<th>T∞ (K)</th>
<th>ρ∞ (kg/m³)</th>
<th>U∞ (m/s)</th>
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</table>
**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
Test Configuration

1D Cf Sensor
2D Cf Sensor
90-deg
270-deg
180-deg
0-deg

- AoA
+ AoA

Downstream View of Cone

Photograph of Sharp Nose Cone and Skin Friction Sensors
Skin Friction Sensor

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

Integrated Sensor in Cone Surface

Sensing Head $\phi = 0.875''$
Wall Shear Measurements

**Measurement Sensitivity**

Butterfly Mass $\approx 0.5 \text{ g (0.018 oz)}$

Equivalent wall shear $\approx 12.6 \text{ Pa (0.26 psf)}$

for element $\phi = 22.2 \text{ mm (0.875 in.)}$
**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: $\tau_w = 84.7$ Pa (1.77 psf)
- 2D sensor: $\tau_w = 86.1$ Pa (1.80 psf); difference of 1.6%
- CFD: $\tau_w = 81.3$ Pa (1.70 psf), difference of 4-6%

### Condition: C1
Re = 12.1 E6/m

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**Graph:**
- **Legend:**
  - Exp: 190-deg Ray
  - Exp: 270-deg Ray
  - Exp: Uncertainty Bands
  - CFD: Turb. 190-deg Ray
  - CFD: Turb. 270-deg Ray

**Axis:**
- **Y-axis:** Wall Shear Stress (Pa)
- **X-axis:** Angle of Attack (deg)

**Note:**
$\pm 10\%$ uncertainty band

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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

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

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

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

- 2.0x - 2.2x decrease in $\epsilon$ 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
**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

![Diagram showing pressure measurements with various markers for different conditions such as Tunnel Start, Blockage, and Tunnel Off, with Shocktrain Downstream and Upstream of Press. Ports at specific time points.](image_url)
Shockwave/Boundary Layer Interaction (SBLI)

Pressure Plug: 15x Ports

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

Adverse adverse pressure gradient
• 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

Shocktrain Passing Over Sensor

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

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: Taw = 1,875+ ° R
  - Run durations: 30+ min at a time

Other Scramjet Tests:
- AFRL RC-19
- AFRL RC-18
- ATK GASL
- Academia

AFRL Scramjet Research Cell 22
Curved Wall Test Section
Questions

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