Swirl Velocity Measurements for IGT Swirler Concepts
My background
Introduction

• Pitot probes are used in a variety of industries
  – Aerospace
  – Weather stations
  – Maritime usage

• Used for measuring air speed
• From Bernoulli’s principle, velocity is found if static & stagnation pressure are known

\[ P_o = P_s + \frac{\rho V^2}{2} \]
Introduction

• Sensitivity to environmental and geometric applications

• On aircraft, far away from lifting surfaces or plane body—avoid boundary layer/local changes in flow due to fluid/structure interaction

• Icing, clogging (from dirt, debris, sand, etc.) can have devastating impact on effectiveness/accuracy

• Potential cause for deadly accidents
Introduction

- Standard 1-hole probes only measure mean velocity (1 direction)
- Multi-hole probes capable of measuring multiple velocity components
  - 1 hole: 1 component ($V_x$)
  - 3 hole: 2 components ($V_x, V_y$)
  - 5 hole: 3 components of flow ($V_x, V_y, V_z$)
  - >5 holes: highly 3D flow field with high angle variation ($60^\circ$ and above)

Aeroprobe

Motivation

• Swirl-stabilized combustors
  – Common method for stabilizing combustors
• Recirculation zone is created, anchors the flame
• Majority of gas turbine combustors implement high swirl (HS) number combustors (S > 0.6)
• Low swirl (LS) number criteria of 0.4 < S < 0.55
• Research has shown that low swirl number designs can reduce emissions/operate stably over wide range of conditions

2. Meadows et al.
Motivation

• Low swirl number designs can burn very lean
• Lean blowout limit (LBO) capability improved over high swirl designs
  – Stresses reduced, decreasing non-uniform heat release
• Reduction in emissions for LS vs. HS
• Although counter-intuitive, creates more stable flame
• Create divergence in flow field, where mean air speed matches turbulent flame speed
Literature Review

• Some patents and licensing exists
  – Maxon Corporation for ultra-low NO\textsubscript{x} industrial market
  – Patent from Lawrence Berkeley Lab

• Low swirl injectors tested in a Solar Turbines T70 gas turbine – converted their high swirl number injector to low swirl number

• Difference in residence times

\[ 2.5X \text{ NO}_x \text{ reduction} \]

4. Cheng et al.
Literature Review

• Attractive for industrial burners due to lower emissions, high turndown ratio
• Lifted flame keeps burner cool to touch
• Normalized shear stresses
Approach

• Measure swirl components with 5-hole conical Aeroprobe™ pressure probe

• Map swirler’s flow field as precursor to hot fired combustion testing

• Confirm flow exhibits expected behavior as CFD

• Realize optimal design for combustor performance
Setup

- Mount and position traverse system for taking measurements 1/32” intervals
- Create mounting system for probe
- Utilize FTT’s flowbench for testing
Swirl velocity experiments conducted at ambient conditions only

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Setup

- Use the switching board designed at FTT to switch between pressure readings (large cost savings)
- Using handheld barometer to measure pressures in each port
- 3 DOF traverse system for mapping flow field
- Experimental coefficients can then be interpolated to find flow angles
- Probe measurements valid in flow field that is within 5 m/s to Mach 2.0 range
- Probe is accurate within ± 1°
- Handheld barometer accurate to 0.025%
- Probe’s measured velocity magnitudes within <1% or 1 m/s (whichever is larger value)

6. Lee et al.
Setup

- Calibrated in a uniform flow field with known velocity
- Create a map with even spread of flow angles

\[ C_{p,yaw} = \frac{P_2 - P_3}{P_1 - P} \]
Setup

- Structural analysis of probe mounting fixture (fluid-structure interaction)
- Vortex shedding frequency vs. natural frequency of mounting structure
- Ensure resonance does not occur and damage the probe
- \[ St = \frac{f \cdot L}{U} \]
- \( f \sim 77 \text{ Hz} \)
- Probe mounting estimated as simplified beam structure
- \[ \omega = 1.875^2 \sqrt{\frac{E \cdot I \cdot g}{\rho \cdot A \cdot L^4}} \]
- \( f = 542 \text{ Hz} \)
- Mass flux ratio (between swirler and perf plate flow) is critical

\[ S = \frac{2}{3} \tan \alpha \frac{1 - R^3}{1 - R^2 + \left( m^2 (1/R^2 - 1)^2 \right) R^2} \]

- \( m = \frac{m_c}{m_s} \)
Results – Velocities

- 3-Component velocity results for each configuration
- Help determine what downstream plane the flame will anchor at (based on axial velocity)

\[ W_3 = 0.12854 \text{ lbm/s} \]
\[ P_3 = 1.4836 \text{ psig} \]
\[ P_4 = 0.0519 \text{ psig} \]
(PR = 10%)
Results

- Measurements taken on 1/32” intervals
- Probe diameters and separating wall marked on data

\[ W_3 = 0.12854 \text{ lbm/s} \]
\[ P_3 = 1.4836 \text{ psig} \]
\[ P_4 = 0.0519 \text{ psig} \]
(PR = 10%)
• Increase vane height so that measurements can be taken within swirl passages, but away from wall
• Literature suggests anywhere from 2 – 5 probe diameters away from wall is sufficient
• Measurements taken every 1/16”
Data Reduction

• Probe calibration valid in ±60° window
• Starting at ±40°, standard calibration technique breaks down
• Need for various normalization schemes to reduce data
• Sectoring method is successful for flow angles in fringes
Traditional Method  PN94IR-395-012

High Swirler, Swirler exit plane, 3%

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Data Reduction – Baseline Design

Sectoring Method

High Swirler, Swirler Exit Plane, 3%

PN94IR-395-012

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Traditional Method

High Swirler, Static tap plane, 3%

PN94IR-395-012
Sectoring Method

High Swirler, Static Tap Plane, 3%

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Results

- Importance of vane-to-vane-positioning for the probe
Results

- Flow variation across vane profile
- Flow angles can vary significantly depending on position relative to vane trailing edge
Conclusions

• For low swirl swirler - mass flow through core (perf plate) is too low, so that velocities are below specified range for probe (5 m/s to ~ 700 m/s)
  – Increase PR so that velocities are within range
• Vane height is too small for ample traversing area
• Wall effects are/may be present throughout much of vane section
• Swirl angle is most accurately measured close to vane exit
• Swirled flow diffuses significantly as downstream distance increases (addition of α flow component)
Conclusions

- Streamlines diverge, flow spreads at diffuser section

Reduction in radial swirl angle near wall, flow spreading outboard ($\alpha$ component)
Conclusions

- Low velocities shown to be leading cause for unsteady & unreliable readings
- High Swirl perf plate flow within bounds ($V \sim 17 \text{ ft/s}$)
- Low Swirl perf plate flow out of bounds ($V \sim 7 \text{ ft/s}$)
Conclusions

- Effect of core flow on swirl angle is significant – effect of aerodynamic wall
- Careful consideration towards design target accounting for core flow effect in design tool
- Influence of vane height, combined with lack of perf plate flow, increases overall swirl angle

**PN94IR-010-010**
Conclusions

Cost savings by replacing expensive commercialized software

PN94IR-010-009
Conclusions

- Reasonably good error limits, within a couple of degrees
- Error includes propagation of pressure measuring device, and intrinsic error of probe
• Permitting velocities and swirl angles are within range, swirl angles and velocity components can be obtained
• Effective diagnostic tool for pre-hot fired testing
• Flow field can be mapped throughout different regions of the swirler
• Surface finish differences between wax printed & SLA
  • SLA → Metal parts
  • Wax printed → Casting or DMLS
• Hone in on MATLAB’s interpolation techniques
• Use of non-invasive diagnostics (LDV, PIV) to measure velocities
• Validate flow behavior with CFD


