Experiments and LES Modeling of Flashback in a Model Swirl Combustor

Noel Clemens
The University of Texas at Austin

Venkat Raman
University of Michigan

Sponsored by DOE NETL (DE-FE0007107)
Objectives

Joint Experimental/Computational program

• Investigate boundary layer flashback in swirl combustors with hydrogen enriched fuels
• Develop improved LES models for this challenging target problem
• Use OpenFOAM platform to facilitate transfer to industry
• Conduct experiments in a newly-developed swirl combustor under varying pressure conditions
• Make high-fidelity time-resolved measurements for physics and validation
Current Presentation

• New Experimental Results
  ▪ Solid particle seeding to enable velocity measurements in unburnt and burnt gases
  ▪ Tomographic PIV and flame front measurements
  ▪ Measurements of flashback at pressures up to 5 atm

• New LES Results
  ▪ New models have been developed to improve prediction of turbulence in non-reacting flow and in presence of flame
    – Extensive validation with literature and UT data
Model Swirl Combustor
Model swirl combustor

- combustion tube
- mixing tube
- center body
- swirler
- plenum
- flow condit.
High-Pressure Combustion Facility

- Designed to operate at up to 10 bar
- 8” internal diameter
- Stainless steel construction
- Allows mounting of various burners
  - Flashback
  - Stratified flames
- Optical access through sides and top
- To date we have operated it only to 5 bar
High-Pressure Combustion Facility

- Laser sheet
- Top Window
- Water out
- Water in
- After-cooler
- Drain
- To Back-pressure regulator
- Cooling air
- Surface igniter port
- Rectangular Windows
- Combustor assembly
- Fuel and air supply ports
- Air co-flow

Side view z-r-plane:
- Combustor tube
- Laser sheet
- Mixing tube center body swirler

Top view:
- Circle with dimensions
- θ4
- 25.4 mm
Measurements at 1 atm

$\text{CH}_4$-air flames
Flashback: CH$_4$-air at Re$_h = 2000$

- High-speed chemiluminescence imaging (2 kHz)
- Flashback along center body in swirling motion
- Flame stabilizes on trailing edges of swirler vanes
High-speed particle image velocimetry

Simultaneous 3-component (stereo-)PIV and flame luminescence imaging

• 4 kHz framing rate
• Spatial resolution: one vector every 0.4mm
• Flame front detection based on vaporized seeding particles
BL flashback (last year’s results)

Channel flow

Gruber et al. *JFM*, 2012

Swirling flow

Heeger et al., *EXIF*, 2010

Current work

- Is this flow reversed or separated?
- Need 3D measurements
Planar PIV in unburnt and burnt gas

flame luminescence

axial velocity

Side view z-r-plane:

flow
Planar PIV in unburnt *and* burnt gas

**Improved data for validation**

- Moderate acceleration in the axial direction in burnt gas farther downstream of flame tip
- Swirl decreases in burnt gas – realignment of streamlines
Measurements at 1 atm

$\text{H}_2$-enriched flames
Flashback Modes (new interpretation)

• “Swirl-flow flashback”
  • Flame tongues swirl around centerbody as they propagate upstream
  • Found in both CH₄ and H₂ cases

• “Channel-flow flashback”
  • Flame cusps convex towards reactants propagate upstream in streamline direction
  • Occurs on windward side of flame tongue
  • Found in H₂ and CH₄ flames
  • Mechanism seems to be similar to that in non-swirling channel flow flashback
Flame Spread – Effect of Hydrogen

Matched laminar flame speeds
1 atm

CH$_4$-air

\[ \phi = 0.8, \quad T_{ad} = 2000 \text{K}, \quad Re_h = 5,000 \]

H$_2$-air

\[ \phi = 0.4, \quad T_{ad} = 1400 \text{K}, \quad Re_h = 5,000 \]

$S_L = 0.26 \text{ m/s}$
3D Measurements
CH$_4$-air Flames
Pressure: 1 atm
High-speed tomographic PIV

• It is clear that fully 3D measurements of the complex flowfield would be beneficial

⇒ Tomographic PIV – 3D velocity in a volume
3D flame surface reconstruction

1. Raw images

2. Image preprocessing
3D flame surface reconstruction

1. Raw images

2. Image preprocessing

3. Reconstruction of 3D-particle field

4. Determining interrogation volumes occupied by flame
3D flame surface reconstruction

• We have developed a new method to reconstruct the 3D flame surface

• Uses tomographic reconstruction of aerosol particles

• Method gives flame surface + velocity field at 4kHz
Time-resolved 3D flow-flame interaction
Effect of flame on approach flow

3D displacement of streamlines

![Diagram showing 3D displacement of streamlines with z-distance and axial velocity scales.]
Summary of upstream flame propagation

**Flame Tongues**
- Elevated pressure
- Flame front
- Negative axial flow

**Flame Bulges**
- Reverse flow

Legend:
- Flame speed \( s_u \)
- Local flow velocity \( \mathbf{v} \)
- Lab-frame
- Propagation velocity of flame front \( \mathbf{v}_f \)
Flashback experiments at pressures up to 5 atm
CH$_4$-air flashback at 1 atm and 4 atm

- Equal volume flow rate
- Increased flame wrinkling
- Less flame spread (remains closer to centerbody)
Flashback at different pressures

Maintain same average volume flow rate
Average axial velocity of 2.2 m/s
Effect of pressure on flame shape

1 atm

5 atm

t = 49.75 ms

t = 19.00 ms
Effect of pressure mean velocity profiles

Velocity [m/s]

Axial, 1 atm
Azimuthal, 1 atm
Axial, 5 atm
Azimuthal, 5 atm

$u_z$, 1 atm
$u_z$, 5 atm
$u_\theta$, 1 atm
$u_\theta$, 5 atm

$r - r_{wall}$ [mm]
Large-Eddy Simulation Results
Swirler Flow Calculations

• LES computations in complex geometry
• Maintaining turbulent flow structures is non-trivial
  • Discrete kinetic energy conservation needed
• OpenFOAM collocated minimal dissipation solver
  • Developed at UM
  • Available as part of UM gas turbine simulation package

Radial velocity in bluff body jet with kinetic energy conservation
Radial velocity in bluff body jet without kinetic energy conservation
Swirler Computations

• Swirl vanes are sources of unsteady vortex shedding
  • Capturing these structures is critical

8M cells (no refinement)  12M cells
Non-reacting Flow Statistics

Mean/Azimuthal Axial Velocity

RMS Axial Velocity (grid convergence)

- Mean velocity insensitive to grid size
  - RMS velocities require much higher resolution to capture vane-generated turbulence
  - Similar results at all axial positions
Reacting flow simulations

- Filtered-tabulated chemistry model
  - Wrinkling factor added to model sub-grid flame structure
- Filter size of 0.5 mm
- Grid size from 0.4 to 1 mm
  - Note that filter size is enforced using a filtered chemistry model
- This approach provides a natural transition to stratified flames
Stable flame configurations

- Blockage effect induced by the flame creates upstream reverse flow pockets
- The effect is enhanced at high pressure

1 ATM/CH4
4 ATM/CH4
Flame topology during flashback

- Flame front more uniform in azimuthal direction
- Flame tongue appears only when flashback is triggered
- Both observations differ from experimental data
Flame Laminarization

- LES solvers based on low Mach number approximation
  - Necessary for accelerated calculations in low speed flows
- Flame propagation affects upstream turbulence more significantly than experiments
  - Low Mach number solver seems to spread out pressure disturbances over entire domain
- Are basic flow assumptions not valid in unsteady confined flame motions?
Program Outcomes

• New 1-atm and high-pressure swirl-flame facilities have been constructed to enable study of flashback at a range of pressures

• Extensive measurements have been made of boundary layer flashback with varying
  ▪ Reynolds number
  ▪ Fuel composition (CH\textsubscript{4}+H\textsubscript{2})
  ▪ Pressure (1 to 5 atm)

• Used high-speed PIV and 3D flame surface imaging

• Measurements have provided new physical insight and proved valuable for LES model validation
Program Outcomes

• Developed a new flamelet approach for premixed flames with wall quenching
  ▪ Targeted for boundary layer flashback
  ▪ Validated using DNS data and experimental measurements

• Developed a minimally dissipative collocated numerical scheme for unstructured grids
  ▪ Implemented and verified in OpenFOAM open source package
  ▪ Adapted for industrial use, and validated in complex geometry test cases

• Identified potential shortcomings
  ▪ Low Ma assumption may not produce flashback flame structure
  ▪ Pressure effects might be transient in nature
END