Turbulent Flame Propagation Modeling in Premixed/Stratified Combustors

Application to Flame Flashback

Venkat Raman
University of Michigan

Noel Clemens
The University of Texas at Austin
Background

• **Flashback in lean premixed combustor**
  - Nature of premixed flame, lead to severe damage
  - Transient and difficult to predict
    - Time scales of millisecond
  - Boundary layer flashback
    - Low momentum streaks
    - Reaction vs. near-wall quenching

• **Challenges in practical combustion device**
  - Complex geometry
  - Extension to stratified flame and even partially premixed

(Lewis and Von Elbe, 1943)
Project Objectives

• **Goal:** Understand flame structure and propagation in high pressure premixed/stratified mixtures
  ➡ Lean combustion in high strain conditions
  ➡ Stratified combustion
  ➡ Flame flashback in high hydrogen-content combustion
  ➡ Staged combustion with hydrogen as fuel

• **Approach**
  ➡ DNS/LES based modeling flames
  ➡ Experiments of low and high pressure flames in stratified environments
  ➡ Including flashback
Outline

• Experimental studies of flashback
  ➡ UT swirl burner
  ➡ Low and high pressure test cases
  ➡ Summary of findings

• Computational modeling of premixed and stratified flames
  ➡ Solver development
  ➡ Flamelet-based models
  ➡ Validation test cases
  ➡ Summary of findings
Stratified Flames and Flashback

- Goal is to identify physical structure of flashback
- UT Swirl Burner with Nozzle-based Injection
Demonstration of Stratification: Nonreacting Methane-air

- Global equivalence ratio: 0.63
- Reh = 6100
- Average axial velocity: 2.5 m/s
- Non-reacting flow with acetone-seeded air through the fuel-nozzles
Equivalence ratio distribution snapshots

- Flow was found to be stratified in an average sense
- Occasional presence of fuel-rich mixtures found close to the center-body
- Swirl and turbulence in the mixing tube may bring reactive pre-mixture close to the center-body boundary layer

Histograms compare instantaneous equiv. ratio distribution in the inner half ($r<6\text{mm}$) to the outer half ($r>6\text{mm}$)
Propagation along the inner boundary layer

- Flame surface identified by evaporation of PIV seed particles (white region in the axial velocity map)
- Bright structures in the luminosity impose strong deflection of the approach flow
- Flame surface curvature is higher than the fully premixed flashback at same Re
Acetone PLIF snapshots during Flashback

- Instantaneous acetone PLIF signal maps were obtained for the reacting cases.
- Flame curvature was found to be enhanced by the local distribution of the equivalence ratio.
- Regions of positive and negative flame surface curvature are shown (in red circles).
Effect of hydrogen-enrichment: Luminosity images

- Early stage: Flame propagates along inner wall for CH4 and H2 early stage.
- Final stage: At later time H2 flame propagates on outer wall.
Propagation along the outer wall

- Flame starts propagating along the center-body boundary layer,
  - Switches to the outer wall after a few milliseconds

- Simultaneous Mie scattering images show the thin acute-tipped flame-strand propagating along the outer wall

- The outer wall propagation continues until the flame stabilizes itself on the fuel ports
Elevated pressure flashback: Premixed vs Stratified

- Premixed flashback at elevated pressures exhibit very small radial spread,
- Stratified flame flashback stops at an intermediate location in the mixing tube
- The flame brush is more wrinkled and exhibits large radial spread reaching up to the outer wall

Flow parameters
- Fuel: Methane
- Average axial velocity: 2.5 m/s
- Pressure: 3 atm
Summary of Findings

• A methodology for initiating flashback was developed
  ➡ Advanced laser diagnostics used

• Stratification leads to arresting of flame flashback
  ➡ As expected
  ➡ But, hydrogen seems to get around this solution

• At elevated pressures, flashback behavior is similar

• Radial spread of flame brush larger for stratified flame
  ➡ Flame propagation through regions with equivalence ratios outside flammability limit
Numerical Setup

- Variable density low Mach solver - umFlameletFoam
  - OpenFOAM based
  - Low Mach solver
  - Minimize dissipation
- 10M hexahedral-dominant mesh
  - Local refinement at swirler
- Run for 10,000 core hours on 1008 processors
Numerical details

- 9.5 million control volumes with clustering near the vanes
- Block-structured mesh
  - save computational time
  - reduce numerical dissipation
Boundary conditions

• Role of outlet box
  ➡ Drive vortices outside the chamber
  ➡ Dissipate the vortices

• Fuel Inlet
  ➡ Dirichlet BC, fixed in time
  ➡ Mass flow rate matches experiments

• Turbulent velocity inlet
  ➡ From auxiliary annulus simulation
Fuel Distribution

- Nozzle injection causes non-uniform fuel distribution in the radial direction

ACETONE PLIF

HISTOGRAM OF FUEL CONCENTRATION

- Richer mixtures closer to outer wall
Non-reacting Case Study

- Fuel stream replaced by acetone seeded air
- PLIF measurement of equivalence ratio

Operating Condition
Temperature: 300K
Pressure: 1 atm
Global equivalence ratio: 0.5
Bulk velocity: 2.5 m/s
Non-reacting Case Study

- Stratification effects inside mixing tube:
  - Fuel rich near outer wall
  - Small structure slightly unresolved

- Velocity measurement:
  - Dissipates slightly faster than measurement
  - Overall, predict reasonable well for velocity field

- Equivalence Ratio $\phi$
  - $x<18.7\text{mm}$
  - $x>18.7\text{mm}$

- Probability Density Mean
  - $x<18.6\text{mm}$, CFD
  - $x>18.6\text{mm}$, CFD

- Probability Density Variance
  - $x<18.6\text{mm}$, PLIF
  - $x>18.6\text{mm}$, PLIF

- Probability Density of $x$ (mm) and $U_z$ (m/s)
  - $x<18.7\text{mm}$
  - $x>18.7\text{mm}$

- CFD vs PIV

- Equivalence Ratio $\phi$ vs $x$ (mm) and $U_z$ (m/s)
Modeling Approach

• Based on large eddy simulation (LES)/flamelet approach

• Stratified mixtures
  ➡ Mixture fraction and progress variable required
  ➡ Flamelet progress variable (FPV) method

• Heat loss
  ➡ Additional coordinate for enthalpy defect
Heat Loss Modeling

- Introducing heat loss into flamelet
  - Modify flamelet equations to account for heat loss
    \[ \frac{\rho C_p \chi}{2} \frac{\partial^2 T}{\partial Z^2} = \dot{\omega}_h - \lambda \frac{T(Z) - T_w}{\delta} \]
  - Fourier heat loss term, varied based on \( \delta \)

- Transport equation of enthalpy defect
  \[ H = h_{tot} - h_{tot,Ad} \]
  \[ \frac{\partial \tilde{\rho} \tilde{H}}{\partial t} + \nabla \cdot (\tilde{\rho} \tilde{v} \tilde{H}) = \nabla \cdot \left( \frac{\mu_T}{Pr} \nabla \tilde{H} \right) + \nabla \cdot (\lambda \nabla T) - \nabla \cdot (\lambda_{Ad} \nabla T_{Ad}) \]
Adiabatic Reacting Case Study

Chemiluminescence

CFD

Eq. Ratio

2.000e+00

1.5

1

0.5

-0.000e+00
Non-adiabatic Reacting Case Study

Adiabatic
(1/50 real time speed)

Non-adiabatic
(1/50 real time speed)
Non-adiabatic Reacting Case Study

Chemiluminescence
Adiabatic
Non-adiabatic
Lean Premixed Combustion at High Pressures

- **MILD combustion conditions**
  - High recirculation rate to maintain combustion

- **Asymmetric nozzles**
  - Recirculation predominantly below the nozzles
  - Very high jet velocities

- **Broad reaction zones**
  - Strain influenced
  - Large heat loss to walls

- **Methane or hydrogen as fuel**

- **Experimental data from DLR**
DLR 3-jet Case: Numerical details

- 8 M grid points in the flow DNS limit
- Dirichlet BC for velocity and progress variable
- Extended pipes at the inlet to generate turbulence
- Inlet velocity 120 m/s
DLR 3-Jet Case - Heat Loss Effect

• Wall temperature has significant effect on flow structure
  ➡ Higher heat loss leads to smaller recirculation zone

• Simulations capture flow structure reasonably well
  ➡ Lack of adequate experimental data
  ➡ Some issues with measurements noted
Validation - DLR 1-Jet Case

- Modification of the 3-Jet case

  - Single nozzle inflow

  - Preheat premixed methane-air:
    - Operating pressure: 1atm
    - Jet bulk velocity: 90m/s
    - Wall temp: 1000K
    - Equivalence ratio: 0.67
Effect of Strain

- 1D unstrained model based tabulation
  - Overpredicts flame speeds even with heat loss
  - Combustion pushed towards thin reaction zone
- Approach: Incorporate strain effects
  - Consider opposed premixed flames
- Strain effects can lead to varying mappings

Obtained from B. Coriton, M. Smooke, A. Gomez (2016)
Counterflow Premixed Flame Tabulation

- Flow solution known to have hysteresis effect

- Two control variables
  - Mass flow (strain)
  - Product temperature (enthalpy)

Obtained from M. de Joannon a, A. Matarazzo b, P. Sabia b, A. Cavaliere (2007)
Comparisons with Experimental Data

- New flameout description highly accurate
  - Captures temperature profiles throughout combustor
Summary of Findings

• LES with modified flamelet closures
  ➡ Accurately predicts flashback processes
  ➡ Captures MILD combustion processes

• Solver plays a key role
  ➡ Non-dissipative numerics key to recovering turbulence characteristics

• Strain rate seen as key parameter for modeling low equivalence ratio MILD combustion devices
  ➡ Non-adiabatic formulations necessary where heat loss to walls is important
Products of Research

• Experimental database on boundary layer flashback
  ➡ Variety of fuels, equivalence ratios, pressures
  ➡ Time-series of velocity and flame front data

• General purpose LES solver for premixed and stratified flames
  ➡ OpenFOAM code base
  ➡ All solvers available cooperative release
    - Already used by 6 universities and industrial partners
    - Models included in low-Mach number version of solvers

• 4 PhDs (2 still in progress) + several journal articles