PREDICTING FLOW SPLITS AND LEAN BLOW OUT IN A GAS TURBINE COMBUSTOR

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- NASA Glenn Research Center
- NJFCP consisting of multiple Federal agencies
- AFRL
- Purdue
- UTRC
- UDRI
- UIUC
OUTLINE

- Motivation
- Objectives
- NJFCP & Referee Rig
- Computational Methodology
  - Non-reacting simulations – Flowsplits
    - Single Hole $C_d$ validation
    - Swirler component-wise flow splits
    - Total combustor flow splits
  - Reacting flow simulations for LBO computation with two chemistry mechanisms
    - Stable flame condition near LBO
    - Approach & Predictions for LBO
    - Flame structure during LBO
- Conclusion
MOTIVATION

• Emission regulations

• Depletion of fossil fuels

• Necessity of developing alternative jet fuels

• To reduce cost and time involved with the fuel qualification process (ASTM D4054) for alternative jet fuels
OBJECTIVES

• To develop a computational procedure based on the LES turbulence model with finite rate chemistry, automatic meshing and adaptive mesh refinement

• To assess the feasibility of these computational models to predict LBO for different fuels

• To accurately capture LBO sensitivity to fuel type
NATIONAL JET FUEL COMBUSTION PROGRAM

- Goals
  - Streamline the alternative jet fuel certification process
  - Generate fundamental fuel kinetics data for alternative fuels
  - Assess fuel effects on engine combustor figures of merit
  - Develop modeling capabilities to reduce the cost and time

- Referee Rig
  - A realistic single cup swirl stabilized combustor
  - Hybrid airblast fuel injector
  - Thousands of effusion injector holes
  - Two rows of dilution holes

- Measurements
  - Swirler flow splits
  - Combustor flowsplits
  - Lean blow out limits
  - Ignition probability at cold start condition
  - Ignition probability at high altitude relight

Figures of Merit (FOM): Lean Blow-Out and High Altitude Relight
# FUELS: A-2 AND C-1

- C-1: Alternative Jet fuel

- C-1 has lower density and surface tension compared to A-2

<table>
<thead>
<tr>
<th></th>
<th>Mol. Formula</th>
<th>Mol. Wt (kg/kmol)</th>
<th>Composition (% by mass)</th>
<th>H/C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cyclo-Paraffins</td>
<td>Iso-Paraffins</td>
</tr>
<tr>
<td>A-2</td>
<td>$C_{11.4}H_{22.1}$</td>
<td>159</td>
<td>31.86</td>
<td>29.45</td>
</tr>
<tr>
<td>C-1</td>
<td>$C_{12.6}H_{27.2}$</td>
<td>178</td>
<td>0.05</td>
<td>99.63</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>DCN</th>
<th>$(E/A)_{stoich}$</th>
<th>Viscosity (mPa s)</th>
<th>Density $kg/m^3$</th>
<th>$\Delta h_c (MJ/kg)$</th>
<th>10% Distillation Temp, $K$</th>
<th>90% Distillation Temp, $K$</th>
<th>Flash Point $K$</th>
<th>Freeze Point $K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-2</td>
<td>48.3</td>
<td>0.06803</td>
<td>1.17</td>
<td>803</td>
<td>43.1</td>
<td>449</td>
<td>517</td>
<td>321</td>
<td>222</td>
</tr>
<tr>
<td>C-1</td>
<td>17.1</td>
<td>0.06665</td>
<td>0.98</td>
<td>760</td>
<td>43.9</td>
<td>451</td>
<td>501</td>
<td>323</td>
<td>212</td>
</tr>
</tbody>
</table>

**IMPACT ON LBO?**
Non-reacting Study

Numerical Simulation of Flow Distribution in a Realistic Gas Turbine Combustor

Veeraraghava Raju Hasti¹, Prithwish Kundu¹, Gaurav Kumar¹, Scott A. Drennan¹, Sibendu Som⁵, and Jay P. Gore⁹¹⁶

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¹Convergent Science, Inc., New Braunfels, Texas 78130 USA
COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS

- Mass flow rate
- Temperature
- Walls: Adiabatic, Law of the wall
- Static pressure

Swirler Cross-sectional view of swirler
- Swirler slot
- Inner Swirler
- Outer Swirler
- Radial Swirler
- Spray

Primary dilution
Secondary dilution
Effusion
Primary dilution
Secondary dilution
Effusion
• Max. cell size: 3 mm
• Fixed embedding
• Boundary embedding
• AMR :
  Velocity: 3 levels
• Min. cell size: 0.375 mm
• Total Count: ~ 10 M
SWIRLER: TOTAL FLOW-SPLIT
(MESH-CONVERGENCE)

Mesh sensitivity results for swirler flow predictions (all passages open for this study) with RANS

<table>
<thead>
<tr>
<th>Computed (RANS)</th>
<th>Max. Cell Size = 3 mm</th>
<th>AMR Level = 3</th>
<th>FE Level (swirler) = 3</th>
<th>Min. Cell Size = 0.375 mm</th>
<th>Total Cells: 10 Million</th>
<th>Max. Cell Size = 3 mm</th>
<th>AMR Level = 5</th>
<th>FE Level (swirler) = 5</th>
<th>Min. Cell Size = 0.09375 mm</th>
<th>Total Cells: 35 Million</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Axial Swirler</td>
<td>Blue</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Inner Axial Swirler</td>
<td>Orange</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radial Swirler</td>
<td>Grey</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cooling Hole</td>
<td>Yellow</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Min. Cell Size, mm
Max. cell size: 3 mm
Min. Cell size : 0.375 mm
Total cell count : ~ 10 M

Comparison of component-wise flow splits for swirler passages for 10 million case.
COMBUSTOR : FLOWSPLITS

Coarse Mesh:
Max. cell size: 3 mm
AMR level : 3
Min. Cell size : 0.375 mm
Total cell count : ~ 10 M

Fine Mesh:
Max. cell size: 3 mm
AMR level : 4
Min. Cell size : 0.1875 mm
Total cell count : ~ 21 M
COMBUSTOR FLOWFIELD
Reacting Flow Simulations
(Compact mechanism)

Lean blow-out (LBO) computations in a gas turbine combustor

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Sibendu Som\textsuperscript{5}, Sang Hee Won\textsuperscript{1,6}, Frederick L. Dryer\textsuperscript{7,8} and Jay P. Gore\textsuperscript{7,9}

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\textsuperscript{9}University of South Carolina, Columbia, SC 29208 USA
COMPUTATIONAL MESH

- Max. cell size: 3 mm
- Fixed embedding
  - Swirl cup: 2 levels
  - Primary zone: 2 levels
- Adaptive Mesh Refinement:
  - Velocity: 3 levels
  - Temperature: 3 levels
- Min. cell size:
  - Coarse mesh: 0.375 mm
  - Fine mesh: 0.18 mm
- Total cell count:
  - Coarse mesh: ~ 10 M
  - Fine mesh: ~ 25 M

Temperature [K]
## CFD MODEL SETUP

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFD code</td>
<td>CONVERGE</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>LES – Dynamic Structure</td>
</tr>
<tr>
<td>Mesh</td>
<td>AMR with min. mesh – 0.37 mm - 0.18 mm</td>
</tr>
</tbody>
</table>
| Spray              | Lagrangian model  
  • Multi ring injection with drop size distribution from non-reacting PDPA data  
  • Secondary breakup: TAB model  
  • Dynamic drag model  
  • Frossling’s correlation for evaporation  
  • Turbulent dispersion model to account for SGS flow field effects on parcels   |
| Combustion model   | Detailed finite rate chemistry (laminar closure)                                                                                             |
| Fuel               | A-2, C-1                                                                                                                                     |
| Chemistry Mechanism| Compact mechanism  
  A-2: 44 species, 229 reactions  
  C-1: 43 species, 267 reactions                                                                 |

**Diagram:**
- PDPA Measurement
- 2 mm
- 25.4 mm

**Graph:**
- CDF
- Droplet Diameter, μm
- R = 0.05 mm, R = 0.15 mm, R = 0.3 mm, R = 0.5 mm, R = 0.7 mm, R = 0.8 mm
FLOW THROUGH TIME (APPROXIMATE)

- This study carried in a reacting case for A-2 fuel at near LBO phi = 0.096 (stable flame condition)
- The combustor filled with a tracer at t= 0.072 (denoted as t=0 in the line plot on right)
- 80% of the mass is moved out of the domain in approximately 15 ms
- Tracer trapped in the recirculation zones may take longer

$t_0 = 72$ ms
LBO SIMULATIONS: APPROACH AND INDICATOR

- Simulations ignited using energy source and higher fuel flow rate
- Fuel flow then ramped down to $\phi=0.096$ with stable combustion
- Run up to quasi steady state
- Reduce the fuel flow rate in a stepwise manner and reaching a quasi-steady state for heat release rate after each reduction
- Heat release rate is used as a criterion for identifying the lean blowout.
- Same factor of reduction in each nozzle “ring”
NEAR LBO : SPRAY VALIDATION
- RADIAL VELOCITY: A-2 FUEL

- Spray data averaged over 40 ms after reaching quasi-steady state for heat release rate
- Matches reasonably well near the dome at 5 mm and 10 mm
- Profile captured very well but under prediction for magnitude at z = 25 mm and 35 mm
NEAR LBO: SPRAY VALIDATION
- RADIAL VELOCITY: C-1 FUEL

- Spray data averaged over 40 ms after reaching quasi-steady state for heat release rate
- Matches reasonably well near the dome at 5 mm and 10 mm
- Profile shape captured correctly but under predicted for magnitude at z= 25 mm and 35 mm
NEAR LBO : SPRAY VALIDATION
– AXIAL VELOCITY

- Spray data averaged over 40 ms after reaching quasi-steady state for heat release rate
- Matches reasonably well near the dome
- Peak location shifted radially outward and under prediction for magnitude further downstream of the dome

NEAR LBO: SPRAY VALIDATION - SMD

- Spray data averaged over 40 ms after reaching quasi-steady state for heat release rate
- Hollow cone spray with larger droplets towards the center and CFD model captured this trend for both fuels
- Better agreement with experiments for the downstream locations

NEAR LBO : FLAME SHAPE

- OH mass fraction averaged over 40 ms after reaching a steady state for heat release rate
- Line of sight averaged excited OH data from experiments compared against LOS averaged OH mass fraction from LES
- Only qualitative comparison
- The simulations capture the qualitative trends accurately with the right radial and axial spread of the flame
- Mesh resolution study for A-2 fuel show similar peak locations for OH

LBO SIMULATIONS

• Each step down in phi is monitored for 2 flow-through times
• HRR is monitored for successive stepdown in global equivalence ratio
• HRR drops rapidly at $\phi = 0.085$ for A-2 and 0.092 for C-1 fuel
LBO : A-2 FUEL

Time = 0.119 [s]

During blow-out
• A-2 fuel has a lower LBO limit compared to C-1
• The CFD model along with compact mechanism is able to capture the LBO trends
A Numerical Study of Flame Characteristics during Lean Blow-Out in a Gas Turbine Combustor

Veeraraghava Raju Hasti\textsuperscript{3}\textsuperscript{*1}, Prithwish Kundu\textsuperscript{5}\textsuperscript{3}, Gaurav Kumar\textsuperscript{3}2, Scott A. Drennan\textsuperscript{3}14, Sibendu Som\textsuperscript{3}5, and Jay P. Gore\textsuperscript{5}34

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</tr>
<tr>
<td>Combustion model</td>
<td>Finite rate chemistry – homogeneous reactor</td>
</tr>
<tr>
<td>Fuel</td>
<td>A-2, C-1</td>
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<tr>
<td>Chemistry Mechanisms</td>
<td>HyChem mechanisms*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>A-2 (# species)</th>
<th>C-1 (# species)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detailed</td>
<td>119</td>
<td>119</td>
</tr>
<tr>
<td>Skeletal</td>
<td>41</td>
<td>34</td>
</tr>
<tr>
<td>Reduced</td>
<td>31</td>
<td>26</td>
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STABLE FLAME CONFIGURATION

Global equivalence ratio – 0.096

<table>
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<th>Detailed</th>
<th>Skeletal</th>
<th>Reduced</th>
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Stable flame condition

1. Plane averaged OH mass fractions from simulations compared against OH* chemiluminescence
2. Time averaged OH mass fractions calculated over 2 flow-through times
3. High concentration of OH corresponds to high temperature heat release
4. Model is able to capture the correct flame stabilization region and spread in radial and axial directions
5. All three mechanisms predict stable flame and similar flame shapes at $\phi_{\text{global}} = 0.096$
6. Computational costs: Detailed mechanism – 50,000 CPU Hrs
   Skeletal mechanism - 20,000 CPU Hrs
LEAN BLOW OUT OF A-2 FUEL

- Temperature and intermediate species contour plots at combustor mid-plane
- Simulations predict LBO at 0.080
- Flame is observed to stabilize inside the swirl cup under stable conditions
- Flame liftoff increases gradually as fuel flow rate decreases and heat release rate shows significant drop as we approach LBO
- Formaldehyde formation is observed near the spray cone surface
- CH2O gets oxidized in the high temperature regions
- Higher CH2O concentrations are observed in downstream regions when approaching LBO indicating partial oxidation

Heat release rate during LBO
LBO SENSITIVITY TO FUEL

Same modeling procedure applied to C-1 fuel with skeletal mechanism
C-1 blows out at higher global equivalence ratio of 0.084
Simulations are able to accurately capture LBO trends
CONCLUSIONS

1. Implemented a LES model with detailed chemistry to compute LBO in realistic gas turbine combustor
2. Rendered all flow paths including effusion cooling holes using autonomous meshing strategy
3. Validation of modeling approach for a single hole, component wise swirler passages and combustor
4. Validation of modeling approach at stable flame condition for both fuels
5. Nearly accurate prediction of LBO limits and trends for two fuels within ±6%
6. Developed and demonstrated the efficacy of chemistry mechanism in predicting LBO trends
7. Feel confident about the methodology to predict High Altitude Relight (HAR)
THANK YOU

Q & A