CFD-BASED DESIGN OF A FILMING INJECTOR FOR N+3 COMBUSTORS

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Motivation for Current Work

• NASA’s N+3 (2030 target) Project Goals:
  – Reduce NOx emissions to 80% below ICAO CAEP6 standards
  – “smaller core-size” and “higher T3” as compared to N+2/ERA
  – Evaluate feasibility of drop-in alternate fuels

• Lean-Direct Injection (LDI) concepts being studied by OEMs and several injector manufacturers to reduce emissions

• Current work: Aerodynamic Design of 3\textsuperscript{rd} generation LDI (LDI-3) Injection modules using the National Combustion Code (NCC)
Purpose of Current Work

• Use CFD analysis with the NCC to evaluate new, updated injector design(s) to meet NASA’s N+3 technology goals

• Impact aerodynamic design of LDI-3 Injection modules
  • Evaluate new Pilot and Main Injection Element design

• CFD predictions of LDI-3 injector performance and emissions
  • Evaluate filming fuel injection strategy for Main Injection Element
Why use NCC for LDI System Design?

M1 Simplex
M2 Airblast
M3 Airblast
P  Simplex

17M element all-tetrahedral mesh
CFD Calibration Results from LDI-2 Data

EINOx for 5-pt Recess Configs 3,7,9, Baseline Config 10

NCC vs Experiment (EINOx)

NCC CFD Emissions Calibrated for a wide range of N+2 Cycle Operating Conditions
LDI-2 vs LDI-3 Injector Layout

- Large decrease in fuel-injection module complexity with LDI-3 while maintaining effective area of individual injectors
- Much denser packing of injectors at combustor dome face
- Higher reference velocity for LDI-3 due to smaller annulus/dome area of combustor
• Large decrease in fuel-injection module complexity with LDI-3 while maintaining effective area of individual injectors
LDI-3 Filming Injector for Main Elements

- Main Injector Air flows through axial bladed swirl venturis
- Two major airflow paths (co-swirling or counter-swirling)
- One center-jet air pathway provides high velocity jet for ‘control’
- Fuel fed tangentially into cross-flowing air-stream of inner air swirlers
Parametric Design Goals with NCC CFD

1. Maximize the total $A C_d$ of the five-element array (Pilot and four Mains)

2. Provide an ‘optimal’ central recirculation downstream of the Pilot

3. Fuel-air mixing and burning in all injector elements to meet N+3 performance, emissions
Summary of National Combustion Code (NCC)

- Finite-Volume solutions of Time-dependent, Navier-Stokes equations
- 2-equation, k-ε turbulence models (non-linear, low-Re or wall-functions)
- Lagrangian spray-modeling with primary/secondary breakup and atomization options, multi-component fuels
- Reduced-kinetics, Finite-rate chemistry models
- RANS time-integration and/or VLES with Time-Filtered Navier-Stokes (TFNS) approach
Parametric I: LDI-3 Single Swirler Design

<table>
<thead>
<tr>
<th>Swirler Configuration</th>
<th>Expt</th>
<th>CFD</th>
<th>Error (%)</th>
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<tr>
<td>52°/60° (OAS/IAS) co-rotating</td>
<td>0.137</td>
<td>0.1411</td>
<td>3.0</td>
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<tr>
<td>52°/60° (OAS/IAS) counter-rotating</td>
<td>0.134</td>
<td>0.1259</td>
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<tr>
<td>48°/60° (OAS/IAS) counter-rotating</td>
<td>0.144</td>
<td>0.1467</td>
<td>1.9</td>
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Single-Element Optimization
Single-Element Spray Optimization
Five-Element Module Design

• A central ‘Pilot’ element (pressure-atomizing injection) and four adjacent ‘Main’ elements (pre-filming injection)
• Four Main elements with CFD-optimized 48°/60° outer/inner counter-rotating axial air swirlers
• Central Pilot injector with multiple, radial inflow slots for airflow. Air inflow direction is 51% offset with respect to the injector centerline.
• Two rows of cooling holes on pilot venturi surface, with 18 and 24 cooling holes respectively
Five-Element Module CFD Setup
Non-Reacting Flow: RANS vs TFNS
Non-Reacting Flow: RANS vs TFNS

<table>
<thead>
<tr>
<th>Method</th>
<th>Total (in²)</th>
<th>Mains (in²)</th>
<th>Pilot (in²)</th>
<th>Error (%)</th>
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<tbody>
<tr>
<td>Measured</td>
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<td>0.575</td>
<td>0.145</td>
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<tr>
<td>NCC RANS</td>
<td>0.744</td>
<td>0.620</td>
<td>0.124</td>
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<tr>
<td>NCC TFNS</td>
<td>0.752</td>
<td>0.621</td>
<td>0.131</td>
<td>4.4</td>
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Parametric II: LDI-3 Main Swirlers
Parametric III: LDI-3 Pilot Swirlers
5-Element Module: Reacting Flow
5-Element Module: Reacting Flow

EINOx = 25

EINOx = 29
Effect of Turbulence-Chemistry Interaction (PDF)
Effect of Turbulence-Chemistry Interaction (PDF)

![Diagram showing the effect of turbulence-chemistry interaction with different EINOx values](image)

- **EINOx = 9**: TFNS w/PDF Chemistry (Pilot, MAINS, Main), TFNS w/Laminar Chemistry (Pilot, MAINS, Main)
- **EINOx = 29**: TFNS w/PDF Chemistry (Pilot, MAINS, Main), TFNS w/Laminar Chemistry (Pilot, MAINS, Main)

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Summary and Future Work

• NCC CFD shown to be useful to narrow the design matrix for LDI-3 injector aerodynamic design (Main, Pilot Swirlers)
• NCC CFD shown to compare well with experimental data for filming injector spray particle distribution
• Proposed LDI-3 injector redesign improves on LDI-2 injector design with
  – Reduced number of injection elements
  – Reduced Complexity of fueling circuits
  – Better thermal management of fuel system
• Drawbacks of transverse fuel-injection approach (JPC 2015) successfully redesigned with filming-injection approach
• Turbulence-chemistry interaction approach shows large influence of temperature and emissions predictions
Summary and Conclusions

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Future Work

• NCC CFD to be used to evaluate 7-element module of 19-element configuration
• Evaluate NCC CFD turbulence-chemistry interaction models (PDF and LEM) with available LDI-2 experimental database for EINOx predictions
• Investigate sensitivity of CFD solution to spray specifications for modeling of filming injection in main swirlers
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