Parametric CFD Analysis of Low NOx Combustor Designs for Commercial Supersonic Aircraft

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Motivation and Approach

- NASA's Commercial Supersonic Technology (CST) Project Goals:
  - Design a combustor that produces EINOx emissions below 10 at Supersonic Cruise for an advanced gas-turbine engine
    - CST Combustors will operate 'hot' for much longer durations (90-95% of cycle) than current subsonic combustors. Unique challenges for fuel burn, **emissions**, thermal stability of fuels and thermal load management.

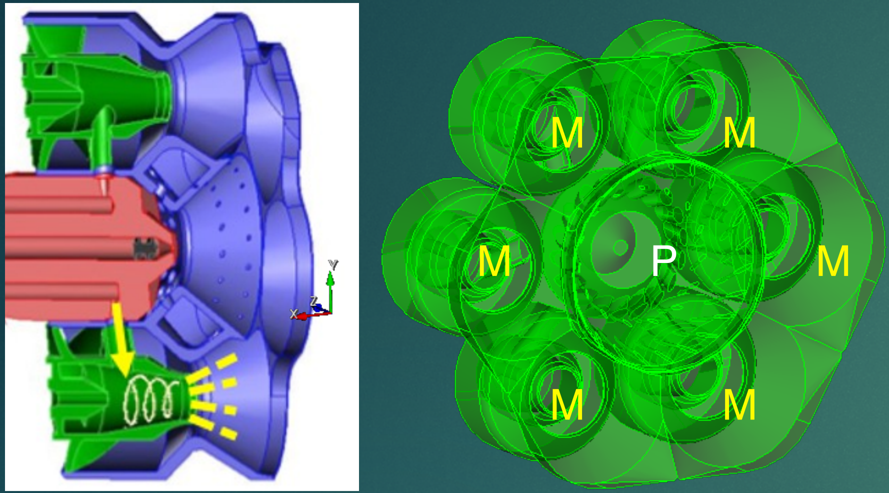
- NASA CST Project Focus (Combustion):
  - Evaluate NOx emissions of new Lean Direct Injection (LDI) designs for NOx reduction.

- Current Work: Parametric CFD analysis of design variations in a single-cup Low NOx injector at supersonic cruise with the Open National Combustion Code (OpenNCC)

What are the impacts of varying the swirler angles of axially bladed Main swirlers on combustor flame characteristics and EINOx emissions?

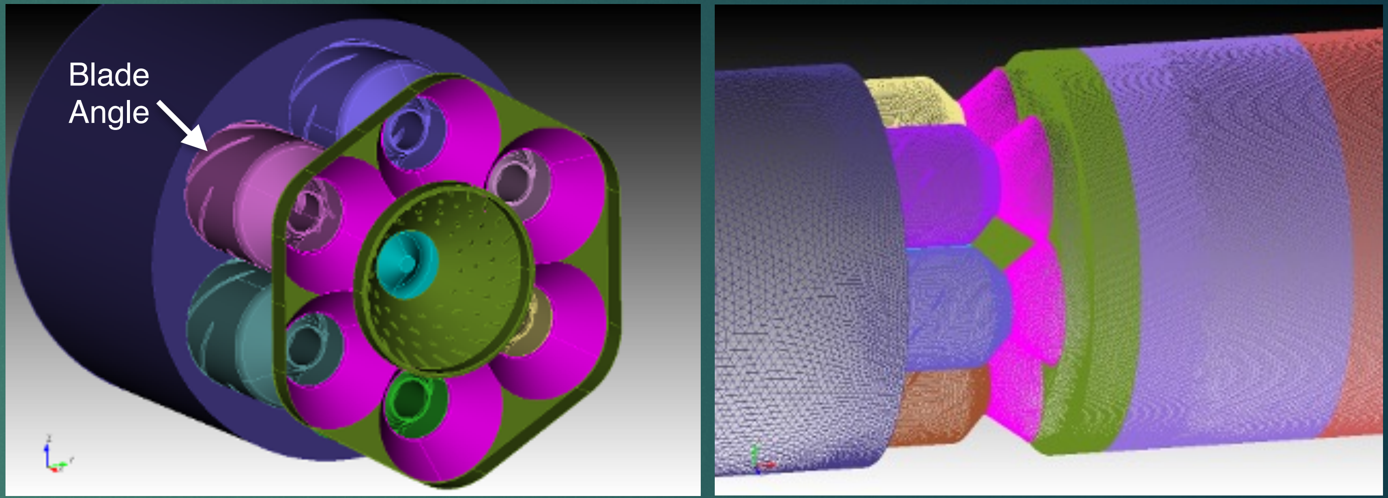
Low NOx Single-Cup Designs for CST

- Redesign Woodward FST Inc. LDI3 Single-Cup Injector with 7 injection elements



Six Mains (M): Axially Bladed Swirler Passages (6 each)
Pilot (P): Two angled rows of cylindrical slots (angled)

Flametube Geometry (Left) and Surface Mesh (Right)



Four Swirler Variations from Baseline* for Mains (M)
Pilot (P) swirler is identical for all design variations

Main Swirler Blade Angles	60°	55°	55° (Alt)	52°	48°
Mains ACd, in^2 (CFD)	0.7	0.8	0.8	0.9	1.0
Mains ACd, % change	-20%	-10%	-10%	0%	10%

Pilot Swirler ACd (All Designs) = $0.125 in^2$

*Ref. ACd (LDI-3, Mains): Expt. = $0.85 in^2$, CFD = $0.91 in^2$ [Ajmani et al, AIAA 2019-4371]

Four design variations of Main swirler angles identified for reacting-flow CFD analysis

Physical Models for OpenNCC

- Time-Filtered Navier-Stokes (TFNS) solver, LES solver (two-equation, cubic k-ε model)
- Lagrangian spray-modeling for liquid fuel droplets (prescribed droplet distribution, number of droplet groups, injection velocity and direction)
- Multiple Time-Scale Flamelet Progress Variable (MTSFPV) Solver with modified mixture fraction equation for fuel droplet evaporation, secondary progress variable equations for NOx species. Energy equation recast to maintain energy conservation.
    - MTSFPV Flamelet Table generated using Flamelet Generation Manifold (FGM) method with assumed pdf approach. 41-species HyChem Skeletal Kinetics[1] for Jet-A fuel.

      [1] H. Wang et. al, *Combustion and Flame* 193 (2018) 502-519.
    - Modified mixture fraction equation to include source terms for droplet evaporation

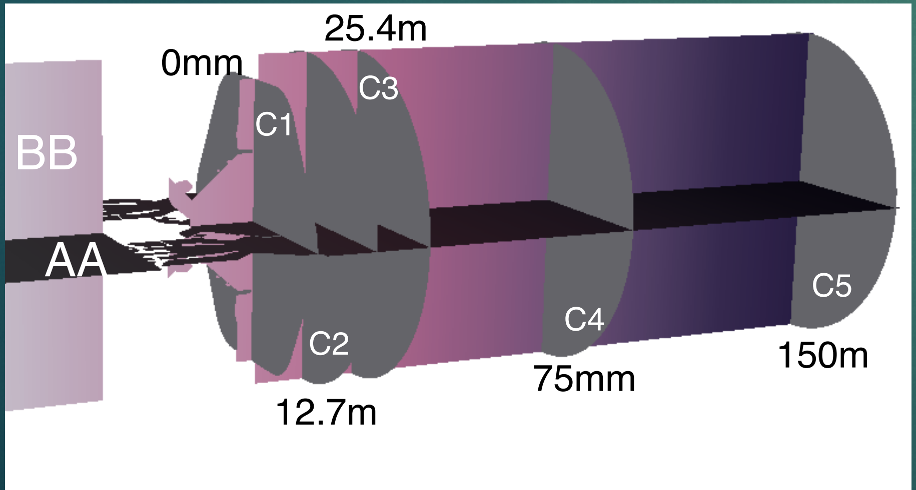
      $$\frac{\partial}{\partial t}(\bar{\rho}\bar{Z}) + \frac{\partial}{\partial x_i}(\bar{\rho}u_i\bar{Z}) - \frac{\partial}{\partial x_i}(\bar{\rho}(D+D_T)\frac{\partial \bar{Z}}{\partial x_i}) = \dot{S}_v$$
    - Secondary progress variables equations for each NOx species (NO, N, NO_2, N_2O). Source terms computed with Cantera using NOx-only reaction set.
        - Slowly evolving NOx species in post-flame region. NO_x chemical source terms expected to be weakly dependent on turbulence-chemistry interactions and evolve downstream of primary flow zone.

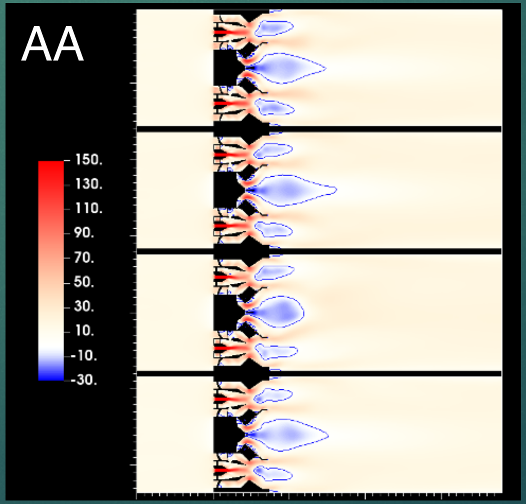
      $$\frac{\partial}{\partial t}(\bar{\rho}\overline{Y}_{p,j}) + \frac{\partial}{\partial x_i}(\bar{\rho}u_i\overline{Y}_{p,j}) - \frac{\partial}{\partial x_i}\left(\bar{\rho}(D+D_T)\frac{\partial \overline{Y}_{p,j}}{\partial x_i}\right) = \overline{\dot{S}_{p,j}}$$

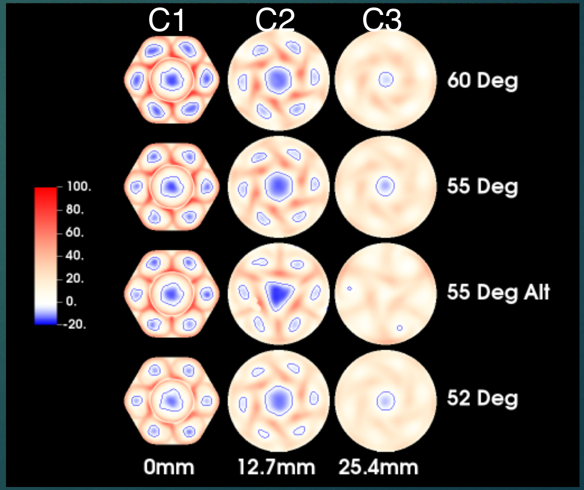
Two-Phase Reacting Flow CFD to predict flame-structure, NOx emissions

Low NOx Injector CFD with OpenNCC

- NASA GRC Axial Swirler Re-design for Single Cup Injector with 7 injection elements.
  - Four blade angle variations of air-flow passages with six Main elements. No change to central Pilot element. Fuel Injection: Pre-filming air-blast for Mains, Pressure-atomizer for Pilot (Woodward FST Inc.) Total fuel flow is evenly split among all seven injection elements.
- Objective: Use pre-test CFD predictions to down-select two injector designs for manufacturing and testing at NASA GRC's CE-13C combustion facility
  - CST Cruise Condition: P_3=1.59MPa (234psia), T_3=884K (1130 F), T_4=1824K (2823F), Δp=3.5% (No Liner Cooling)
- 55^{o} design down-selected as 1^{st} configuration based on non-reacting LES results for better recirculation zones (CRZ) than 55^{o} alt and 52^{o}. 55^{o} alt design eliminated (shortest pilot CRZ).



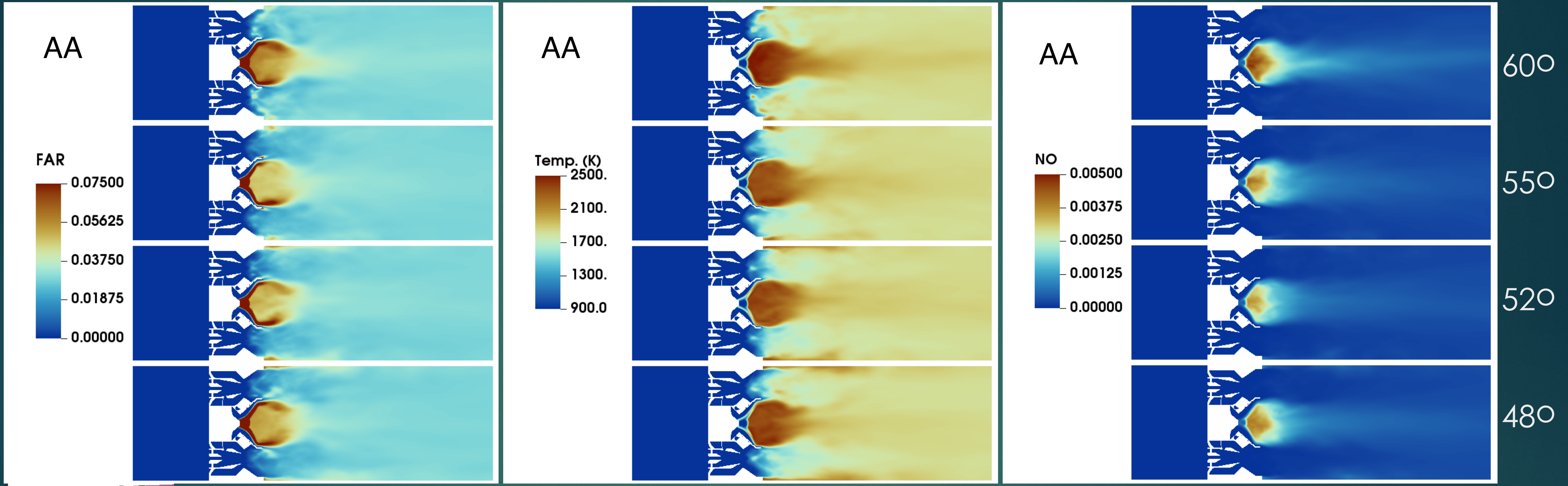


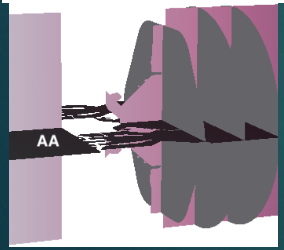


Non-reacting flow LES informed initial down-selection among four swirler designs

Low NOx Injector CFD: 60°, 55°, 52°, 48° Mains

Reacting Flow CFD Comparisons for Mid-Plane Section: FAR, Temperature (K), NO mass-fraction



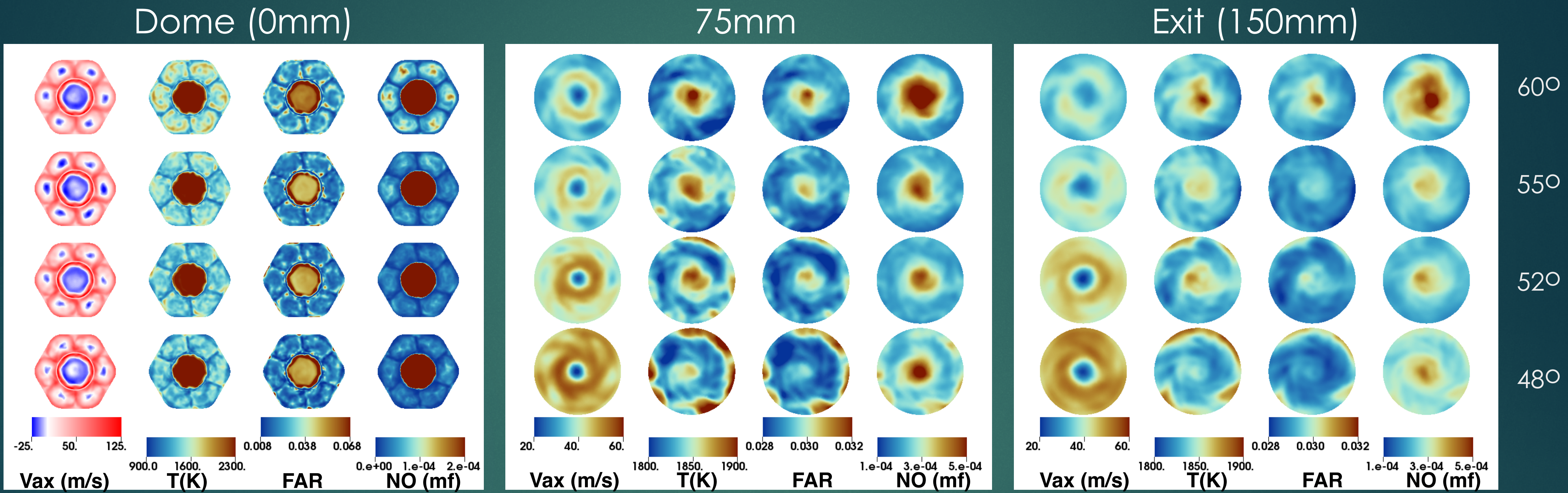


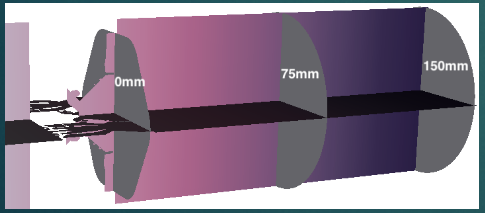
Swirler Angle	60o	55o	52o	48o
EINOx	15.8	12.6	12.3	15.6

55o and 52o swirlers predicted to have ~20% lower EINOx compared to 60o and 48o designs

Low NOx Injector CFD: 60°, 55°, 52°, 48° Mains

Reacting Flow CFD Comparisons for Axial Sections: FAR, Temperature (K), NO mass-fraction





- EINOx production at center PILOT very similar for all designs; highest for 60°
- EINOx production behind MAINS at dome: 60° > 55° > 48° > 52°
- EINOx near combustor wall at 75mm and Exit Plane : 48° > 52° > 55° > 60°
- EINOx distribution at exit is dominated by PILOT, particularly for 60° case
- From a liner cooling perspective, 55° design preferred over 52° design.
  - 48° (baseline)design also has significant liner-cooling challenges

Summary of OpenNCC CFD Results

Swirler Angle	60°	55°	52°	48°
EINOx (CFD)	15.8	12.6	12.3	15.6
Mains ACd, in^2	0.7	0.8	0.9	1.0

- OpenNCC CFD predictions indicate that a ~20% EINOx decrease can be obtained for CST cruise conditions with the selection of 55° Main swirlers.
- Even with its higher EINOx, the 60° design was selected over the 52° for two reasons:
  - (a) potential to further reduce EINOx by performing fuel-staging between PILOT and MAIN injectors
  - (b) lower liner cooling flow requirement at combustor walls as compared to 52° design.
- The reduced effective areas of both down-selected designs (compared to 52° and 48° designs) will require the engine to run at higher FAR for equivalent cycle thrust.

Based on the CFD parametric study with the OpenNCC, the 55° and 60° designs were chosen for manufacturing and testing at NASA GRC's CE-13C facility.

Significance and Future Work

- Starting from a baseline lean direct injection (LDI) design previously tested at CST cruise conditions, the CFD parametric study demonstrated the effect of Main Swirler redesigns on EINOx for a single-cup injector.
- Pre-test CFD results informed cruise NOx targets for a combustor design Technical Challenge under CST.
- The capabilities of multi-phase eddy-resolving CFD simulations of the OpenNCC (with accelerated NOx computation) were applied to identify two designs for manufacturing and testing at NASA GRC.
- Future Work:
    - Detailed comparisons of OpenNCC CFD predictions with measurements from NASA GRC's CE-13 test facility.
    - CFD evaluation of low power operability, performance of two selected designs.

Acknowledgements

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- NASA Advanced Supercomputing (NAS) Facility at NASA Ames
- CUBIT mesh generation software (Sandia National Labs)
- VisIt flow visualization software (Lawrence Livermore National Labs)
- Woodward FST, Inc. provided CAD for the baseline LDI-3 designs developed under NASA's Advanced Air Transport Technologies (AATT) Project.