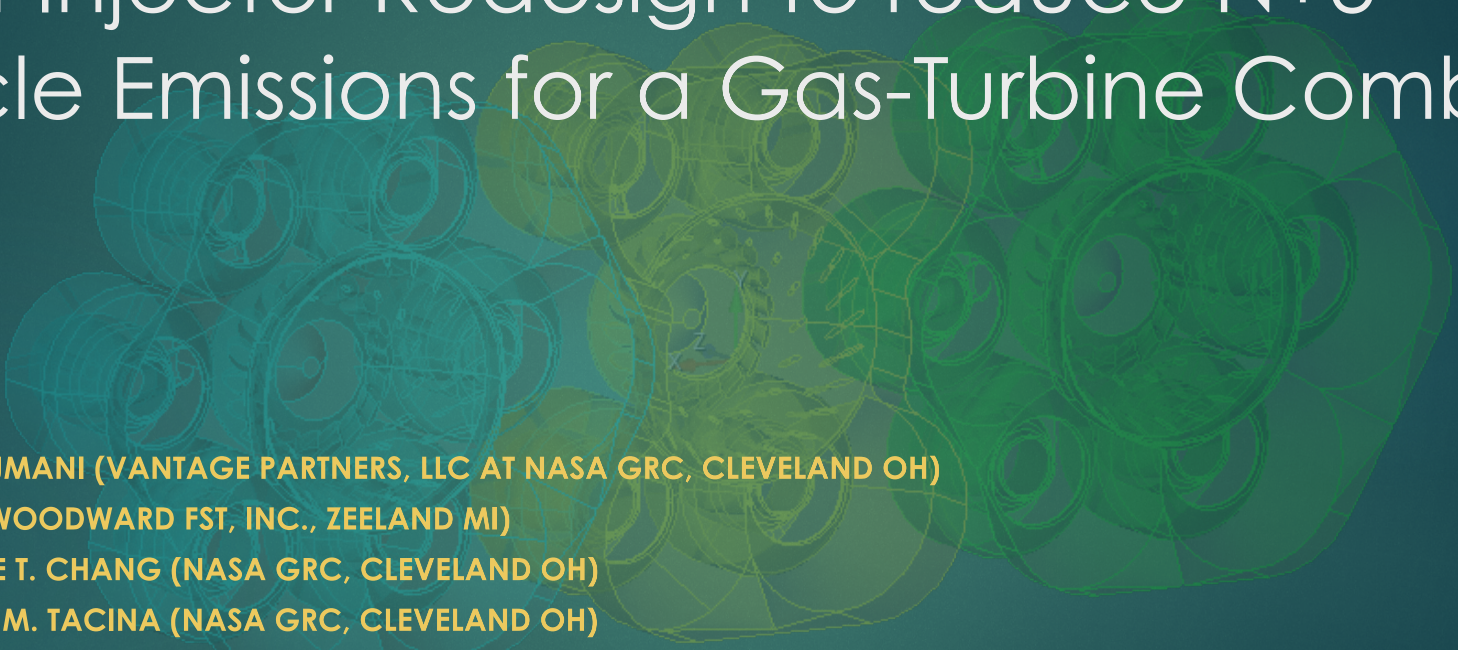
Pilot Injector Redesign to reduce N+3 Cycle Emissions for a Gas-Turbine Combustor



KUMUD AJMANI (VANTAGE PARTNERS, LLC AT NASA GRC, CLEVELAND OH)
PHIL LEE (WOODWARD FST, INC., ZEELAND MI)
CLARENCE T. CHANG (NASA GRC, CLEVELAND OH)
KATHLEEN M. TACINA (NASA GRC, CLEVELAND OH)

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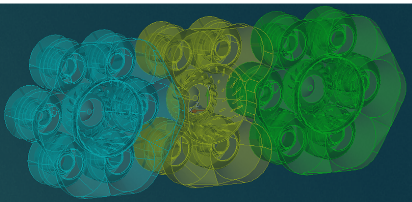
Motivation for Current Work

- NASA's N+3 (2025-2035 target) Project Goals:
  - Reduce NOx emissions to 80% below ICAO CAEP6 standards under Advanced Air-Transport Technology (AATT) NASA project
  - "smaller core-size" and "higher OPR" as compared to N+2/ERA

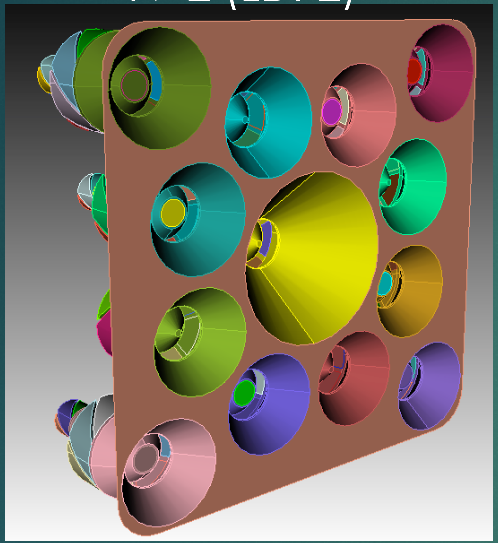
- NASA Glenn Research Center's N+3 Project Focus:
  - Design/Evaluate Lean-Burn/Lean-Dome combustors in partnership with OEMs and injector manufacturers to meet program goals

- Current work: CFD analysis of a *redesigned* 3rd generation Lean Direct Injection (LDI) flame-tube array for medium-power N+3 ICAO conditions using National Combustion Code (OpenNCC)

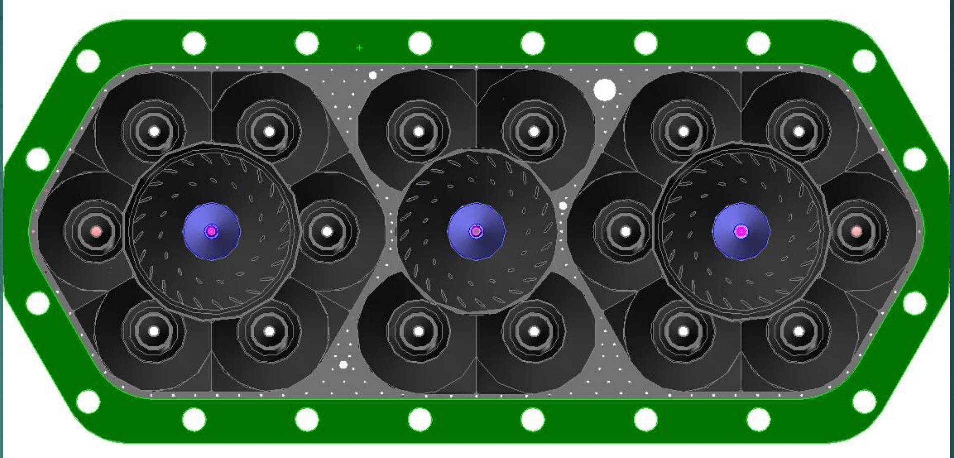
N+2 (LDI-2) vs N+3 (LDI-3) Injector Layout



N+2 (LDI-2)



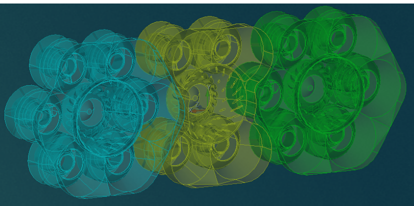
N+3 (LDI-3)

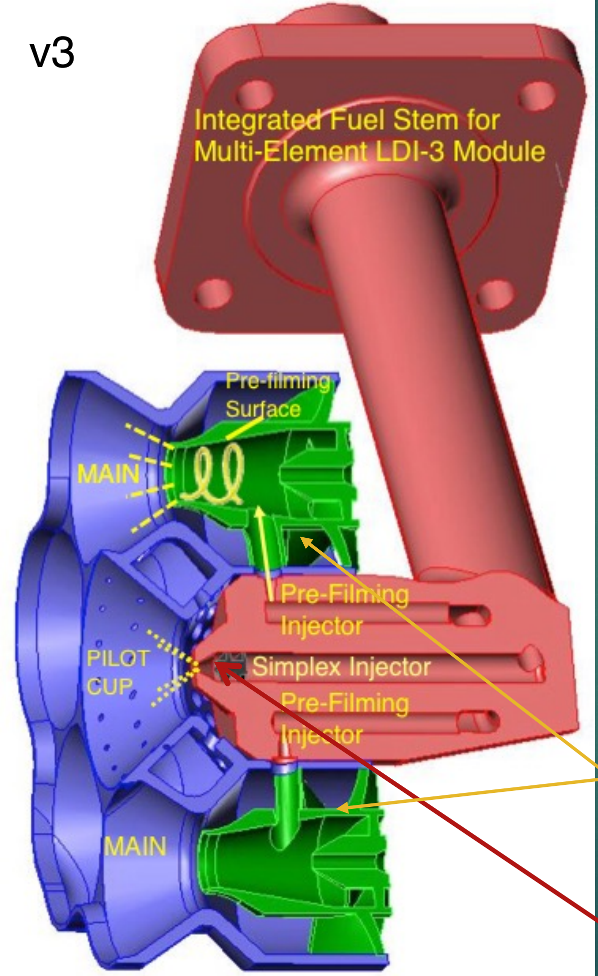


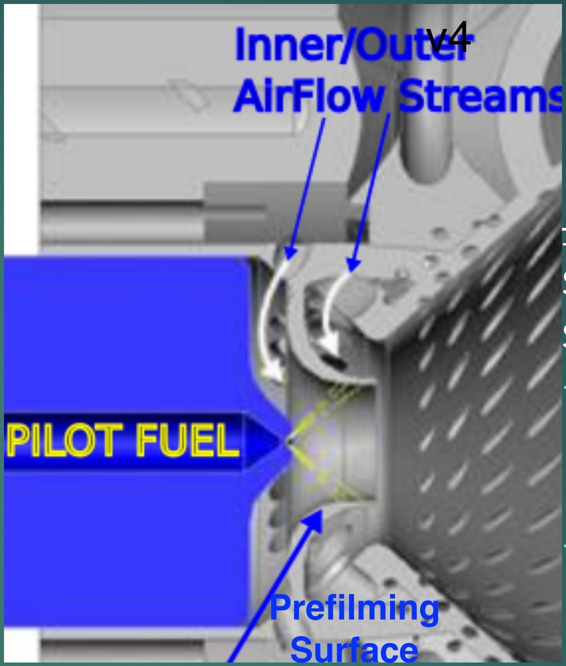
- To accommodate requirements of N+3 combustor designs:
  - Reduce dome height >> denser packaging of injectors at dome face
  - Maintain similar effective area >> higher reference velocity
  - Redesign of Main element fuel injection: plain orifice, pre-filming injector
  - Redesign of Pilot element air-flow passages: compound-angle plain-jets

  - Reduction in fuel-system complexity, better thermal management of fuel >> integration of multiple fuel lines into single fuel stem

LDI-3 Pilot/Main Injector Design







- *Pilot* fueled by simplex injector spraying onto pre-filming surface
  - CFD used to down-select inner/outer airflow stream flow-rates
  - CFD used to decide on relative swirl orientation of airflow streams (co-rotating or counter-rotating)

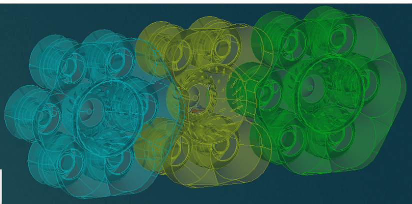
Woodward FST pre-filming injector for *Mains*.

- Fuel injected via plain jet orifice into prefilmer.
- Axial bladed swirlers for air flow

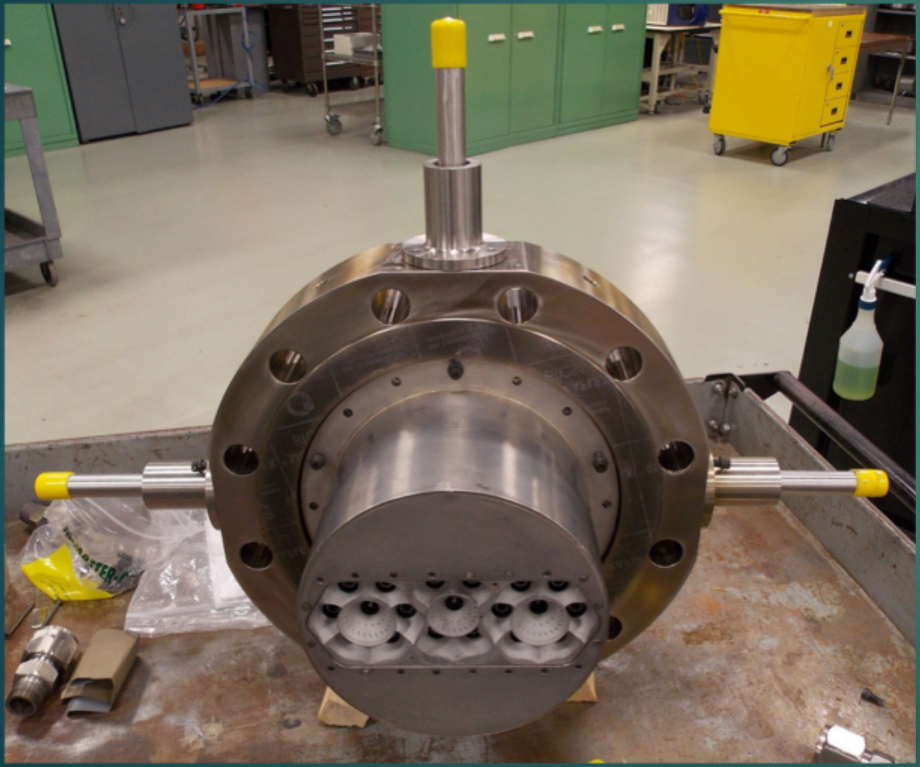
Pilot fueled by simplex injector. Circumferential air-flow

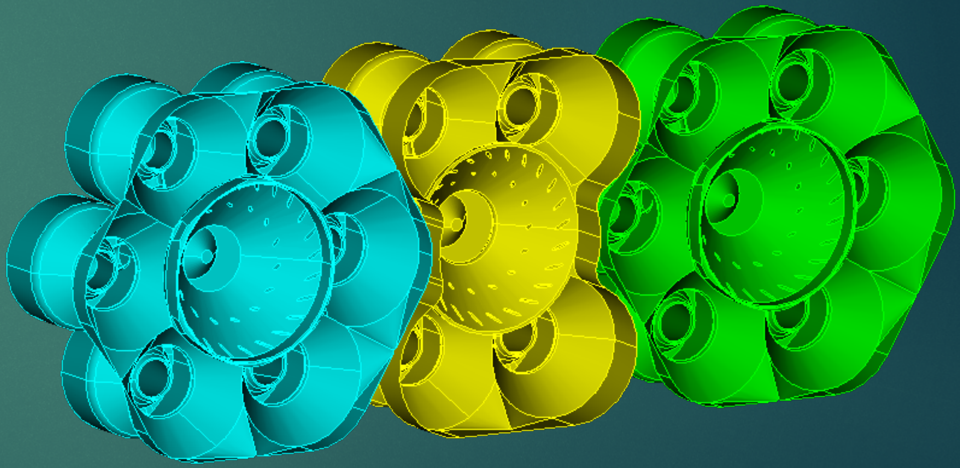
OpenNCC analysis provided design-optimization of main/pilot element airflow passages

19-Element Module Assembly Flametube Setup for NASA GRC's CE-5 Rig



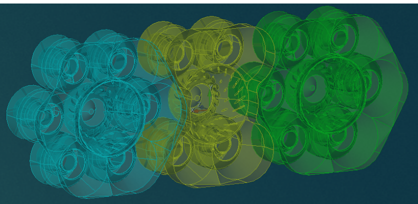
Aft looking Upstream





Aft Looking Upstream

Version 4 vs Version 3 PILOT



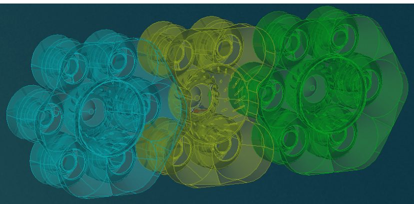
The goal was to arrive at an improved Pilot injector configuration that would meet the design requirements of :

- similar effective area when compared to version 3 design
- ‘optimal’ size of primary recirculation zones for flame stability
- emissions improvements at cruise conditions

Geometry parameters studied with OpenNCC in the current effort included

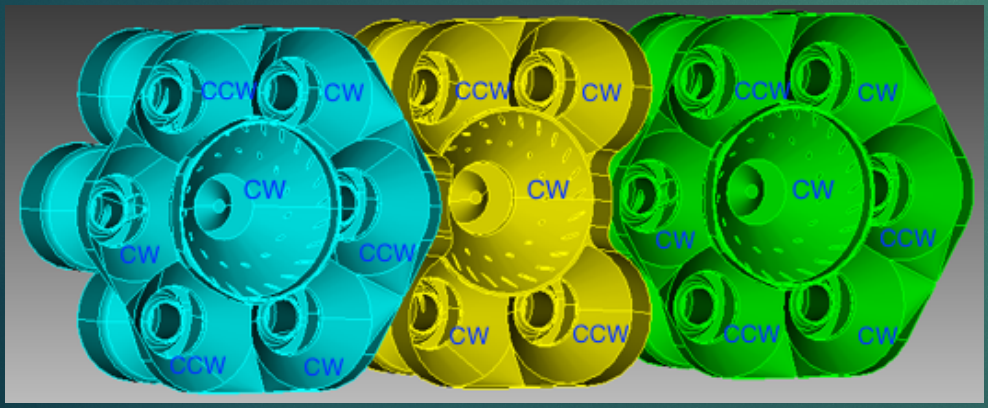
- air-flow splits of primary and secondary air-streams of pre-filming Pilot
- orientation (counter or co-rotating) of the pre-filming pilot injector primary and secondary air-streams

Version 4 vs Version 3 Pilot Injector

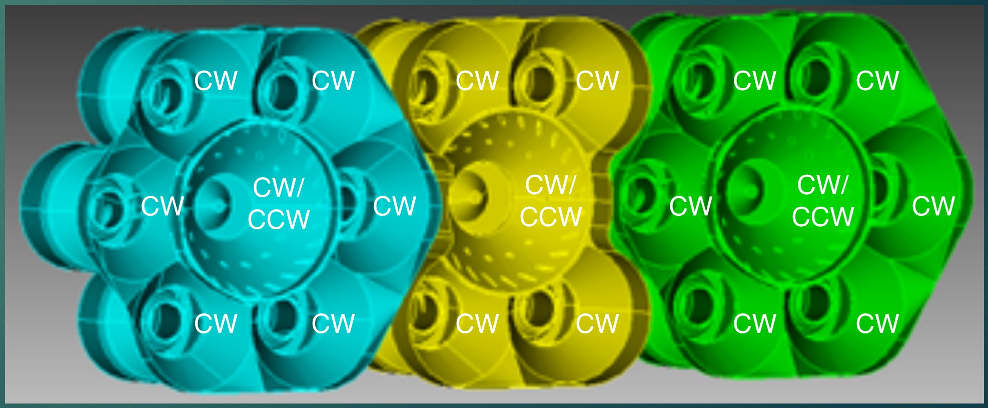


- Partially pre-filming Pilot (v4) vs non pre-filming Pilot (v3)
- All Mains co-Rotating (v4) vs co-/counter-rotating Mains (v3)
- Cooling flow in the pre-filming pilot injector venturi (v4) was increased by 35% as compared to the ‘baseline’ pilot (v3). Cooling flow area at the dome was increased by 10%.

v3 Swirler Orientation

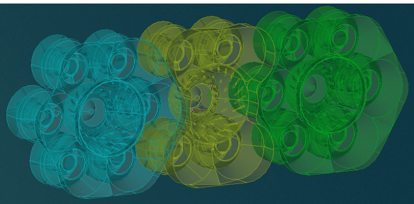


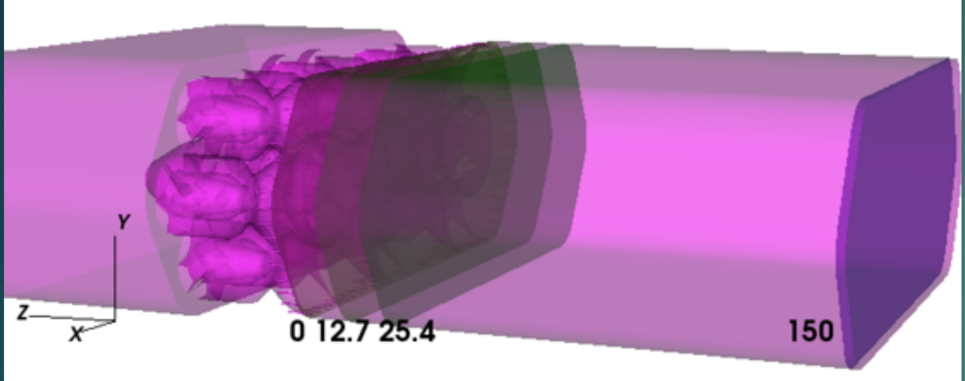
v4 Swirler Orientation

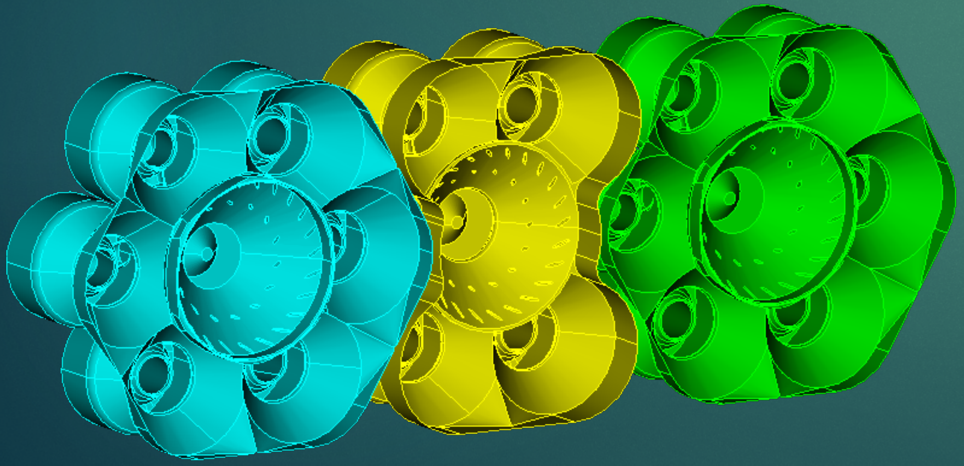


OpenNCC CFD provided design inputs for Pilot element airflows, cooling passage design

CFD Setup for 3-Cup Flametube (Computational Domain, Mesh)

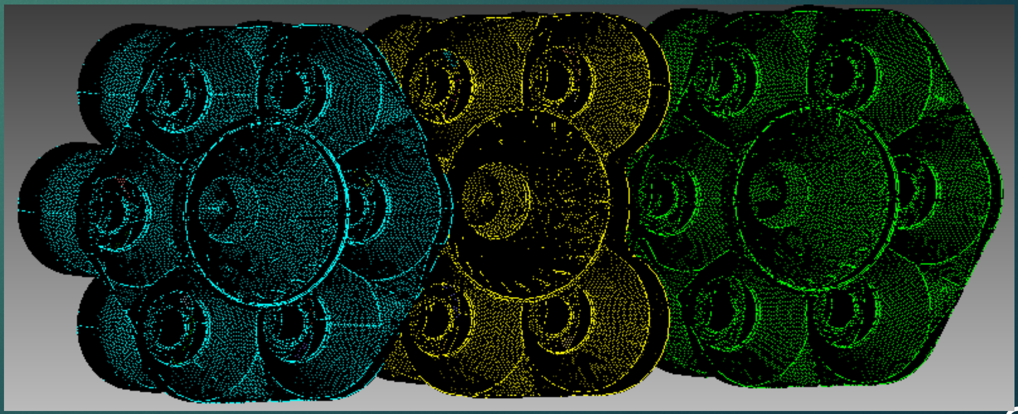




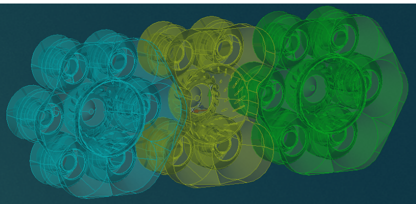


Aft Looking Upstream

Surface Mesh

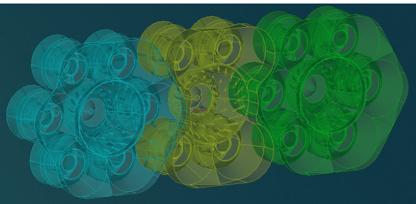


Physical Models for OpenNCC CFD



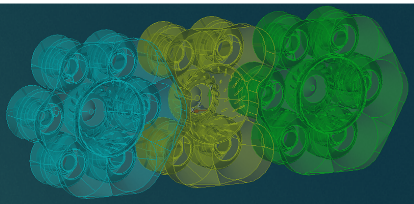
- Finite volume, , 4-stage Runge-Kutta explicit scheme, 2nd order time-accurate
- Time-Filtered Navier-Stokes (TFNS) solver (Liu, Wey AIAA 2014-3569)
- Two-equation, cubic k-ε model with variable Cμ and dynamic wall functions with pressure gradient effects (Shih, NASA TM 2000-209936)
- Reduced-kinetics, finite-rate chemistry. Jet-A fuel modeled as surrogate mixture of decane (73%), benzene(18%), hexane(9%) (14 species, 18 steps)(Kundu, AIAA Paper 2014-3662)
- Lagrangian spray-modeling for liquid fuel droplets (prescribed droplet distribution, injection velocity and direction) (Raju, NASA CR-2012-217294)
- Turbulence-chemistry interaction modeling: Joint Scalar Monte-Carlo PDF solver (Raju, AIAA Paper 2004-0327)

Non-Reacting Flow OpenNCC CFD



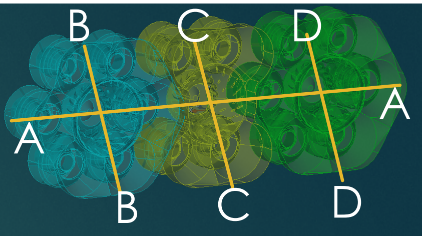
- Use OpenNCC CFD analysis to evaluate aerodynamics characteristics, effective-area of flametube
  - What are the flow-field differences between the ‘baseline’ (v3) pilot injector and the redesigned (v4) pilot injector (w/partial pre-filming)
  - What are the effective-area (ACd) differences between co-swirling and counter-swirling air-streams for redesigned pilot (v4)?
  - How well does the redesigned pilot (v4) maintain the effective area (ACd) as compared to the ‘baseline’ design

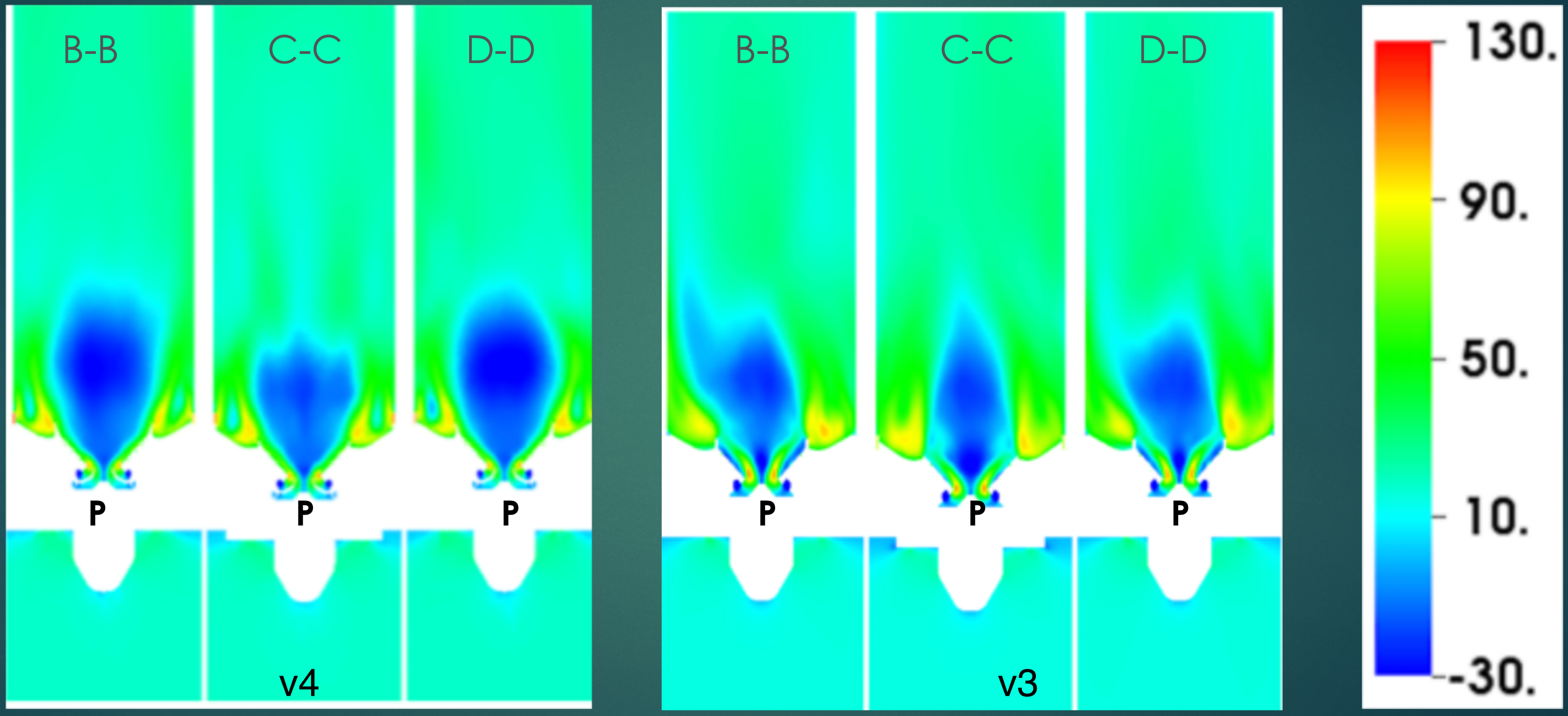
CFD Step 1: Non-Reacting TFNS



- P3=130psi, T3=811K, Dp = 3%
- Fix Ptot, Ttot at Inflow; Fix pressure at Outflow
- Obtain converged RANS solution. Run TFNS (time-accurate) for 20m-s.
- Compute ACd from CFD prediction of mass flow rate at each inflow boundary. *Use same pressure-drop value (P3*Dp) for each inflow boundary.*
  - aggregate of 16 mains
  - each pilot-primary, each pilot-secondary
  - four row aggregate cooling for each pilot venturi
  - dome-face cooling (aggregate)
  - auxiliary cooling (aggregate for each cup)

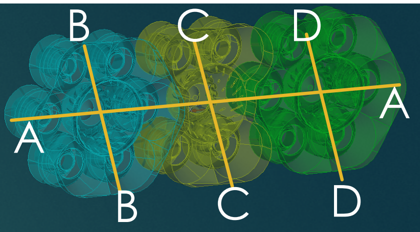
Non-Reacting Flow - Axial Velocity(m/s) Pilot Centerline: v4 vs v3

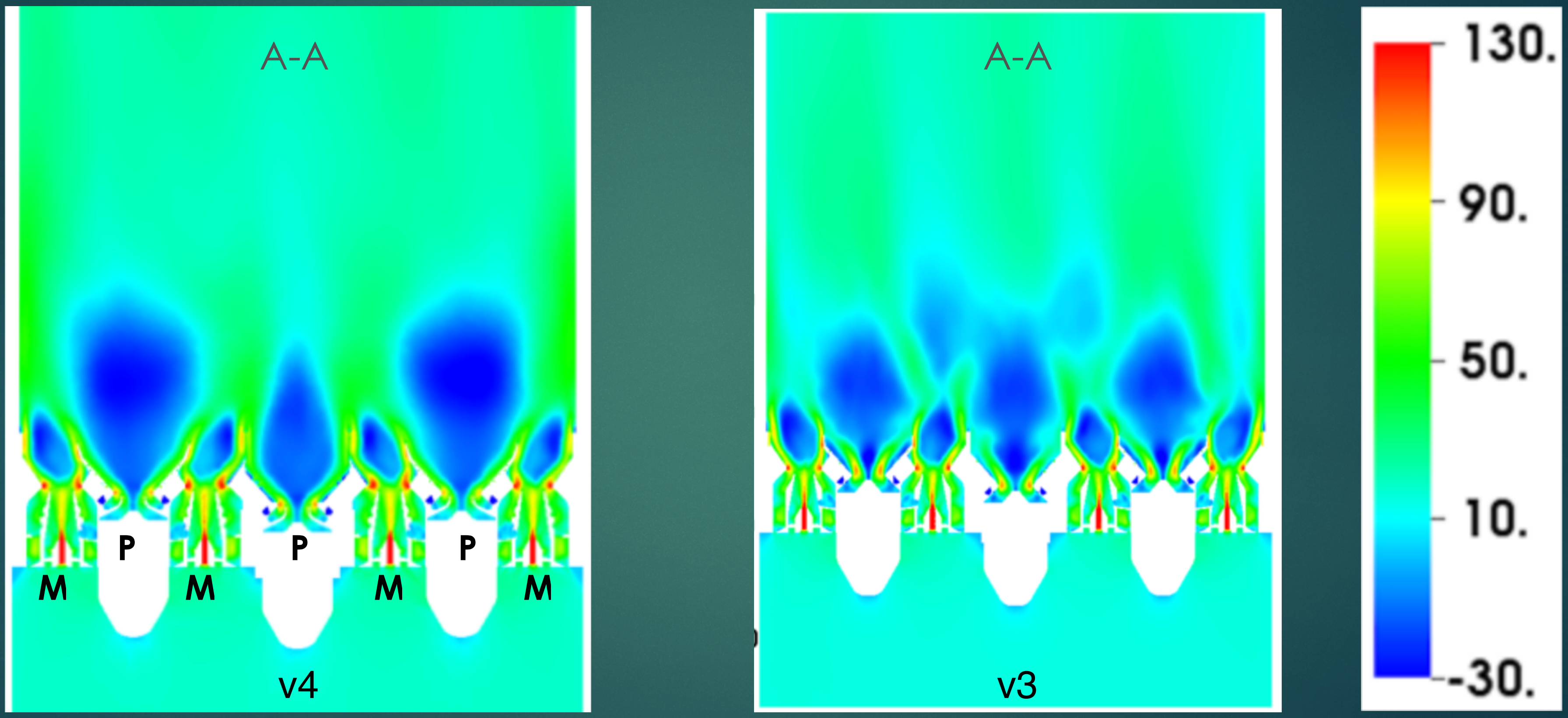




Pilots for v4 show much larger CTRZ as compared to those for v3

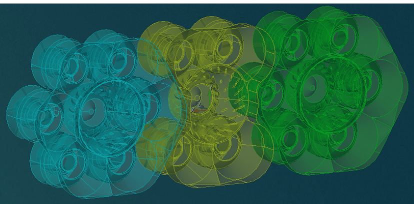
Non-Reacting Flow - Axial Velocity(m/s) Flametube Centerline: v4 vs v3





Pilots for v4 show much larger CTRZ as compared to those for v3

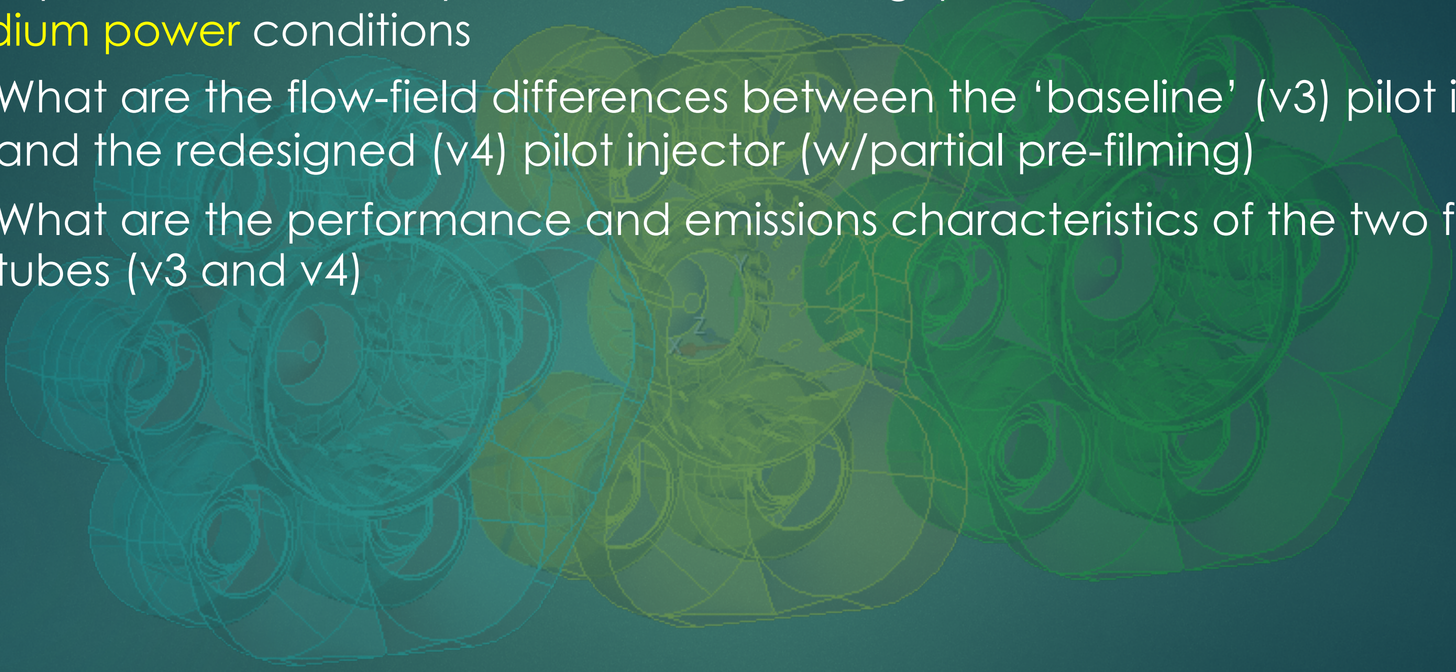
Effective Area Prediction - OpenNCC (v3,v4) vs Experiment



Components	Computed AC_d (in^2) (**v4**)	Computed AC_d (in^2) (**v3**)	Experiment AC_d (in^2) (**v3**)	% AC_d change (**v4 -v3**)/**v3**
Main Injectors (16)	2.413	2.4323	2.3613*	-0.8%
Pilot Injectors (3)	0.327	0.3348	0.3104	-2.3%
Pilot Cooling Holes (2 and 4 rows of holes per pilot for v3 and v4, respectively)	0.117	0.0433	*(included in Mains)	35%
Dome Face Cooling Holes	0.0456	0.0418	*(included in Mains)	9.1%
Total	**2.9026**	**2.8522**	**2.6717**	**1.8%**

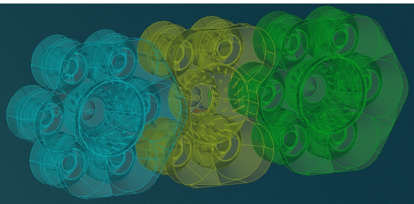
OpenNCC prediction target is for total AC_d to be within 10% of experimental data

Step 2: Reacting-Flow OpenNCC

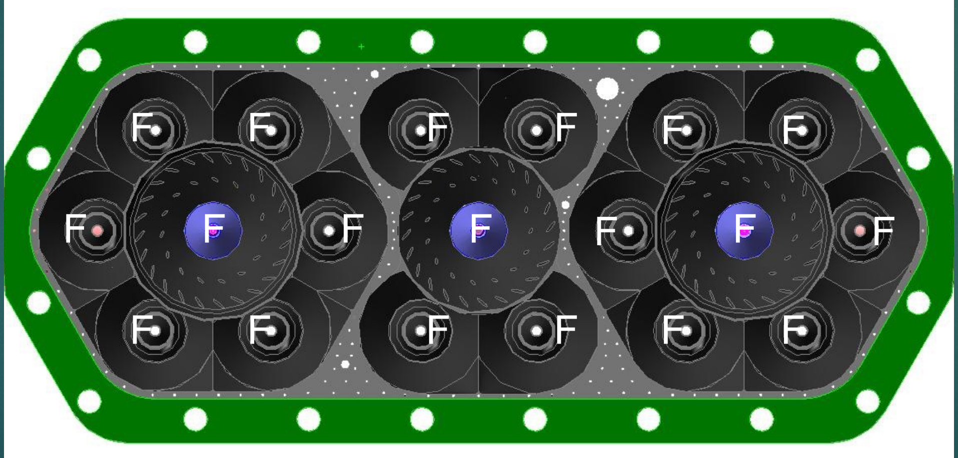


- Use OpenNCC CFD analysis to evaluate mixing, performance and emissions at medium power conditions
  - What are the flow-field differences between the ‘baseline’ (v3) pilot injector and the redesigned (v4) pilot injector (w/partial pre-filming)
  - What are the performance and emissions characteristics of the two flame tubes (v3 and v4)

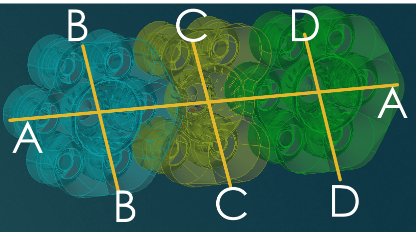
LDI-3 Cycle Condition for CST Cruise

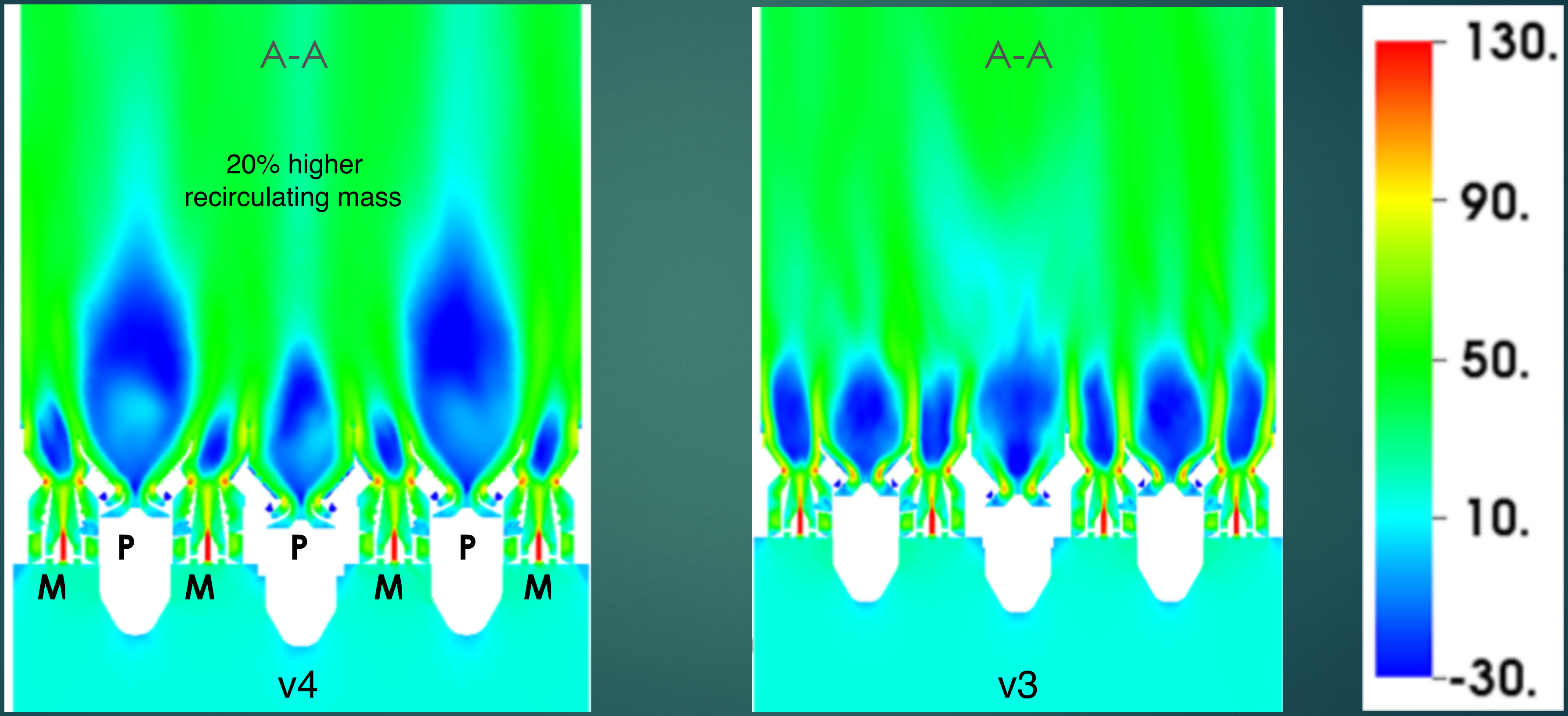


- All Pilots and Mains are fueled at the same equivalence ratio of 0.438 (Fuel/Air ratio = 0.03)
- P_3 = 0.896MPa, T_3 = 811K, **D**p = 3%, T_4 = 1785K



Reacting Flow - Axial Velocity(m/s) Flametube Centerline: v4 vs v3

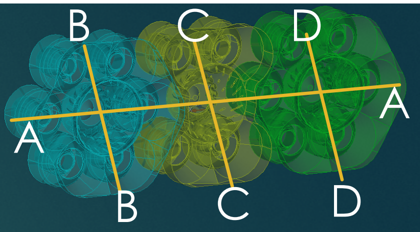


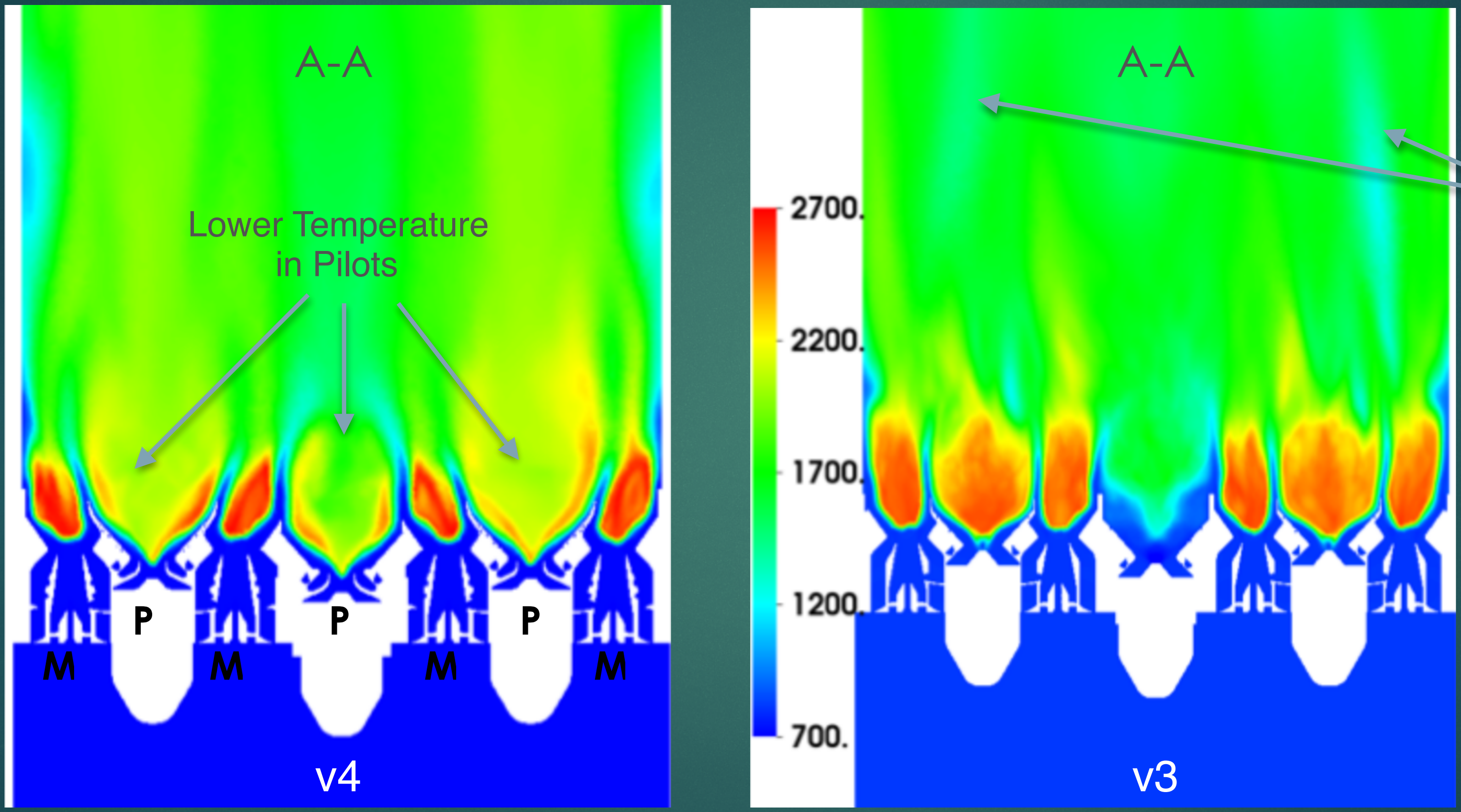


20% higher recirculating mass

Pilots for v4 show much larger CTRZ as compared to those for v3

Reacting Flow - Temperature (K)
Flametube Centerline: v4 vs v3





Lower Temperature in Pilots

Cold Streaks extend far downstream

Exit Plane T_4 :

T_4 (CEA) = 1780K

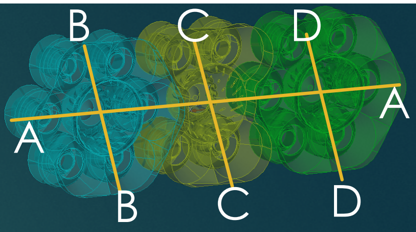
T_4 (v4) = 1775K

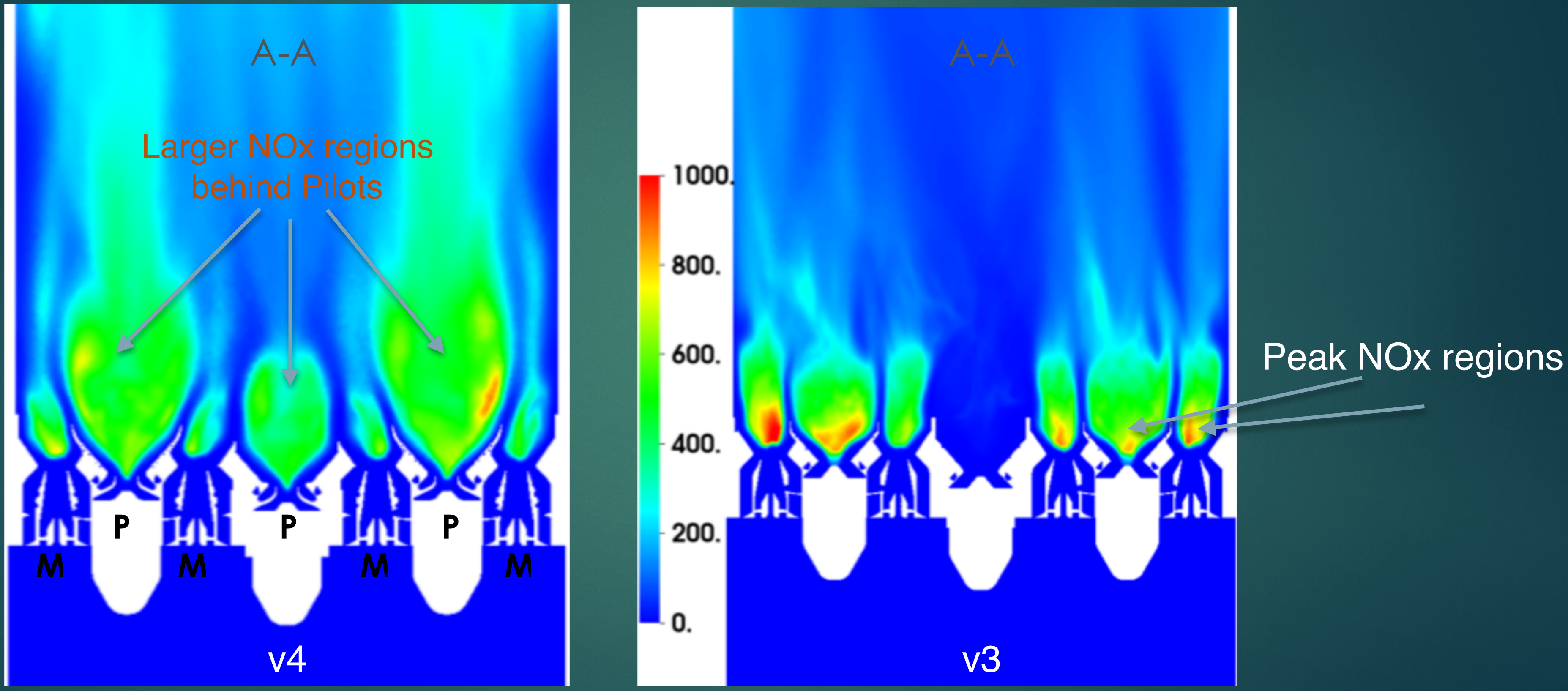
T_4 (v3) = 1755K

Pilots for v4 show lower temperature flame zones near dome face

Much fewer ‘cold streaks’ observed in v4 configuration (better ‘pattern factor’)

Reacting Flow - NO mass-fraction(*1e6) Flametube Centerline: v4 vs v3



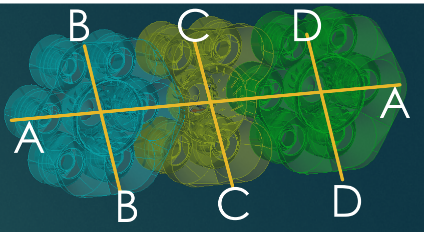


Larger NOx regions behind Pilots

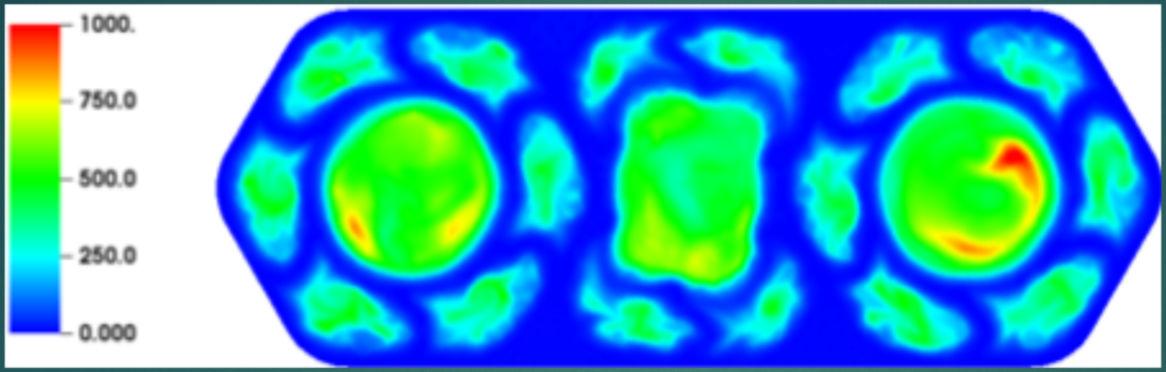
Peak NOx regions

Pilots for v4 show much larger NOx production regions than v3
Peak values of NOx (Pilot AND Mains) are lower for v4

Reacting Flow - NO mass-fraction(*1e6) Combustor Dome Face: v4 vs v3



v4

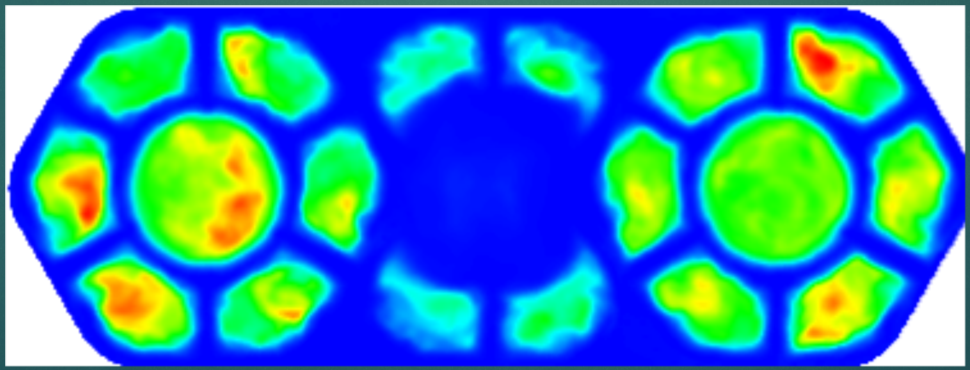


EINOx = 6.5

EINOx (Expt)[1] = 5.0

[1] Tacina et. al GT 2019-90484

v3



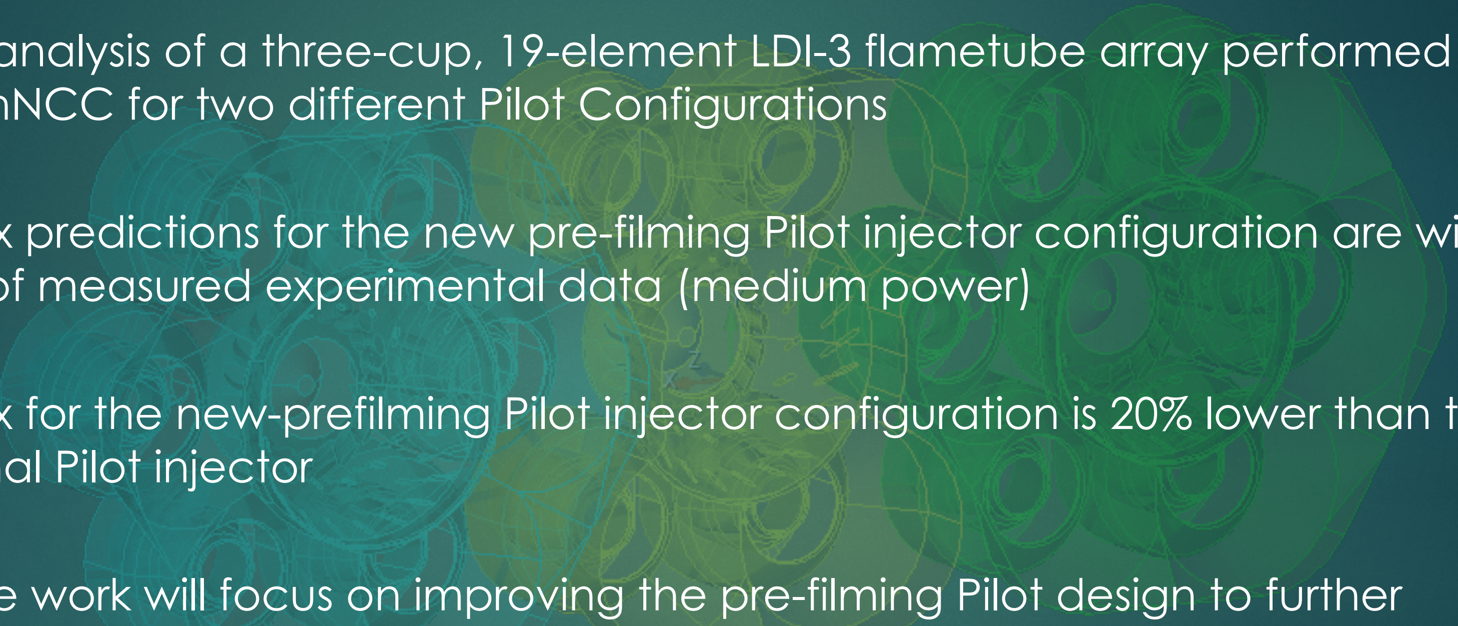
EINOx = 7.7*
(*with CFD correction
for center Pilot)

EINOx (Expt)[2] = 6.1

[2] Tacina et. al ISABE 2017

CFD Prediction of lower EINOx for pre-filming Pilot (v4) matches experimental data trend

Summary and Future Work



- CFD analysis of a three-cup, 19-element LDI-3 flametube array performed with OpenNCC for two different Pilot Configurations
- EINOx predictions for the new pre-filming Pilot injector configuration are within 15% of measured experimental data (medium power)
- EINOx for the new-prefilming Pilot injector configuration is 20% lower than the original Pilot injector
- Future work will focus on improving the pre-filming Pilot design to further decrease EINOx. The current design (v4) will also be analyzed for LTO (idle, takeoff, approach) CST conditions.

Acknowledgements

- This work was supported by the Advanced Air Transportation Technology (AATT) Project within NASA's Advanced Air Vehicles Program
- NAS Supercomputing Facility at NASA Ames
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- VisIt flow visualization software (Lawrence Livermore National Labs)