Simulations of fuel-air mixing in a 7 element Lean Direct Injection (LDI) aviation combustor

Presented at the 13th U.S. National Combustion Meeting
21st March 2023

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Golden, CO

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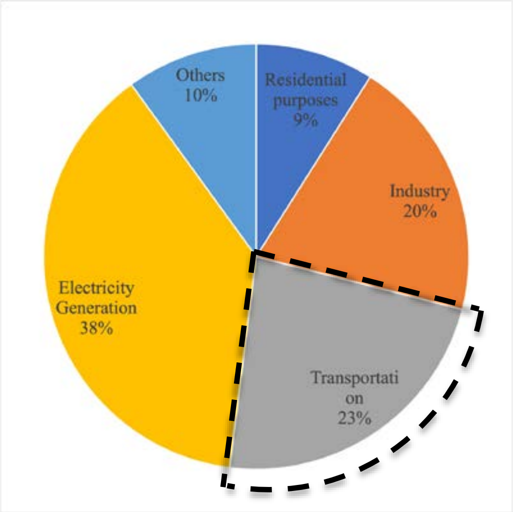
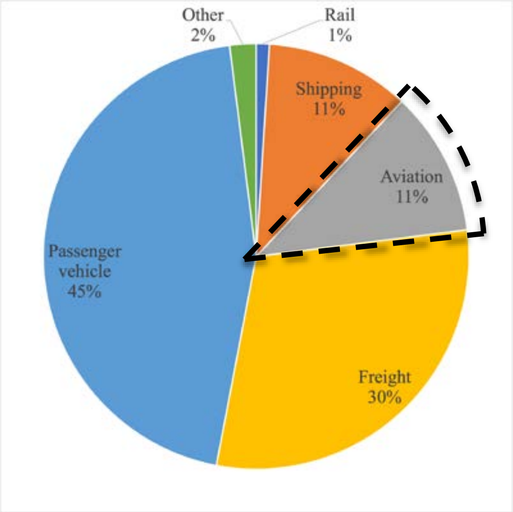
Introduction

Why Sustainable Aviation Fuels (SAFs)?



Percentage of CO_2 produced among various energy consuming sectors[1]



Percentage of CO_2 produced in transportation sector alone[1]

[1] J. Teter *et. al*. Tracking Transport 2020, IEA: International Energy Agency, Report No., 2019

- **ICAO envisions annual fuel efficiency improvement of 2%**
- **Carbon neutral growth from 2020**
- **Use of sustainable aviation fuels (SAFs) one of the strategies to achieve ICAO goals**

SAF is the way to go!

Introduction

What are SAFs?

SAFs is a generic term used to refer

- Fuels derived from non-fossil sources/feedstocks
- Works to close C-cycle

Feedstocks should not:

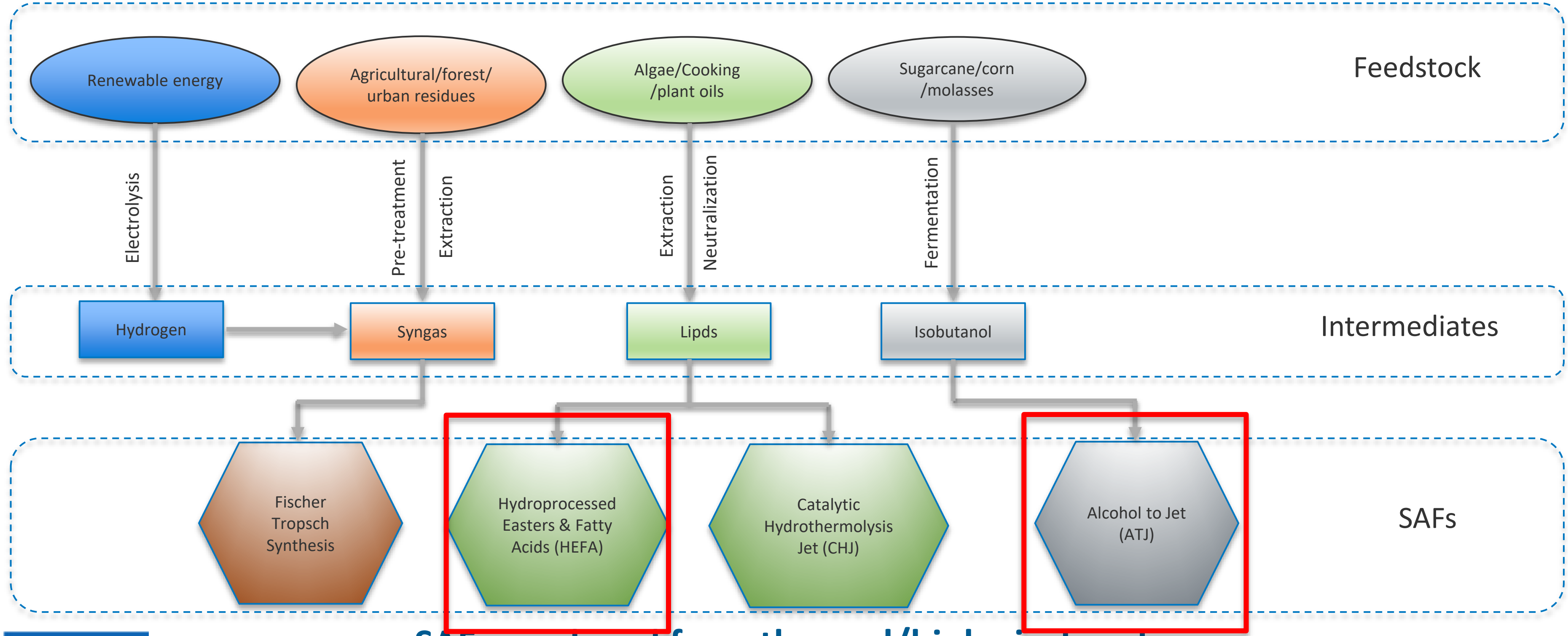
- Adversely affect food production
- Utilize excess water
- Lead to land clearing/deforestation

Today,

- There are 63 airports distributing SAFs
- 42 Billion litres of SAF under offtake agreements
- 9 conversion processes certified for use
- 50 airlines have experience with SAF
- Reduces 80% GHG emissions over its lifecycle

Introduction

SAF production pathways

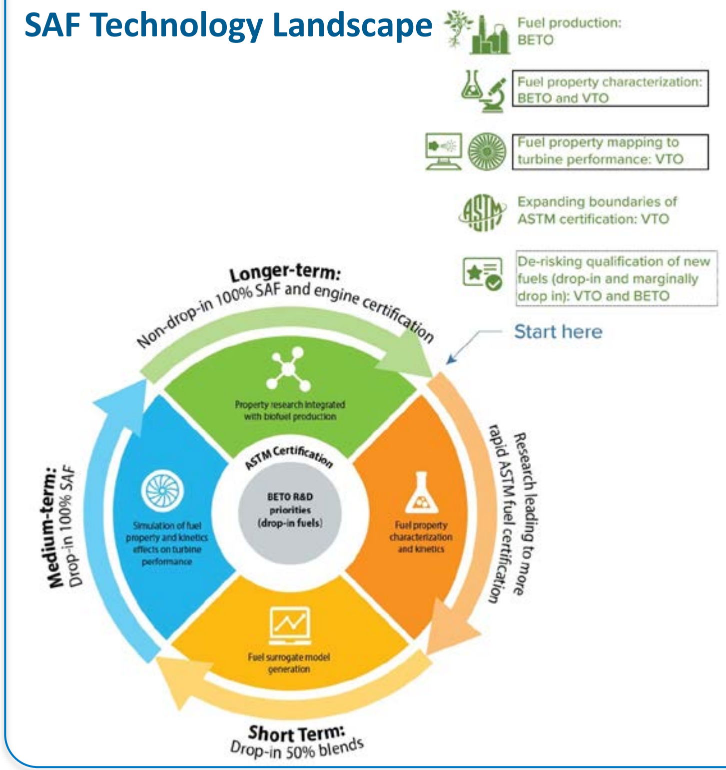


SAFs produced from thermal/biological routes

Objectives of this study

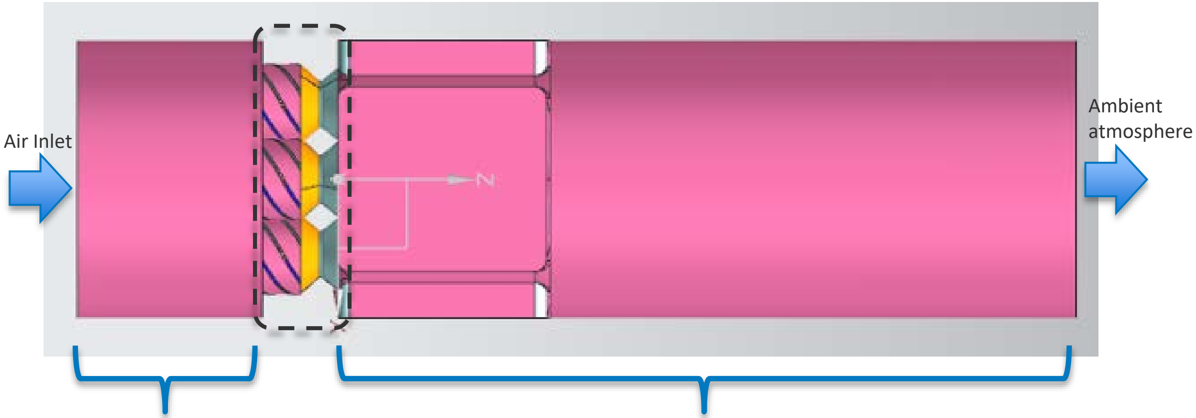
- SAFs currently being blended with Jet-A for commercial aviation
- SAFs intended to be used as 100% “drop-in” fuels in future (minimal changes to existing engine design)
- Certification of SAFs based on current processes→ time consuming + expensive
- Thermo-physical properties of pure and blended SAFs may impact present aircraft engine performance and haven’t been studied in detail

High accuracy, non-reactive numerical simulations to study effect of thermo-physical properties of two pure SAFs namely HEFA and ATJ on aviation combustor performance

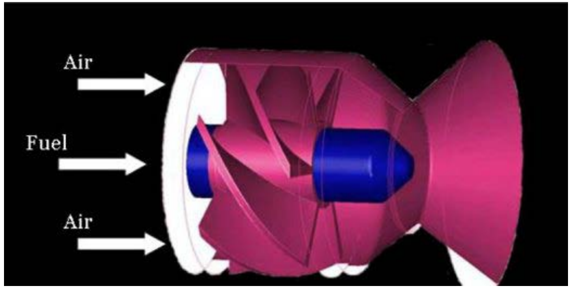


Lean Direct Injection (LDI) Combustor

Schematic of the 7-element LDI test rig at NASA Glenn Research Center



The 7 swirler in the test rig (ALF)



Cross-section of the swirler

- ❑ LDI strategy aims to avoid near-stoichiometric burning for NOx reduction
- ❑ Fuel nozzle and flame tube configurations shared by the NASA Glenn Research Center team
- ❑ NASA team has published detailed measurements, PIV and Chemiluminescence (OH*, CH*, C2*) -> Good simulation validation dataset

7-Element LDI configuration chosen for the present study

Fuel Properties of SAFs and Jet-A

Liquid Fuel Properties used in the study

Liquid Fuel Property	Jet A	HEFA	ATJ
Boiling Point (K)	469.52	488.27	451.85
Latent heat of vaporization (J/kg)	3.100×10^5	2.808×10^5	1.794×10^5
Specific heat (J/kg)	1.963×10^3	2.050×10^3	1.877×10^3
Density (kg/m^3)	819.0	766.0	786.0
Kinematic Viscosity (m^2/s)	1.802×10^{-6}	1.321×10^{-6}	1.778×10^{-6}
Surface tension (N/m)	25.8×10^{-3}	23.5×10^{-3}	22.2×10^{-3}

Property values adopted from
"Jet Fuel Properties", James T. Edwards, AFRL-RQ-WP-TR-2020-0017

"Droplet vaporization model for spray combustion calculations",
B. Abramzon and W. A. Sirignano,
Int. J. Heat Mass Transfer, Vol 32, No. 9, pp 1605-1618 (1989)

Spray Modeling Method:

- Abramzon & Sirignano
- Surface states calculated using 1/3rd rule
- Drag force, calculated using standard drag curve for spheres
- Droplet size distribution: Rosin-Rammler, Lefebvre Correlation for d32.

$$d_{SMD} = d_{32} = 2.25\sigma_l^{0.25}\mu^{0.25}\dot{m}_l^{0.25}\Delta P^{-0.5}\rho_{air}^{-0.25}$$

(all quantities in SI-units)

- Half spray angle: 31 deg. Radius: 0.15mm

2 SAFs (HEFA and ATJ) used for the simulations and compared with Jet A

Pele Suite of Solvers

- ❑ Pele Solvers – developed as a part of DoE Exascale Computing Project, multi-lab collaboration with NLs (SNL/ORNL/LBNL/ANL)
- ❑ Compressible and low-Mach number solvers and associated modeling tools
- ❑ Demonstrated Exascale capability
- ❑ Simulation capabilities:
  - Adaptive mesh refinement
  - Multi-phase (liquid spray fuels)
  - Soot, Radiation, Hybrid DNS/LES
  - Detailed chemistry, Differential species transport
  - ML models
  - Complex geometry

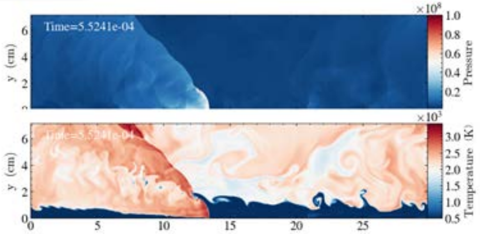
ECP KPP2 Challenge Problem with PeleLMeX (left) and PeleC (bottom) – 2022/2023

Talk by Nick Weimer, USNCM 2023: 2G02

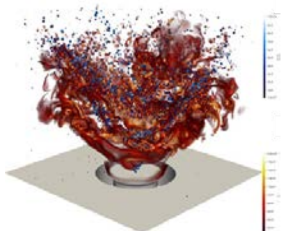
PeleLMeX: https://github.com/AMReX-Combustion/PeleLMeX

Turbulent U-turn gas turbine component- 2020

Supersonic Cavity flame-holder with PeleC - 2020



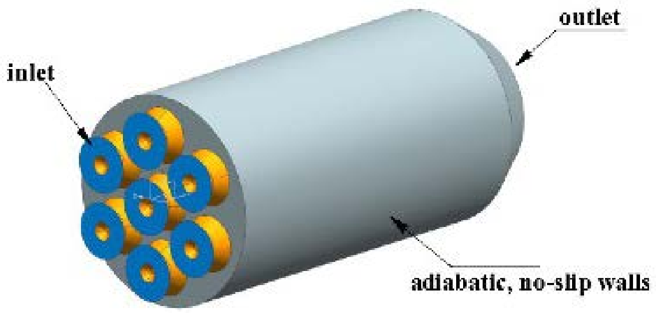
Rotating detonation engine simulations with PeleC-2022



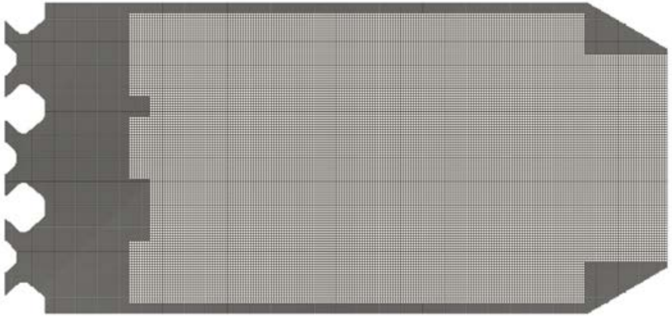
Simulation of SAF in swirled liquid fuelled burner, SNL 2022 (Image courtesy: Landon Owen, Bruno Soriano SNL)

Simulation setup

Computational domain and boundary conditions



Instantaneous cartesian mesh generated
at mid-plane with 2 levels of refinement



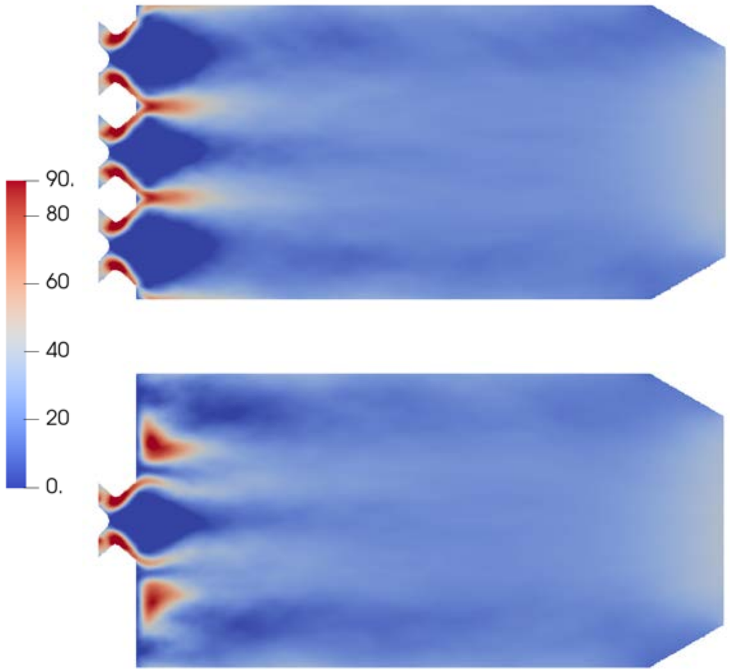
Operating conditions:
Pressure: 20 Bar
Air Temperature: 600K
Fuel Temperature: 300K
Air mass flow rate: 0.263 kg/s
Fuel mass flow rate: 0.007 kg/s

Numerical Settings:
Total number of cells ~ 18 M
Number of AMR levels: 2
Courant Friedrich Lewy #: 0.5
Refinement criteria: Vorticity
Temporal Discretization Scheme: Spectral Deferred Correction
Spatial Discretization Schemes:
Second-Order for diffusion,
Godunov PPM for advection
LES: Implicit LES
Computations carried out at Summit & Crusher (Frontier)

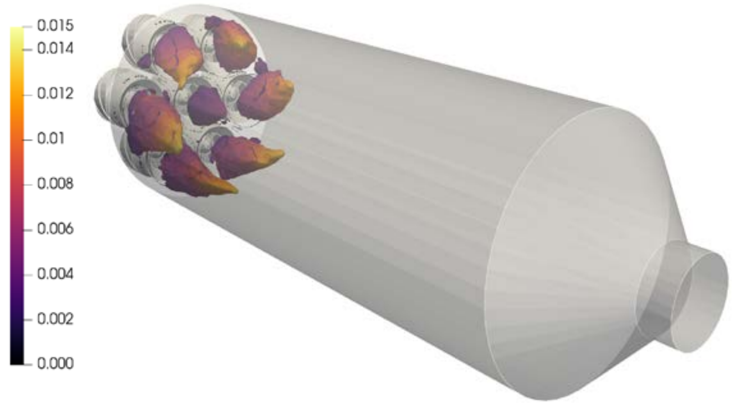
Simulations performed with PeleLMeX

Results

Flow field



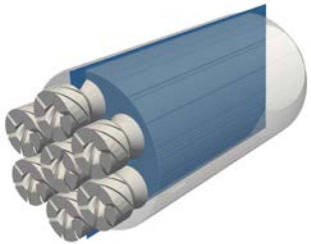
Time-averaged axial velocity (m/s) contours on mid-plane



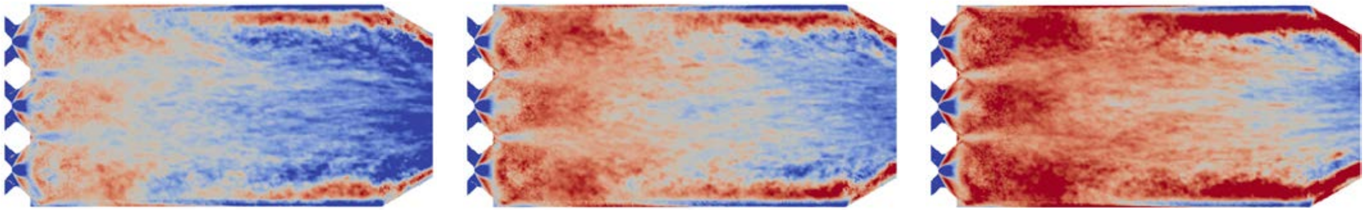
- Recirculation zones observed downstream of main and pilot premixers
- Smaller recirculation bubble observed for central premixer due to bulk swirling motion

Results

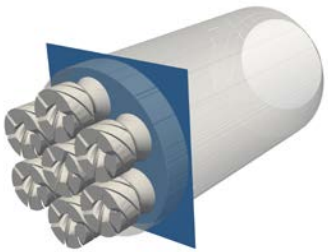
Mean droplet diameter d_{10}



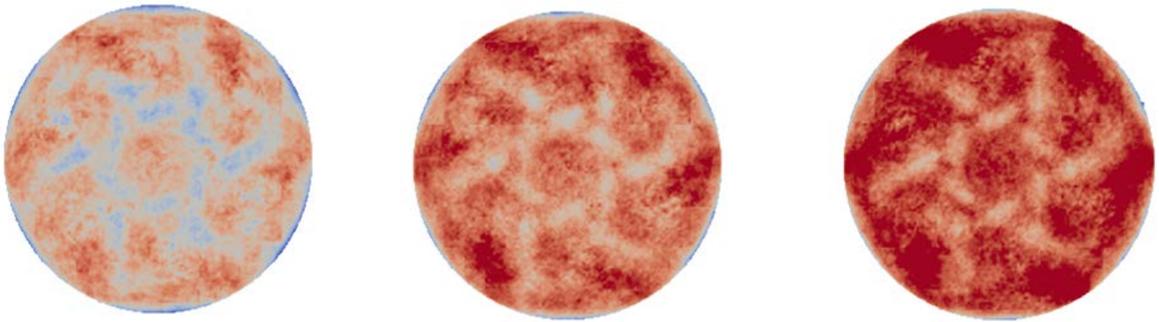
HEFA ATJ JETA

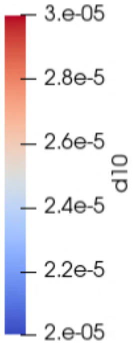


Increasing mean droplet diameter



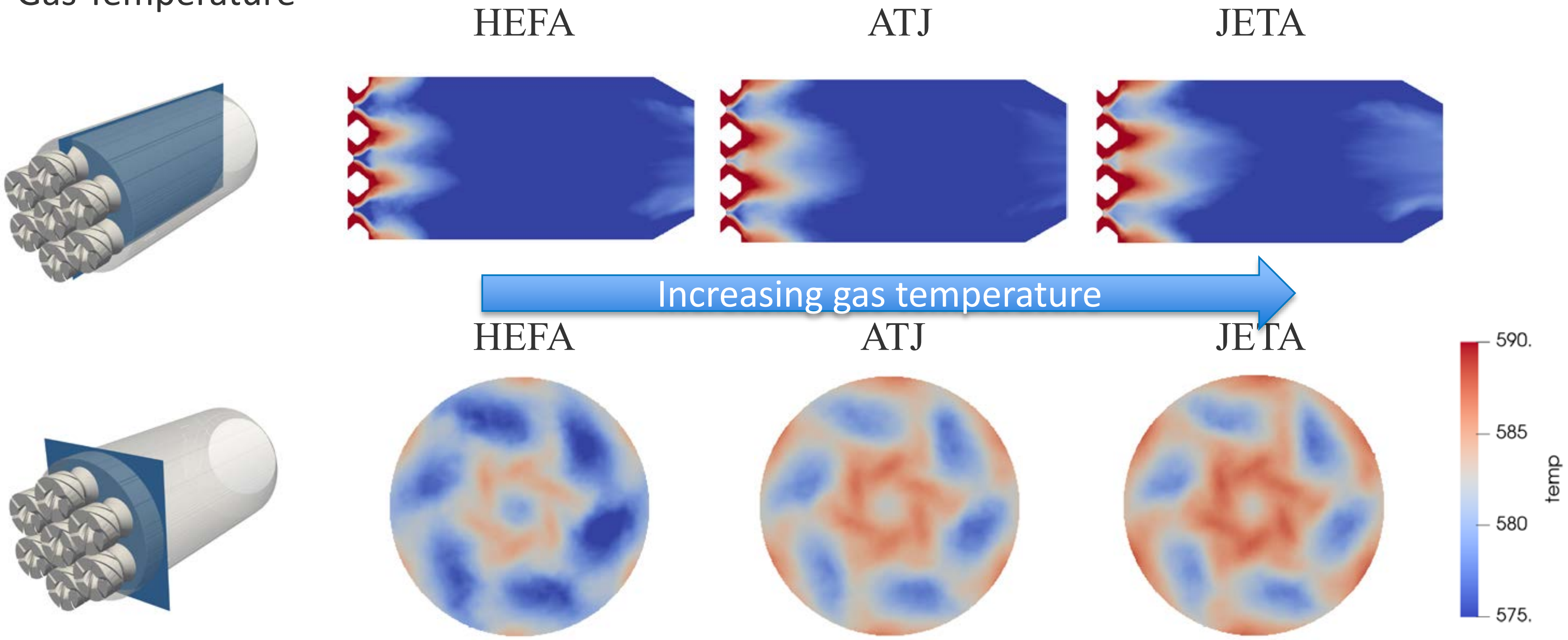
HEFA ATJ JETA





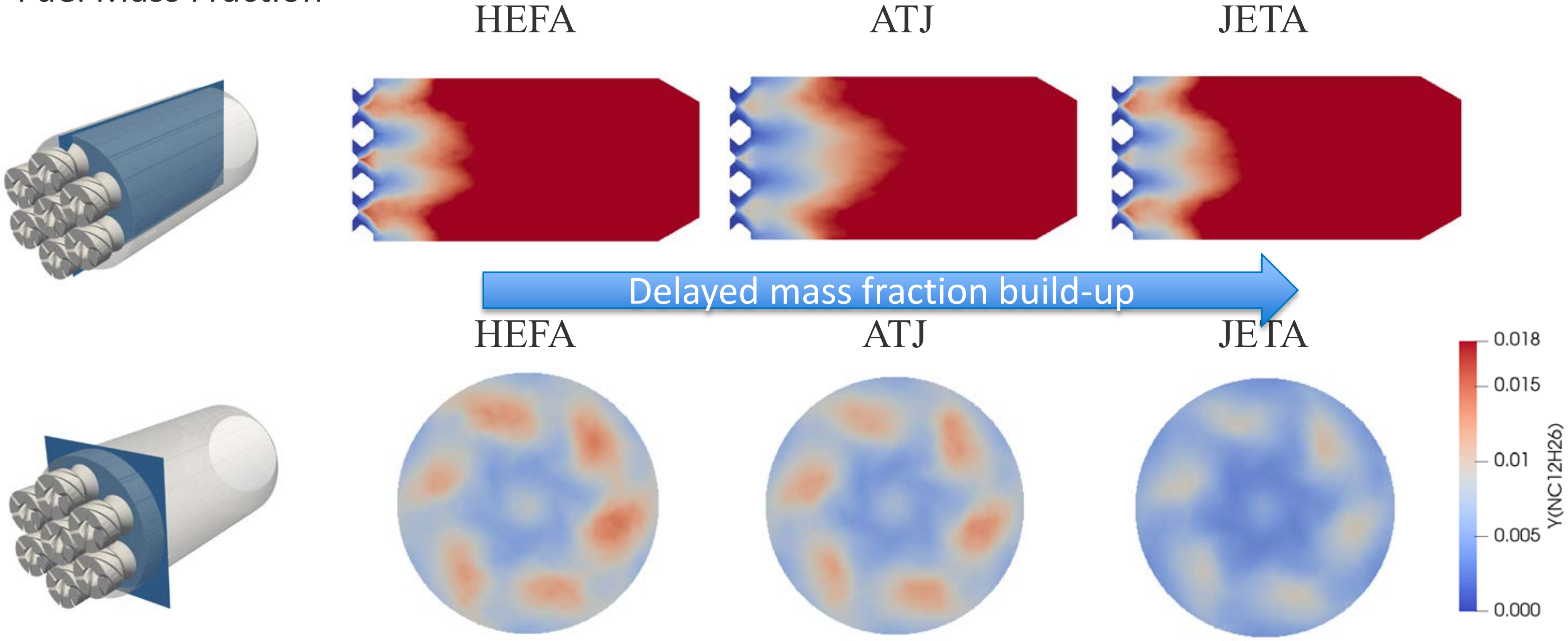
Results

Gas Temperature



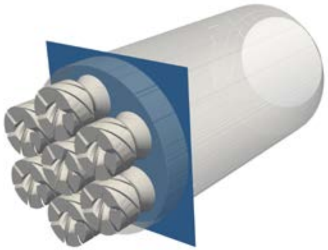
Results

Fuel Mass Fraction

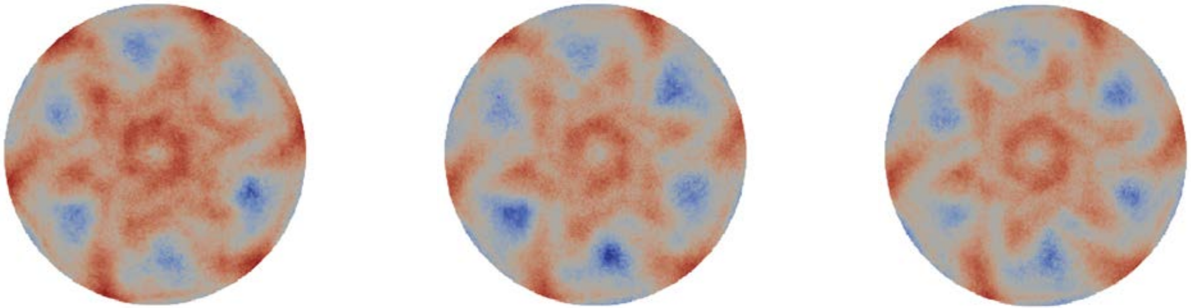


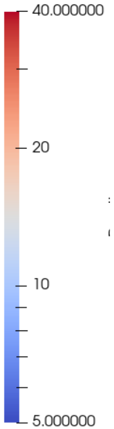
Results

Velocity divergence



HEFA ATJ JETA





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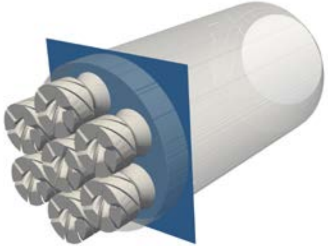

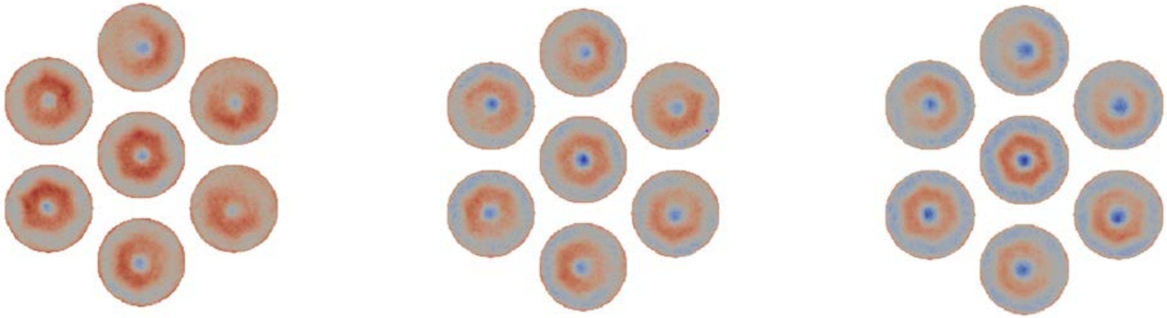

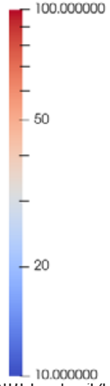

Discussion

Liquid Fuel Properties used in the study

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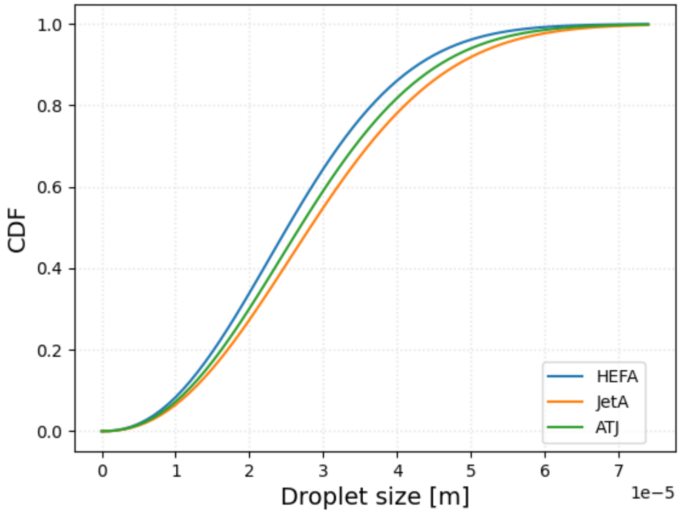

Effect of viscosity and lower density leads to smaller droplets for HEFA

Conclusions & Future Perspectives

- Non-reactive flow inside an aviation LDI combustor studied using 2 SAFs and compared with Jet A
- Low-Mach solver PeleLMeX used for simulations with 2 levels of AMR.
- Flow field in the combustor shows dominant recirculation bubbles downstream of main premixers. Presence of precessing vortex core observed
- Effect of thermophysical liquid fuel properties indicate faster evaporation of HEFA compared to ATJ and Jet A. The lower viscosity and density of HEFA leads to smaller droplet size distribution. The larger number of droplets also lead to enhanced evaporation and hence higher fuel mass fractions. Although ATJ has lower LHV, the effect of viscosity and density is observed to play dominant role for the condition studied
- Implementation of LES model (Bruce Perry's talk IH07, Monday) and multi-component fuels in progress.

THANK YOU

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NREL/PR-2C00-85689

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Science, Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office, and National Nuclear Security Administration. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Transforming ENERGY

APPENDIX