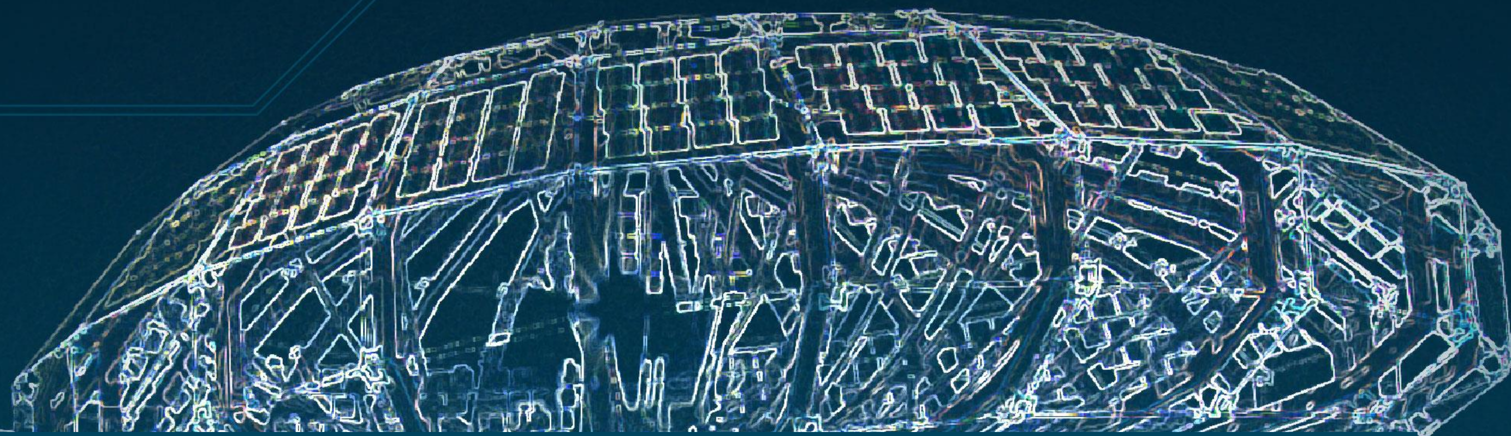


Effects of fuel type / spray definition on lean blow-out prediction in a realistic aero-engine combustor

L. Bravo, US Army CCDC Army Research

G. Ramaekers, F. Tap and P. Priesching, AVL

Contents

Motivation

Lean Blow-out (LBO) is a complex multi-scale phenomenon that is of primary concern in modern lean burn combustors

- *Predictive capability would drastically reduce experimental costs*

Development of accurate physics-based models to streamline the certification of novel alternative fuel candidates

- *Lack of predictive capability of the effect of physio-chemical properties*
- *Replacement with novel fuels should not require retrofitting of aircraft engines*

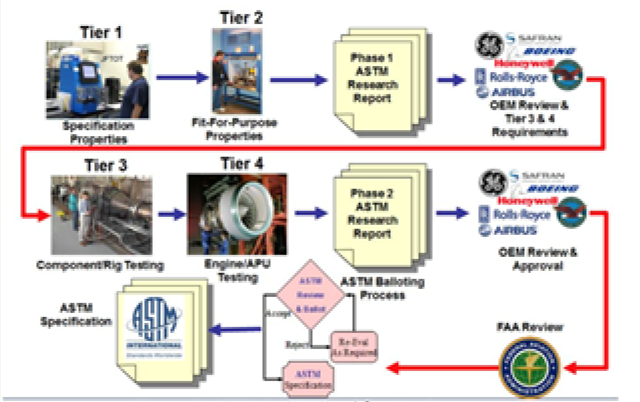


Figure 1. ASTM D4054 Qualification Process

Impact to Army

Rotorcraft

UAVs

eVTOL

Vehicle Propulsion: Improve Energy Supply
Vehicle Platform: Reduce Energy Demand

Research Objectives

To use available LES tools to study the LBO behavior of a realistic gas-turbine engine combustor for different fuels and provide knowledge on the effect of fuel physio-chemical properties.

- Hychem v2.0 kinetic models (A2, C1)
- Finite rate chemistry
- Comparison with NJFCP referee combustor.

Challenges

- Uncertainties in spray boundary conditions
- Physio-chemical fuel properties

Data Used

	A2	C1
Mol Weight (kg/kmol)	159	178
Aromatics	18.66	<0.001
Iso-Paraffins	29.45	99.63
N-Paraffins	20.03	<0.001
Cycloparaffins	31.86	0.05
Alkenes	<0.001	0.32
H/C	1.90	2.16
Δh_c (MJ/kg)	43.1	43.8
DCN	48.3	17.1
T_{10} (K)	450.0	452.1
$T_{90} - T_{10}$ (K)	67.8	45.5
M (322K) [mPa-s]	1.17	0.98

[3] Heyne el al., AIAA Aerospace Sciences Meeting, 2018

V2.0 NJFCP Mechanisms

A2 & C1 fuel mechanisms

- Detailed (119 species)
- Skeletal (41 and 34 species)

```
!*****************************************************************************
!
! A 41-species skeletal model for Cat A2
! Developed by Yang Gao, Tianfeng Lu (tianfeng.lu@uconn.edu)
! University of Connecticut
!
! based on
!
! Reaction model for POSF10325 (Cat A2)
! Version 2.0
!
!*****************************************************************************
! Title: "A experiment-based lumped model of jet fuel combustion at high temperatures"
!
! Hai Wang, Ray Xu, David F. Davidson, Sayak Banerjee, Tom Bowman, Ronald K. Hanson
! Mechanical Engineering, Stanford University
! Stanford, CA 94305
!
! May 24, 2016
!
! Model description: Six reaction steps to describe POSF10325 thermal decomposition
!                    and USC Mech II as the foundational fuel chemistry model
!
! The cracked products considered are CH4, C2H4, C3H6, iC4H8, benzene, tuluene, CH3 and H.
! The oxidation kinetics of these cracking products are described by USC Mech II.
!
! Please contact Hai Wang at haiwang@stanford.edu for questions and comments.
!
!=============================================================================
ELEMENTS
```

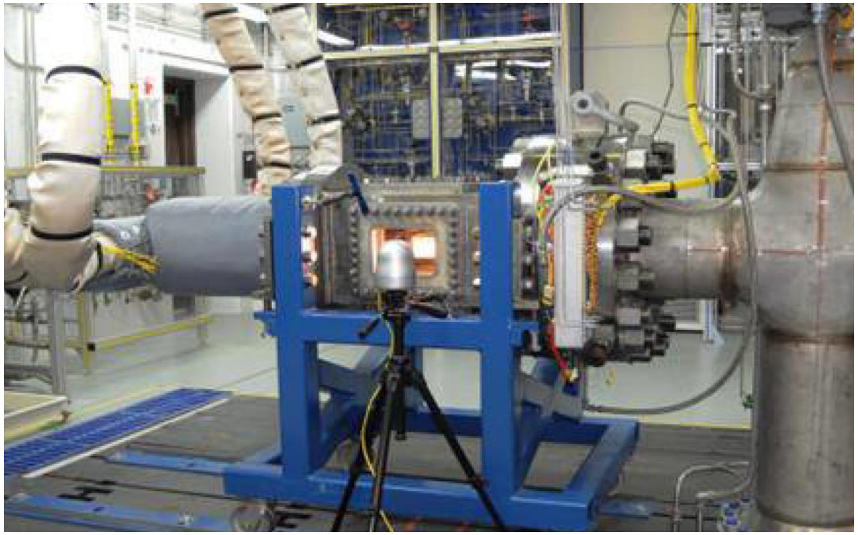
```
!*****************************************************************************
!
! A 34-species skeletal model for Cat C1
! Developed by Yang Gao, Tianfeng Lu (tianfeng.lu@uconn.edu)
! University of Connecticut
!
! based on
!
! Reaction model for POSF11498 (Cat C1)
! Version 2.0
!
!*****************************************************************************
! Title: "A experiment-based lumped model of jet fuel combustion at high temperatures"
!
! Hai Wang, Ray Xu, David F. Davidson, Sayak Banerjee, Tom Bowman, Ronald K. Hanson
! Mechanical Engineering, Stanford University
! Stanford, CA 94305
!
! May 23, 2016
!
! Model description: Seven reaction steps to describe POSF11498 thermal decomposition
!                    and USC Mech II as the foundational fuel chemistry model
!
! The cracked products considered are CH4, C2H4, C3H6, iC4H8, benzene, tuluene, CH3 and H.
! The oxidation kinetics of these cracking products are described by USC Mech II.
!
! Please contact Hai Wang at haiwang@stanford.edu for questions and comments.
!
!=============================================================================
```

[4] Wang et al., 2015

Contents

- Introduction
- **Experimental set-up**
- CFD simulations
- Summary and outlook

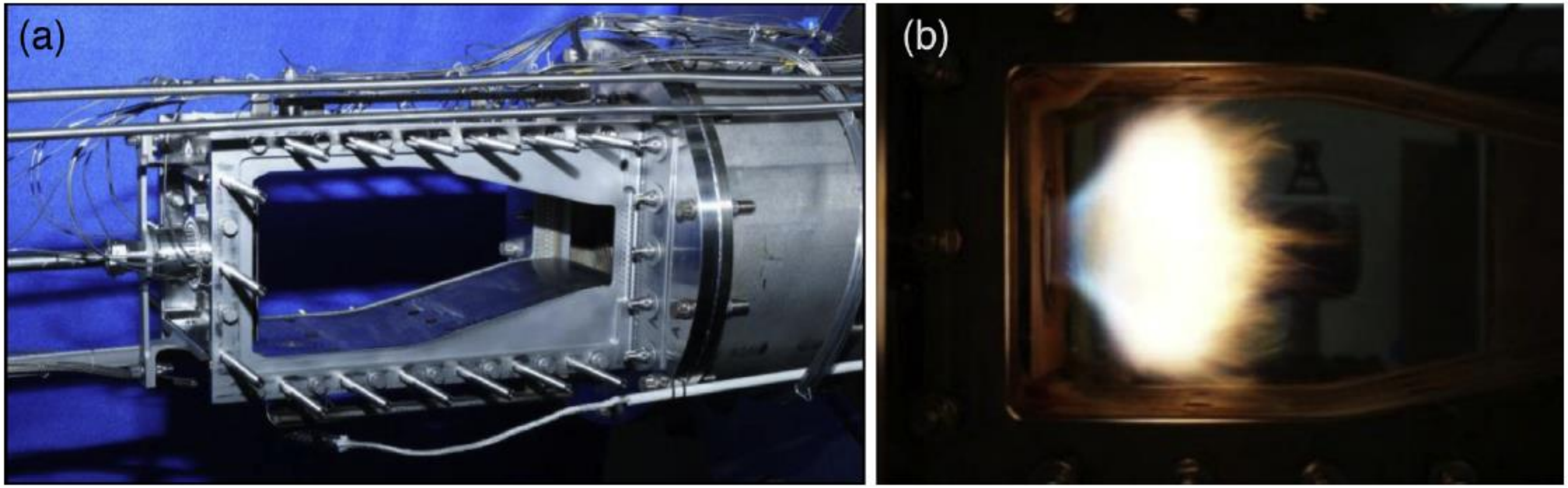
Air Force Referee Combustor



US Air Force Research Laboratory (AFRL) Referee Combustor

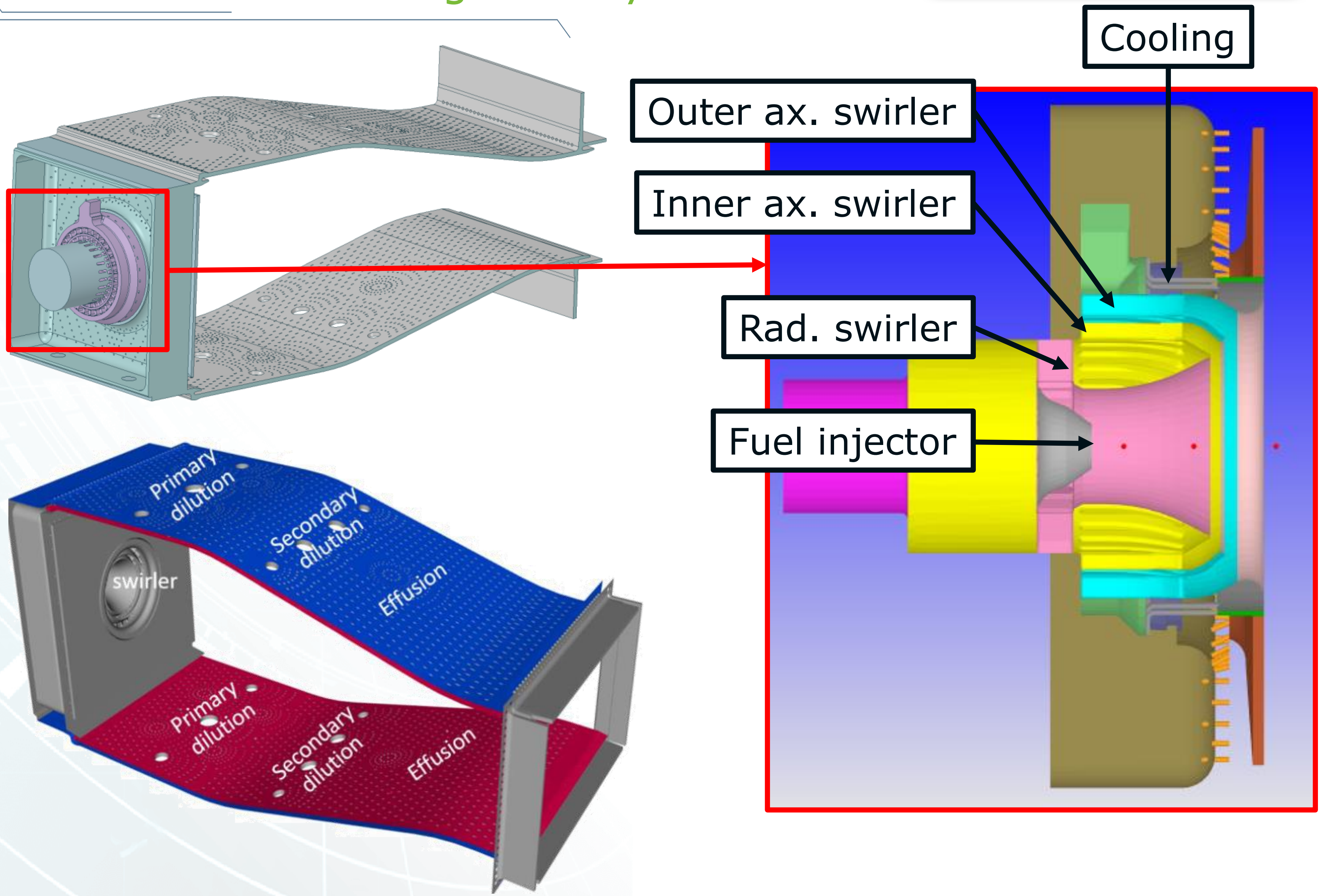
Used for fuel-testing of for aero-engines.

Contains a complex swirler, effusion wall cooling holes and dilution holes.

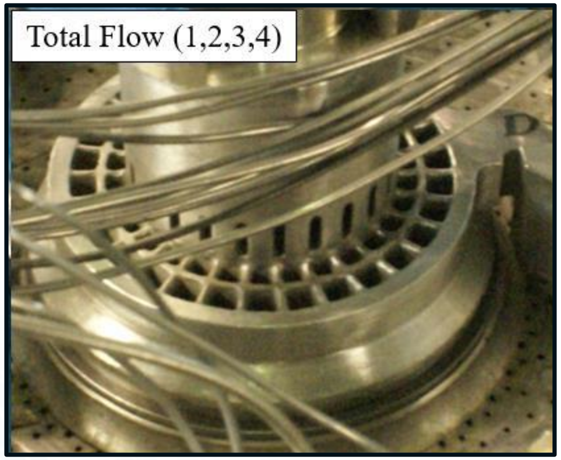


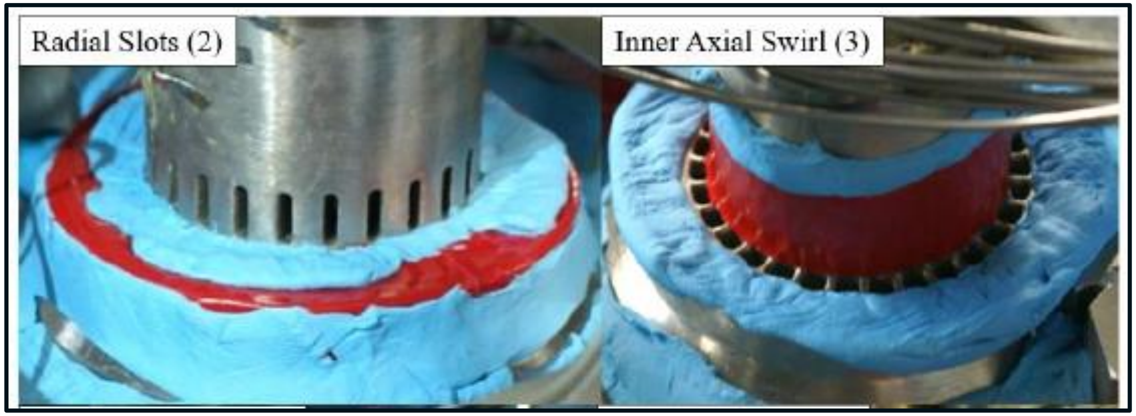
Esclapez et.al., Comb. Flame 181 (2017) pp. 82-99.

Referee Combustor geometry



Cold flow: separate swirlers paths





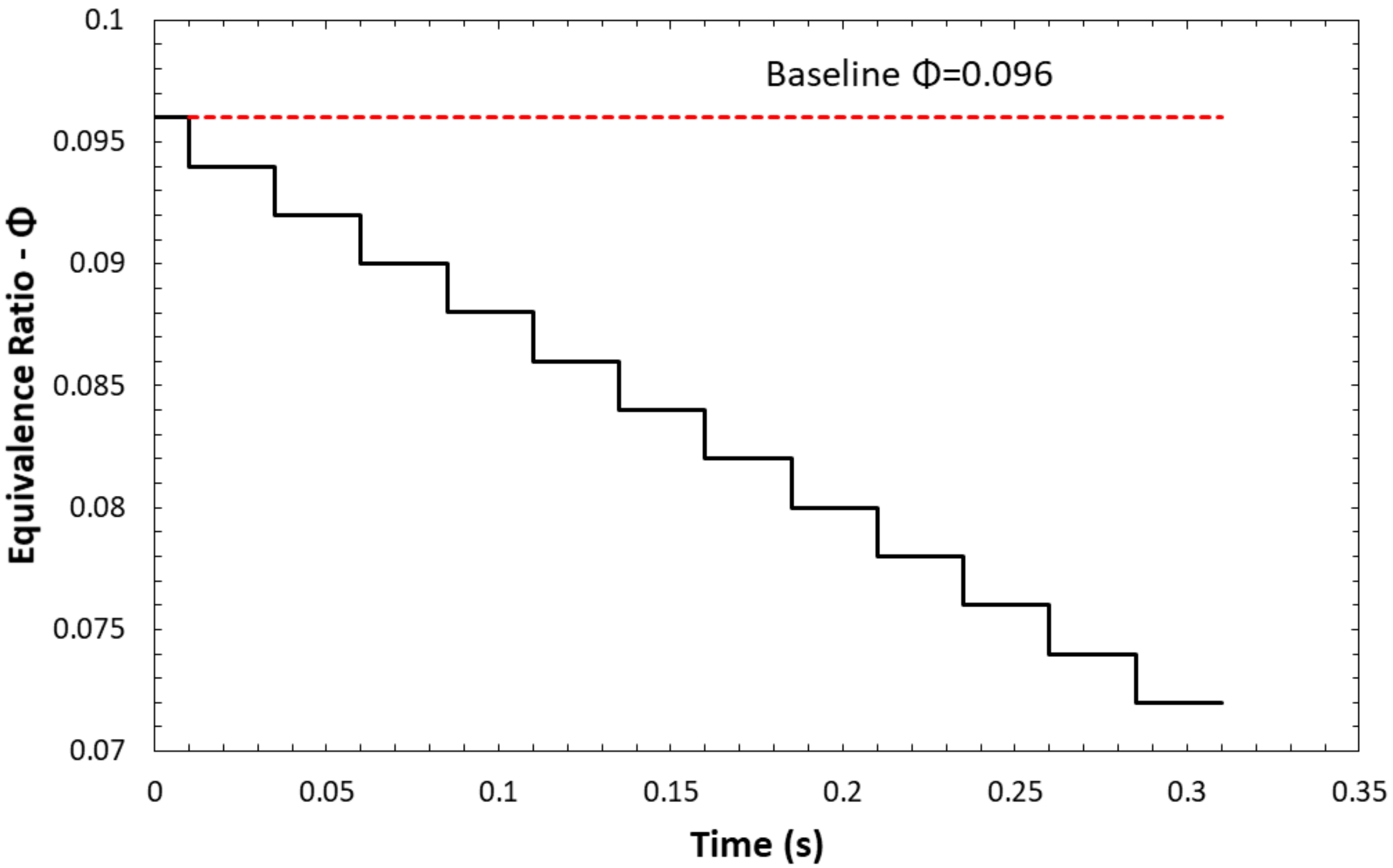
	Exp.[†]	CFD
Outer axial	0.801 [kg/min]	
Inner axial	0.605 [kg/min]	
Radial	0.456 [kg/min]	
Cooling	0.091 [kg/min]	
TOTAL	1.953 [kg/min]	

[†]Erdmann et.al., Proc. ASME Turbo Expo 2017 (GT2017-65252).

LBO measurements

Start at baseline Φ

- Drop Φ by 0.002
- Hold for 0.025 s
- Continue until LBO



Contents

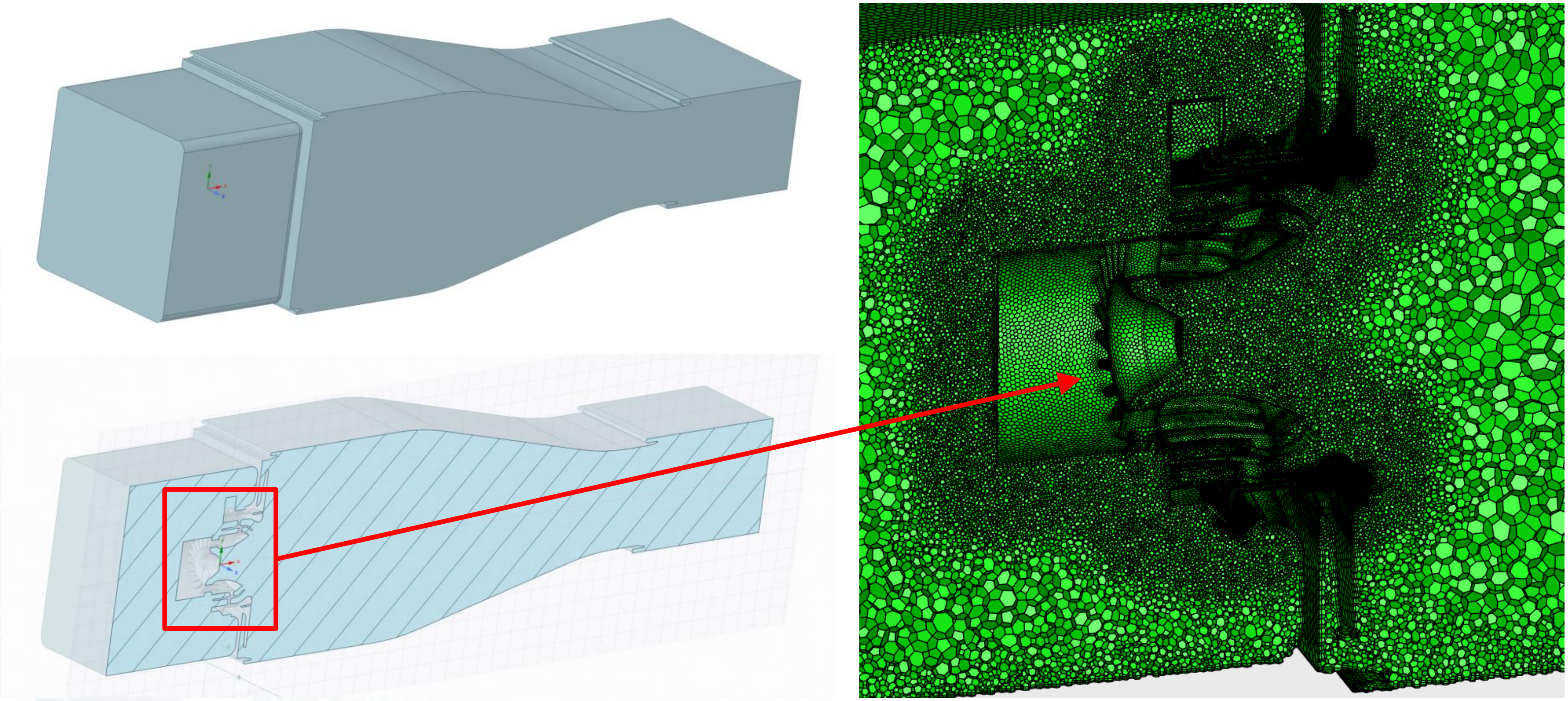
CFD simulations

- Cold flow simulations
- Hot flow preparation simulations
- Hot flow LBO simulations (in progress)

AVL FIRE™

AVL TABKIN™

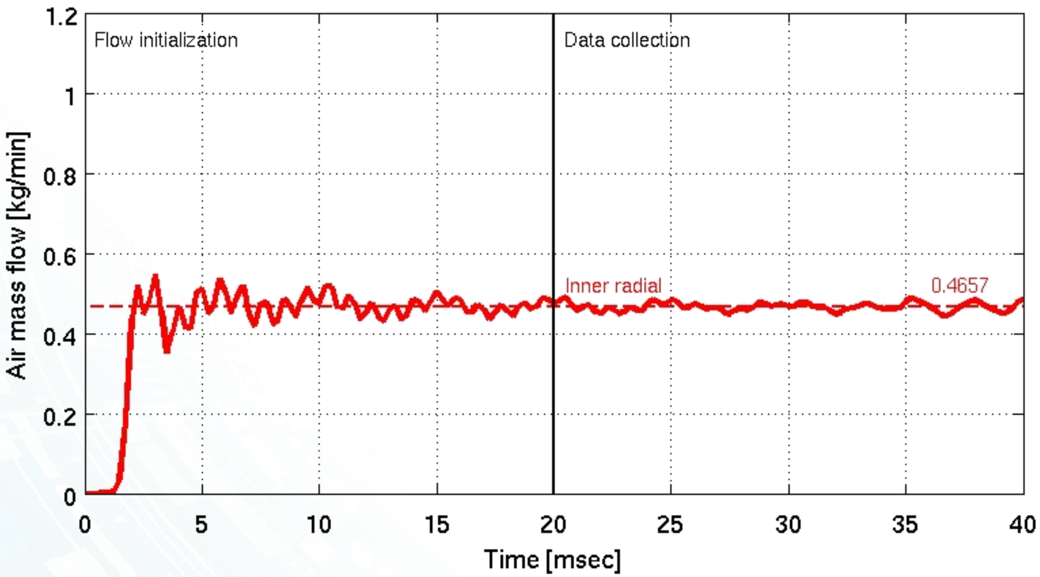
Cold flow: swirlers paths only [1]

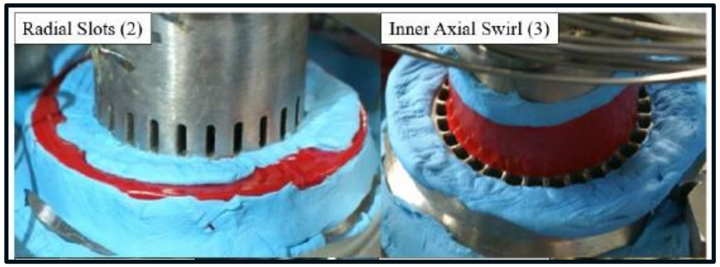


Geometry modifications:

1. Removal of effusion/dilution flow paths.
2. Removal of effusion/dilution holes in combustor liner.
3. Elongation of outlet section.

Cold flow: separate swirlers paths

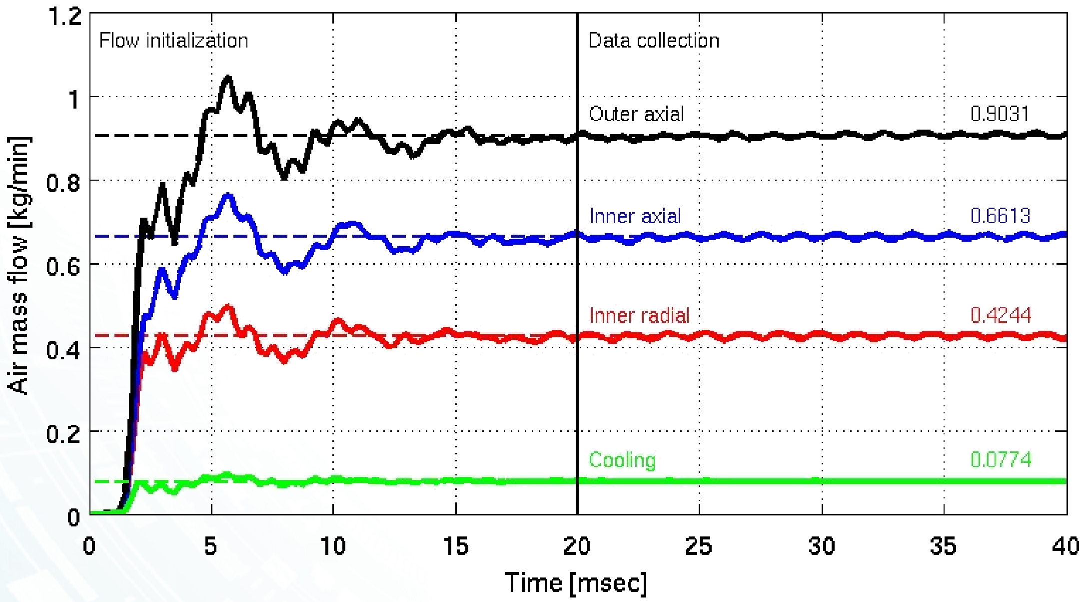


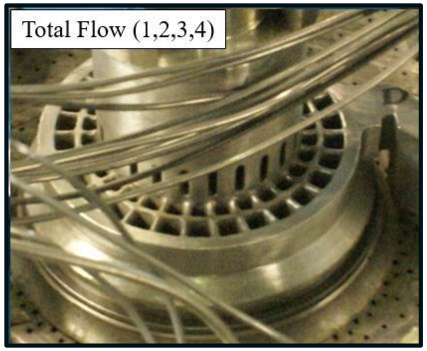


	Exp.[†]	CFD
Outer axial	0.801 [kg/min]	0.843 [kg/min]
Inner axial	0.605 [kg/min]	0.661 [kg/min]
Radial	0.456 [kg/min]	0.466 [kg/min]
Cooling	0.091 [kg/min]	0.076 [kg/min]
TOTAL	1.953 [kg/min]	2.046 [kg/min]

[†]Erdmann et.al., Proc. ASME Turbo Expo 2017 (GT2017-65252).

Cold flow: all swirlers paths open



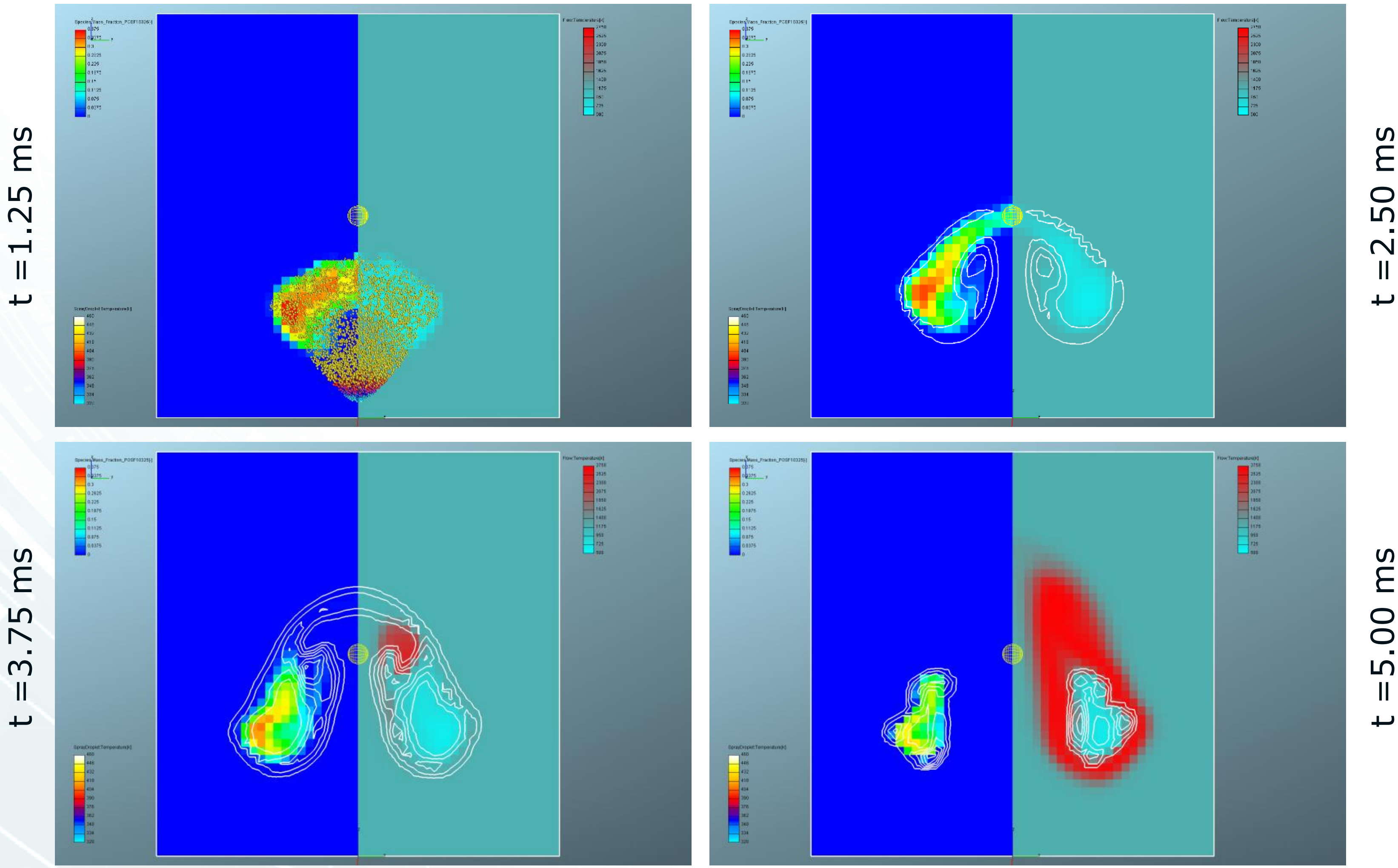


	Exp.†	CFD
Outer axial		0.903 [kg/min]
Inner axial		0.661 [kg/min]
Radial		0.424 [kg/min]
Cooling		0.077 [kg/min]
TOTAL	1.908 [kg/min]	2.065 [kg/min]

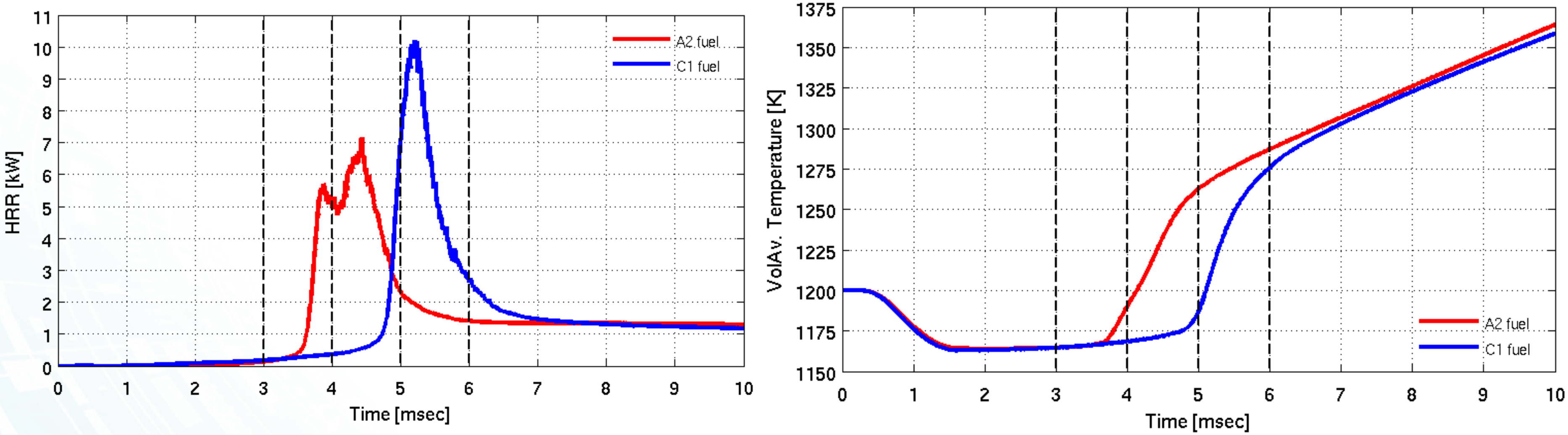
†Erdmann et.al., Proc. ASME Turbo Expo 2017 (GT2017-65252).

Hot flow preparation simulations

Objective: assess vaporization and combustion behavior of A2 (below) and C1 fuel models.

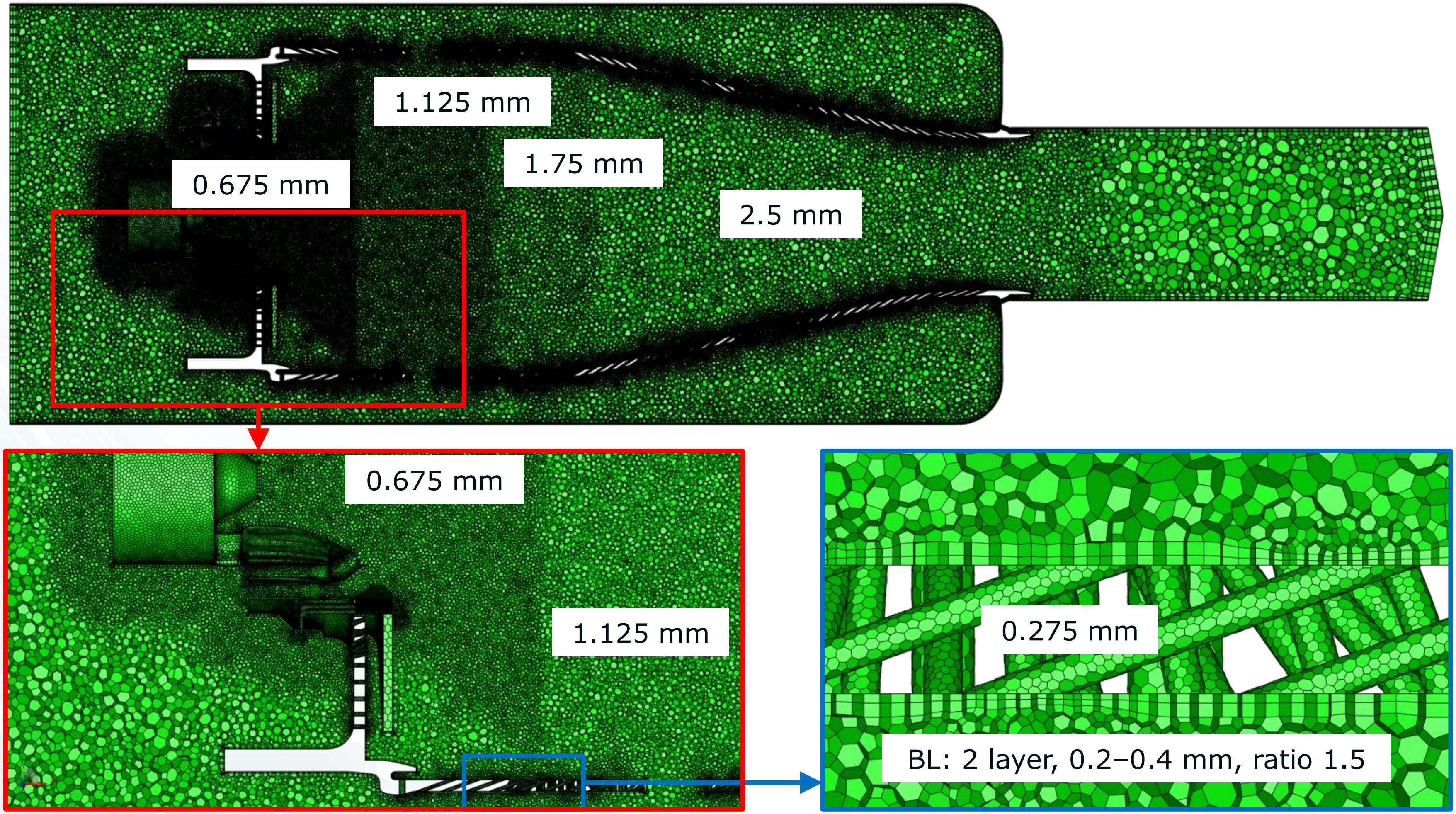


Hot flow preparation simulations [2]



	A2 skeletal	C1 skeletal	C1 detailed
Number of species	41	42	119
Number of elem. reactions	202	286	841
Wall clock time GGPR	36.0 hr @ 16 CPU's	36.7 hr @ 16 CPU's	114.2 hr @ 16 CPU's
Wall clock time table gen.	4.1 hr @ 12 CPU's	4.4 hr @ 12 CPU's	3.0 hr @ 12 CPU's
Wall clock time TABKIN	15.4 hr @ 16 CPU's	15.9 hr @ 16 CPU's	16.6 hr @ 16 CPU's
Speed-up TABKIN	**2.34**	**2.31**	**6.88**

Full geometry: mesh for LBO simulation



LBO simulations: CFD set-up [1]

ARL combustor mesh: 15Mcells, refined in combustion zone.

Reaction mechanisms: HyChem A2 skeletal, HyChem C1 skeletal, tabulated by AVL TABKIN™.

Liquid properties: prescribed by ARL. ρ_{LIQ} and σ_{SURF} are different.

Vapor properties: JANAF polynomials. μ, κ and D from Lennard-Jones data.

Initial conditions: 394.0 K, 204.083 kPa, air ($Y[O_2] = 0.233$, $Y[N_2] = 0.767$).

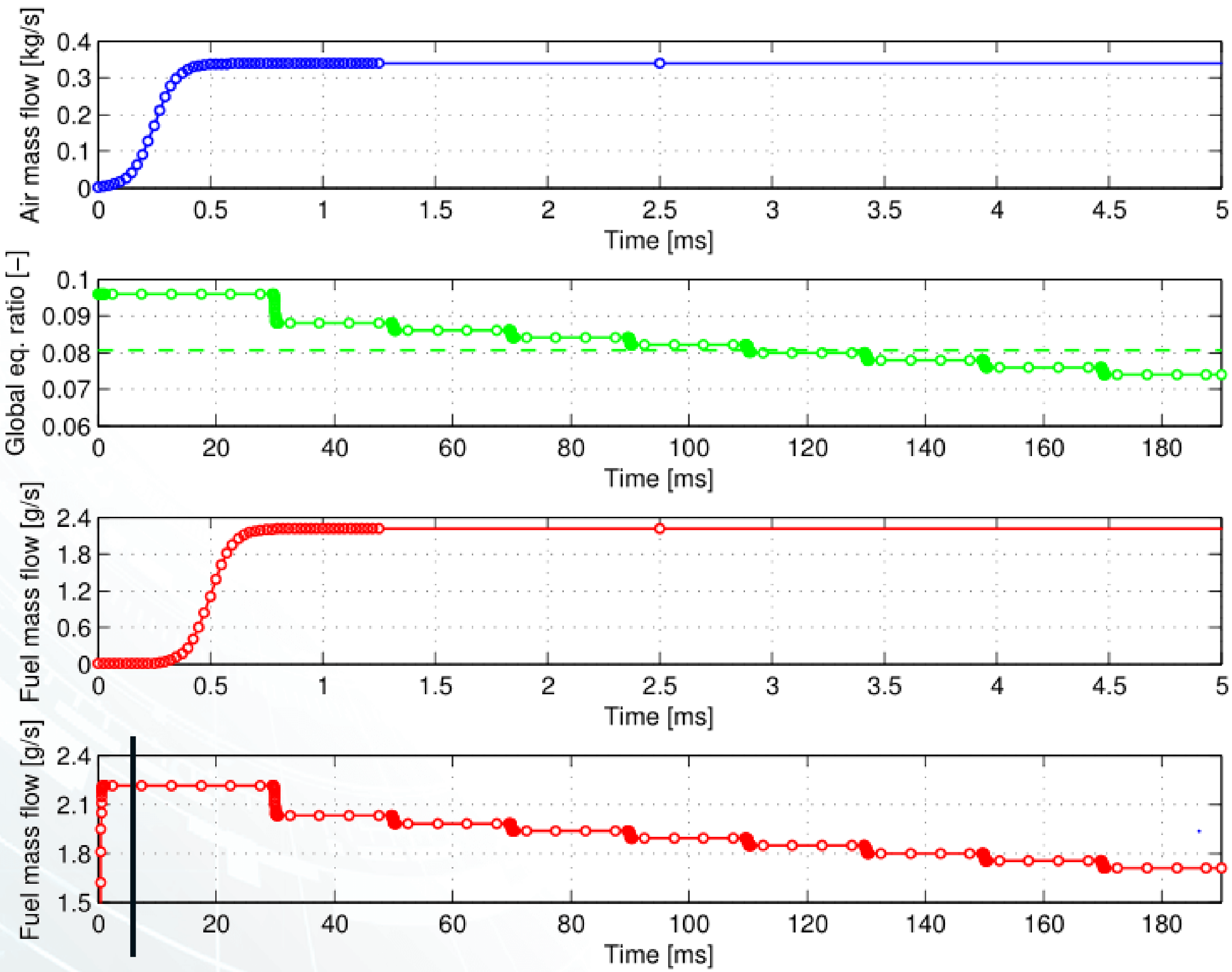
Boundary conditions:

- Inlet: 394.0 K, air ($Y[O_2] = 0.233$, $Y[N_2] = 0.767$), ramp-up function mass flow (next slide).
- Fuel injection: 322.0 K, droplet size 25 μm, spray cone angle 90°, $\varphi_{GLOB} = f(t)$ (next slide).
- Outlet: 204.083 kPa.
- Walls: adiabatic.

Turbulence modelling: LES-CSM turbulence model, hybrid wall functions.

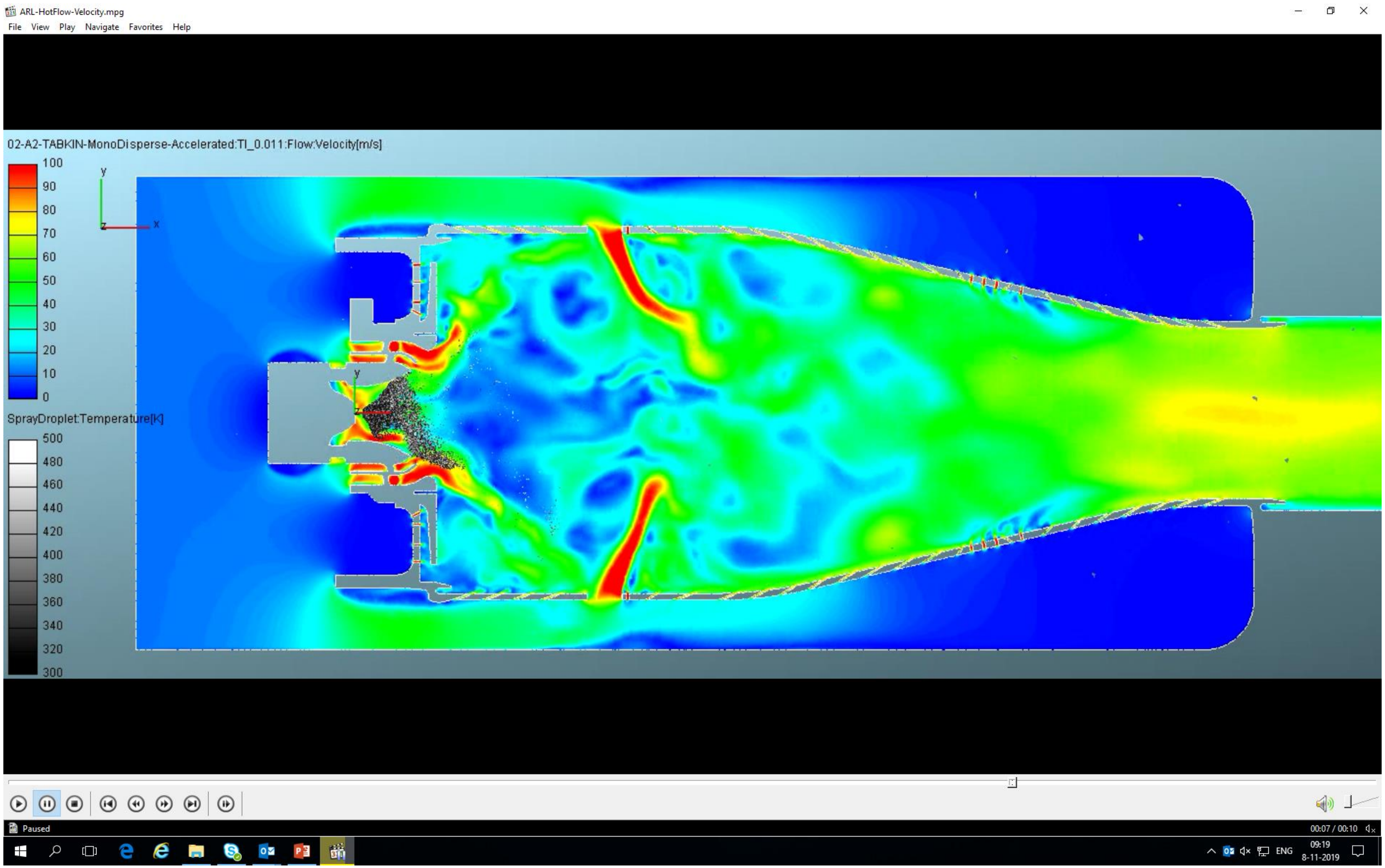
Numerics: time step 2.0 μs, 2nd order accurate discretization in space and time. Run on 256 cores.

LBO simulations: LBO set-up [2]

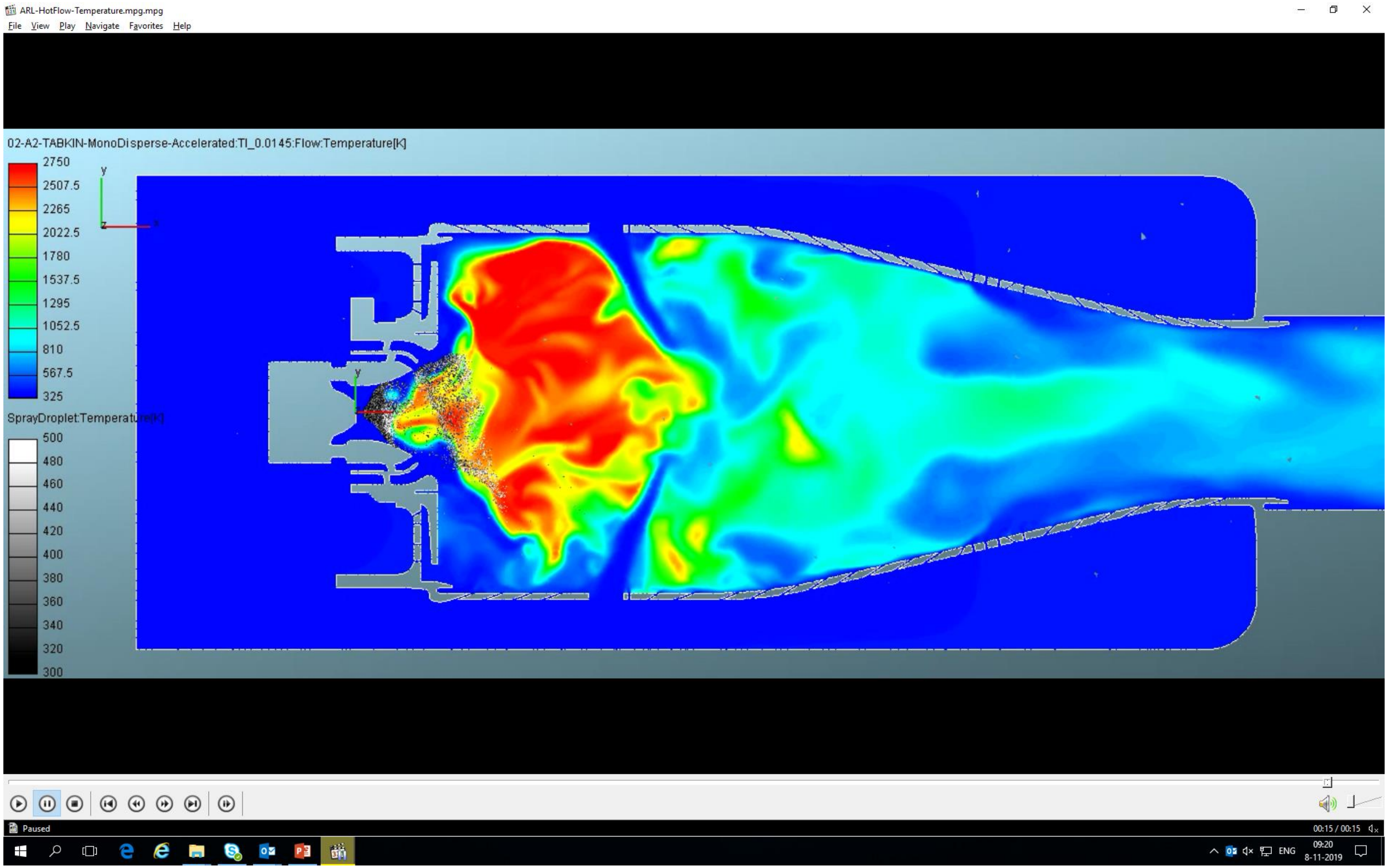


Today

LBO simulations: velocity



LBO simulation: temperature



Contents

Summary and outlook

Summary

- Investigation of Lean Blow-Out (LBO) behavior for 2 jet fuels
- US Air Force Research Laboratory (AFRL) Referee Combustor experiments
- Flow split under cold conditions successfully computed with the AVL FIRE™ CFD code
- Hot flow preparation simulations show differences in fuel evaporation and combustion
- Use of tabulated chemistry (AVL TABKIN™) allows a speed-up of ~2.5x
- LBO simulations ongoing, est. runtime of ~7 weeks on 256 CPU cores

Outlook

- LBO simulations to be continued into 2020 and validated with experimental data
- Effect of mono-disperse vs. poly-disperse droplet size distribution to be investigated

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