Fuel Sensitivity of Lean Blowout in a RQL Gas Turbine Combustor

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Outline

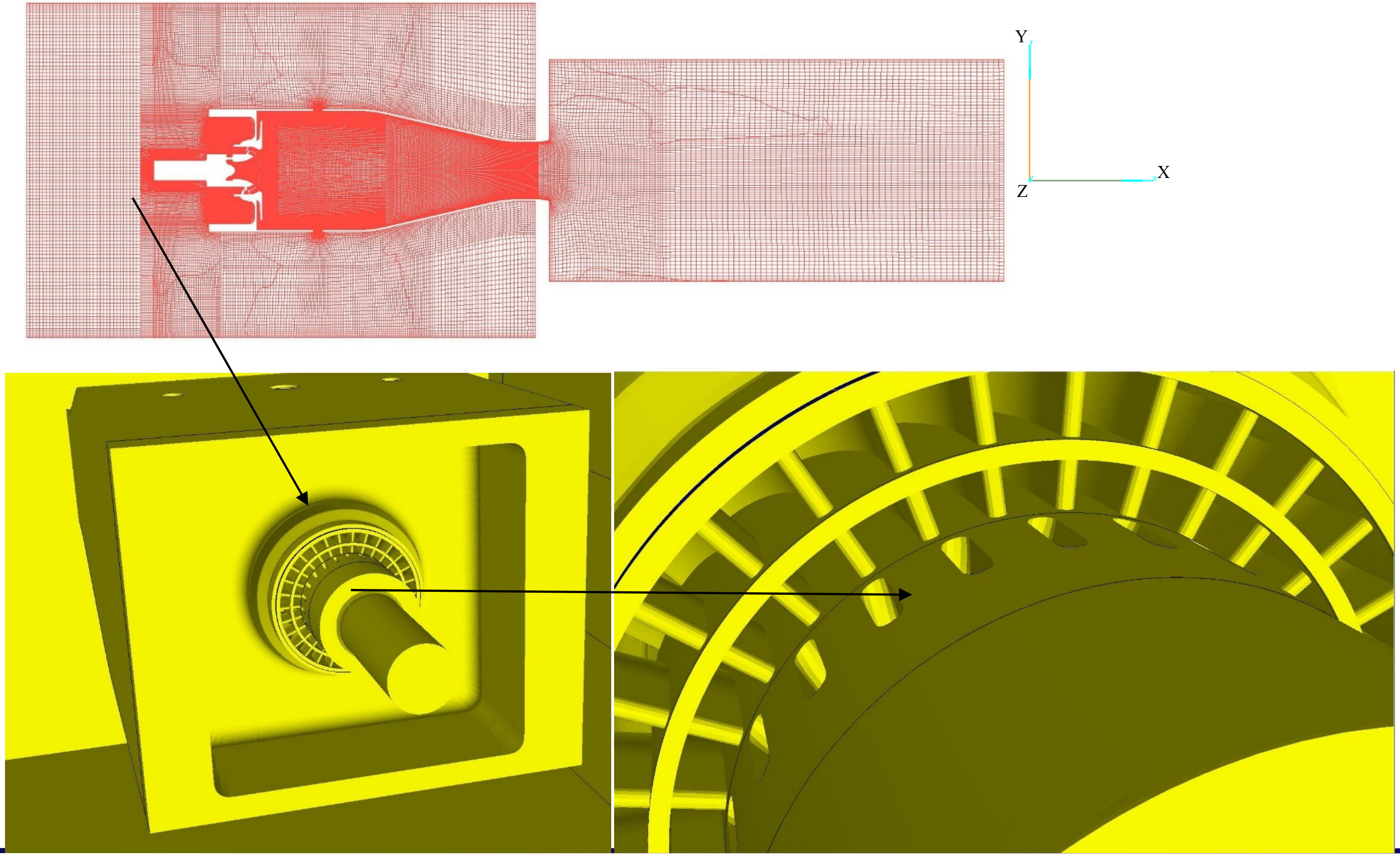
- The transient processes involving lean blow out(LBO) in a RQL combustor such as the single cup combustor in the National Jet Fuels Combustion Program (NJFCP) referee rig were simulated with the reduced mechanisms based on HyChem for two different fuels, Cat-A2 and Cat-C1.

Introduction

- NJFCP has been working to create a more concise and streamlined procedure for approving alternative jet fuels to be used by the aviation industry.
- The sensitivity of LBO, flashback, and combustion dynamics of the alternative fuels is one of the major technical concerns.
- Developing a comprehensive reacting LES strategy of applying the OPENNCC code to the realistic gas turbine combustors for LBO, flashback, and combustion dynamics is currently underway.
- The effort on the LBO is the main topic of the current work.
- Cat-A2 fuel is a Jet A and represents a conventional-type jet fuel with average or nominal properties.
- The Cat-C1, an alternative jet fuel, is a GEVO alcohol-to-jet (ATJ) fuel composed of two iso-paraffin, C_{12} and C_{16}.

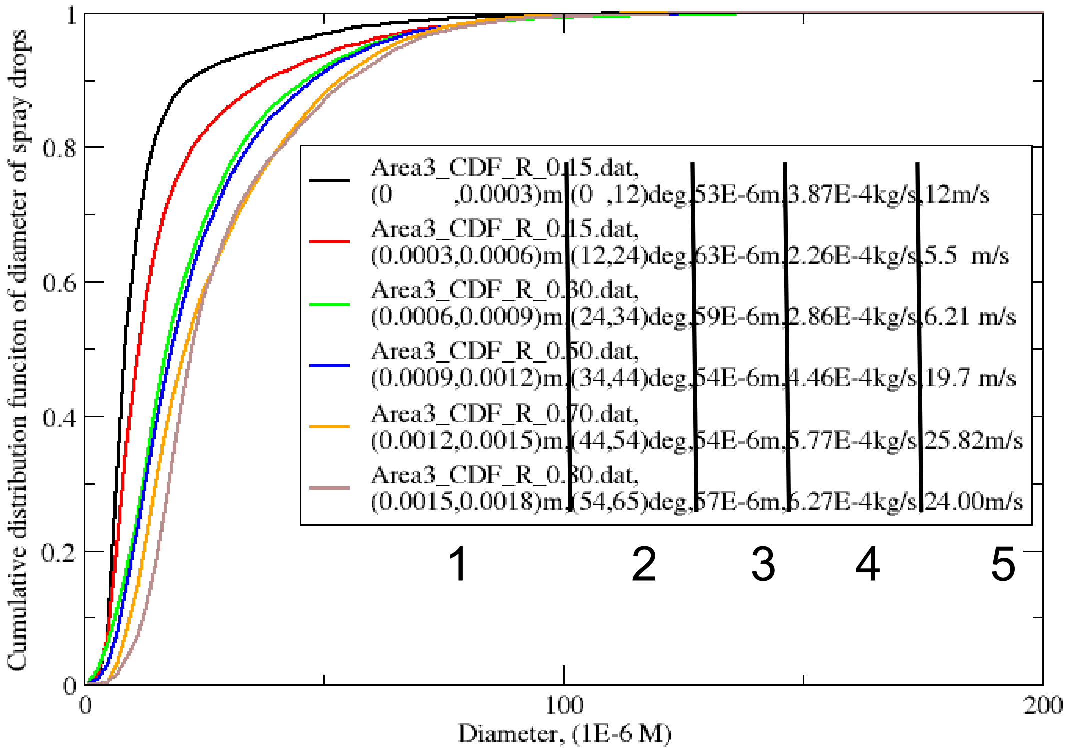
CFD mesh

- 9-block patched 12,640,138 hexahedrons (provided by UTRC through GaTech)
- Linear **extrapolation** and MPI blocking communications are needed due to patched grid. (Non-blocking communication is up to 200% faster than blocking.)



Air and spray boundary conditions & operational inputs

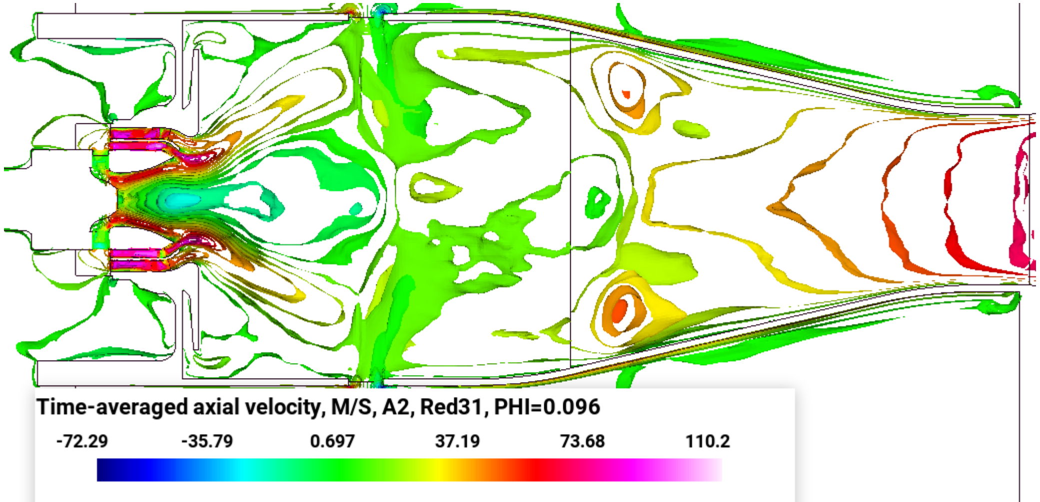
- Air flow rate is 0.391 kg/s. Air temperature is 394 K. Effusion rate is 0.241 kg/s. Exit pressure is 207000 Pa.
- Fuel temperature is 322 K. Baseline equivalence ratio, Φ, is ***0.096*** for Cat-A2 and Cat-C1.
- ***Cumulative distribution functions*** *are used for initial sizes of spray drops by* ***inverse transform sampling (i.e. SMD is not used directly.)***
- *Frossling spray model without secondary breakup is turned on.*
- *3rd order SLAU2 scheme is used for inviscid fluxes (most of simulations).*
- *K-LES turbulence model is used for the reacting cases.*
- *Conservation form of compressible flow is solved.*



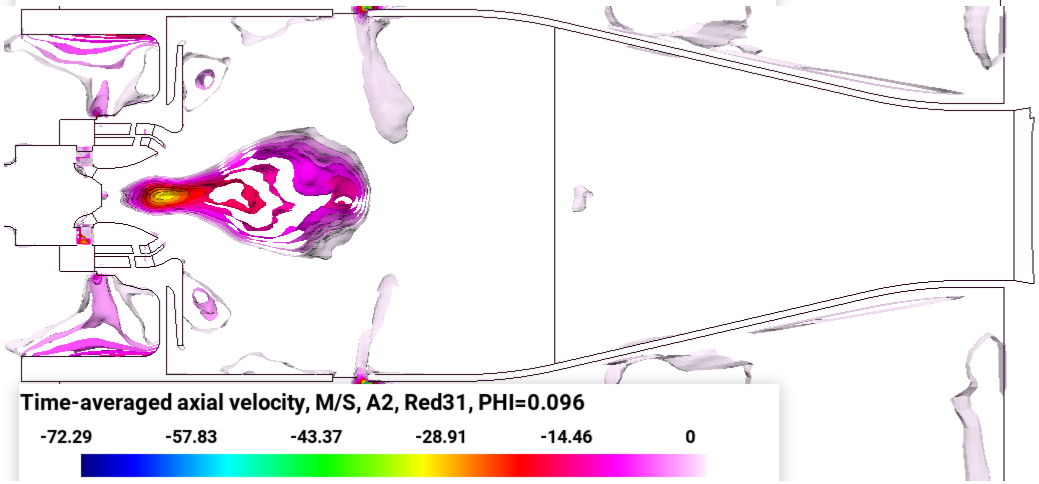
1. Sizes of annulus injectors.
2. directions of injections
3. Computed SMD from CDF.
4. Injection flow rate.
5. Injection speed

Cat-A2(the “nominal” Jet-A)

Axial velocity

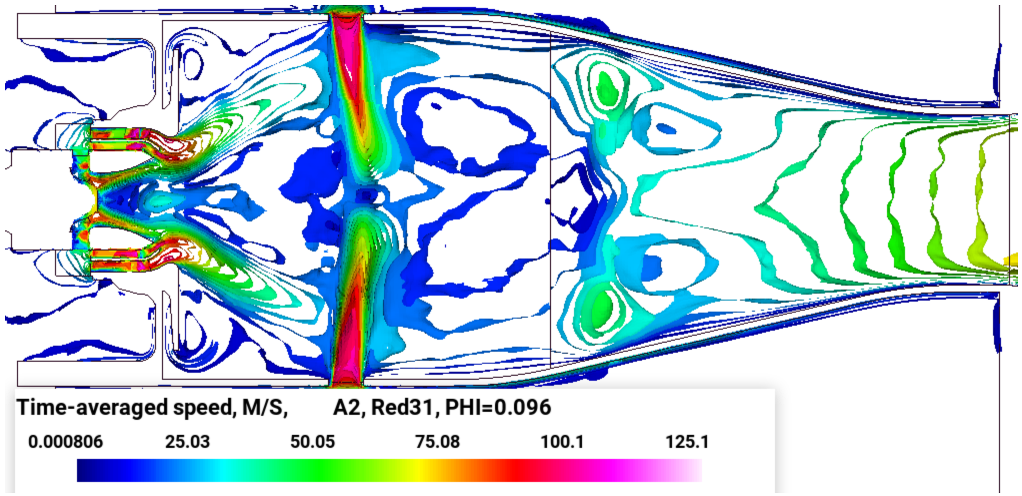


CRZ-
Central Recirculation
Zone

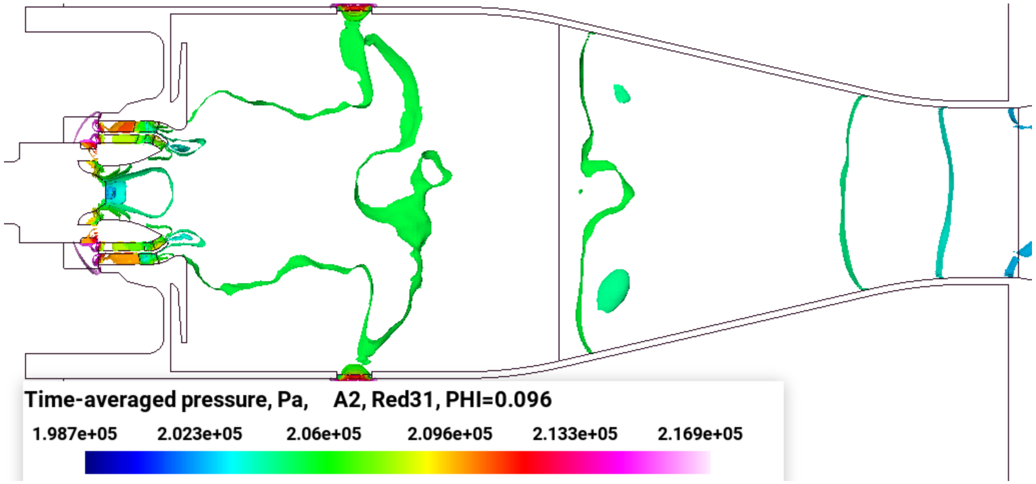


Cat-A2

Speed

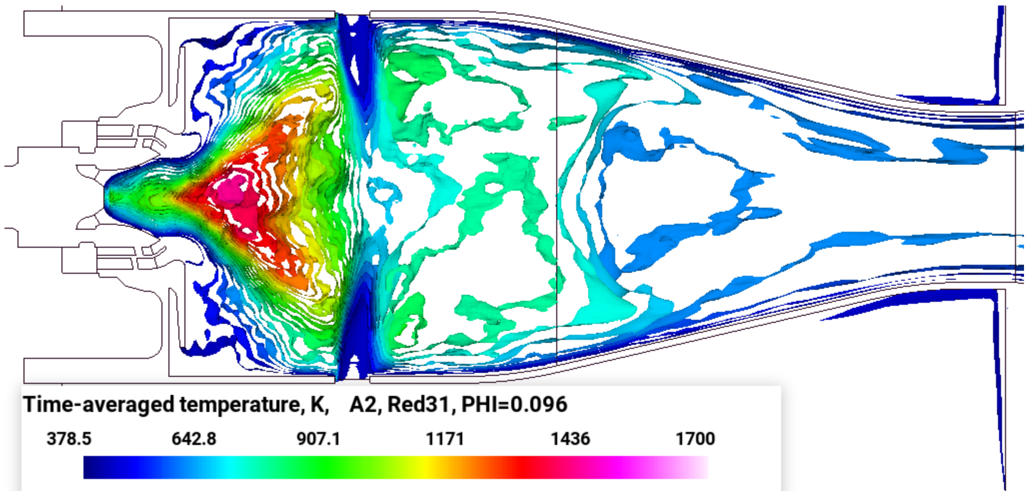


Pressure

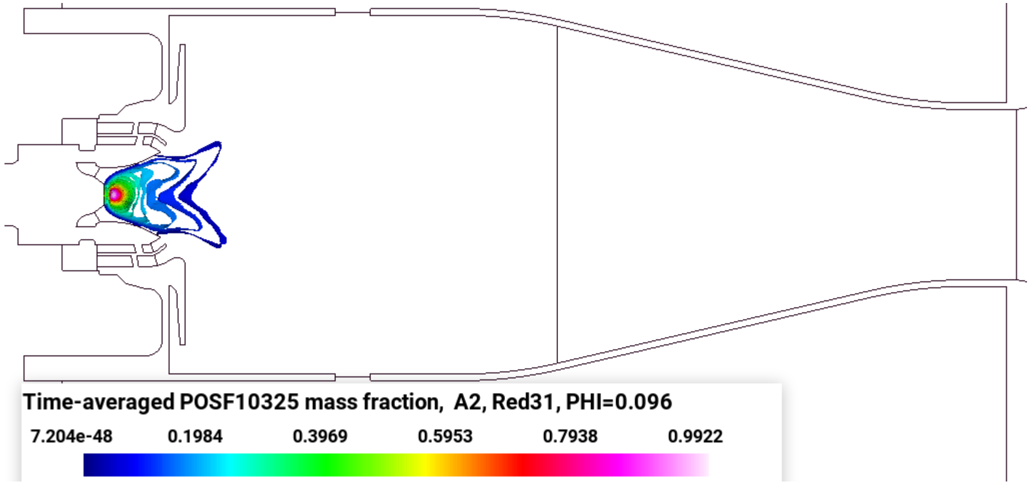


Cat-A2

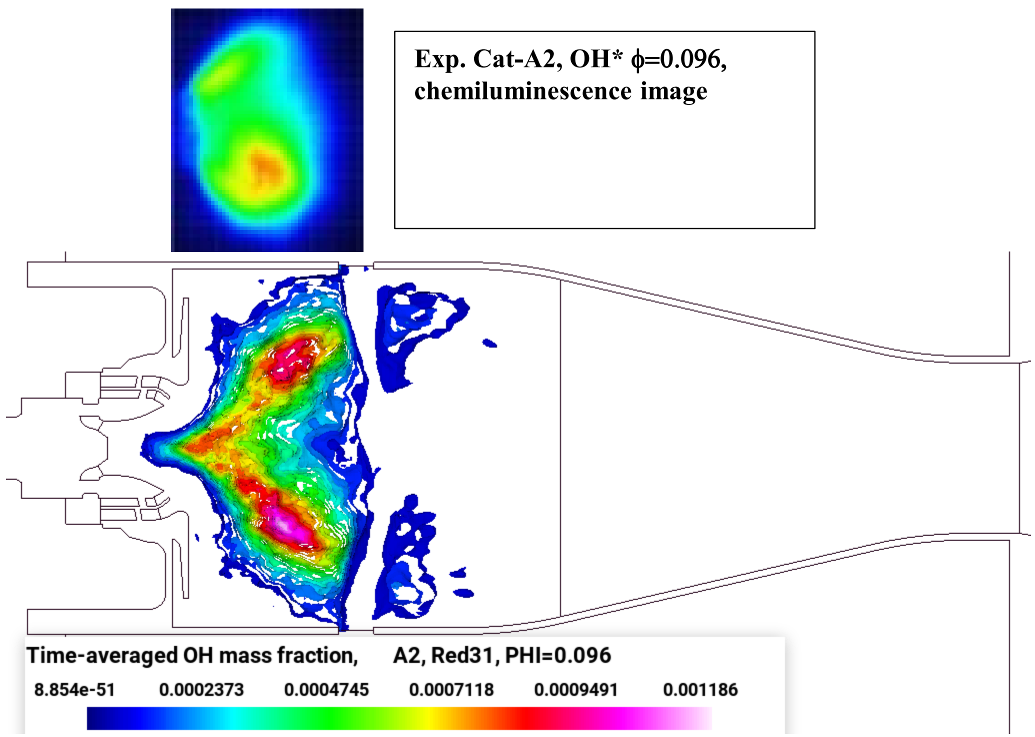
Temperature



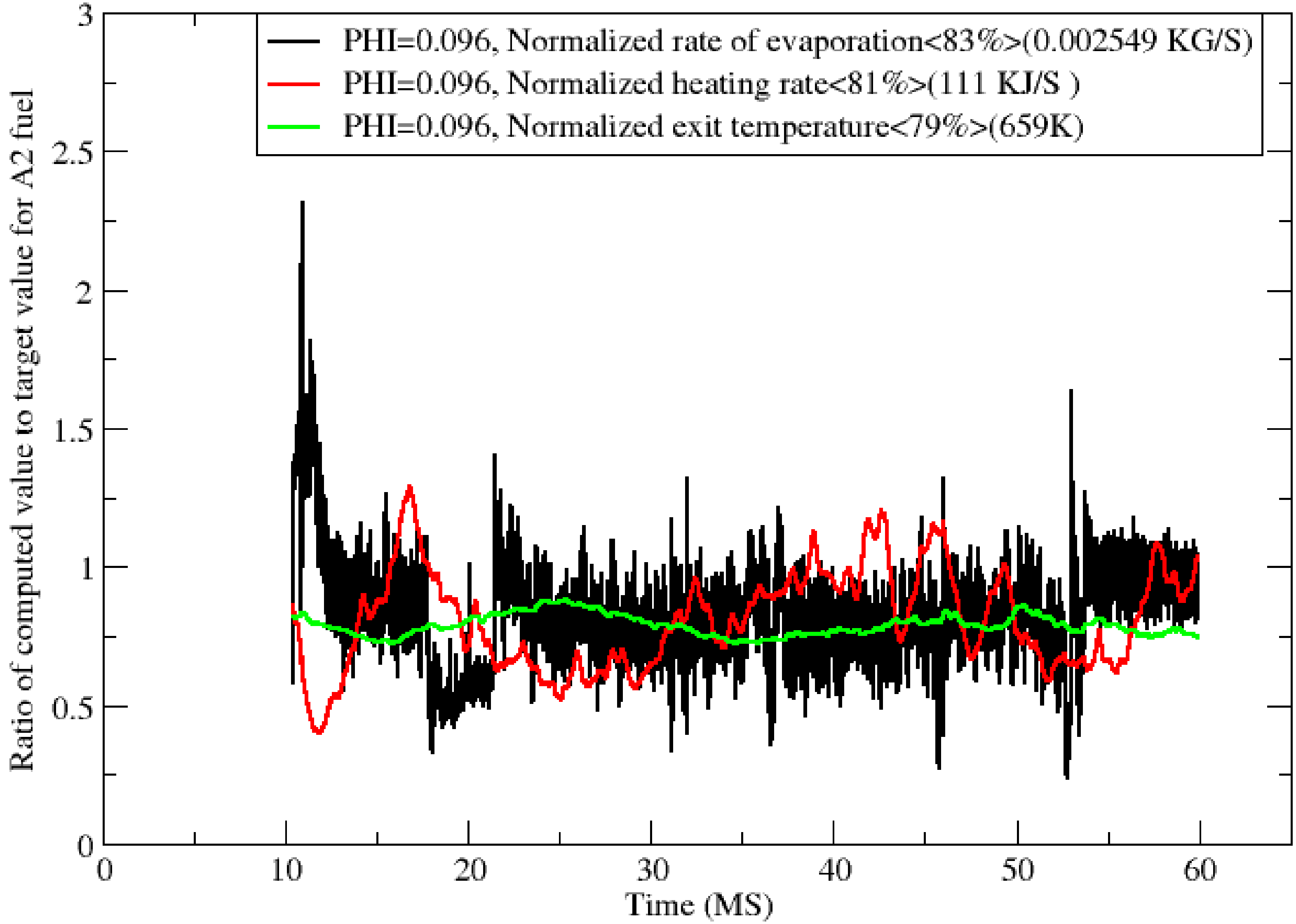
A2 mass fraction



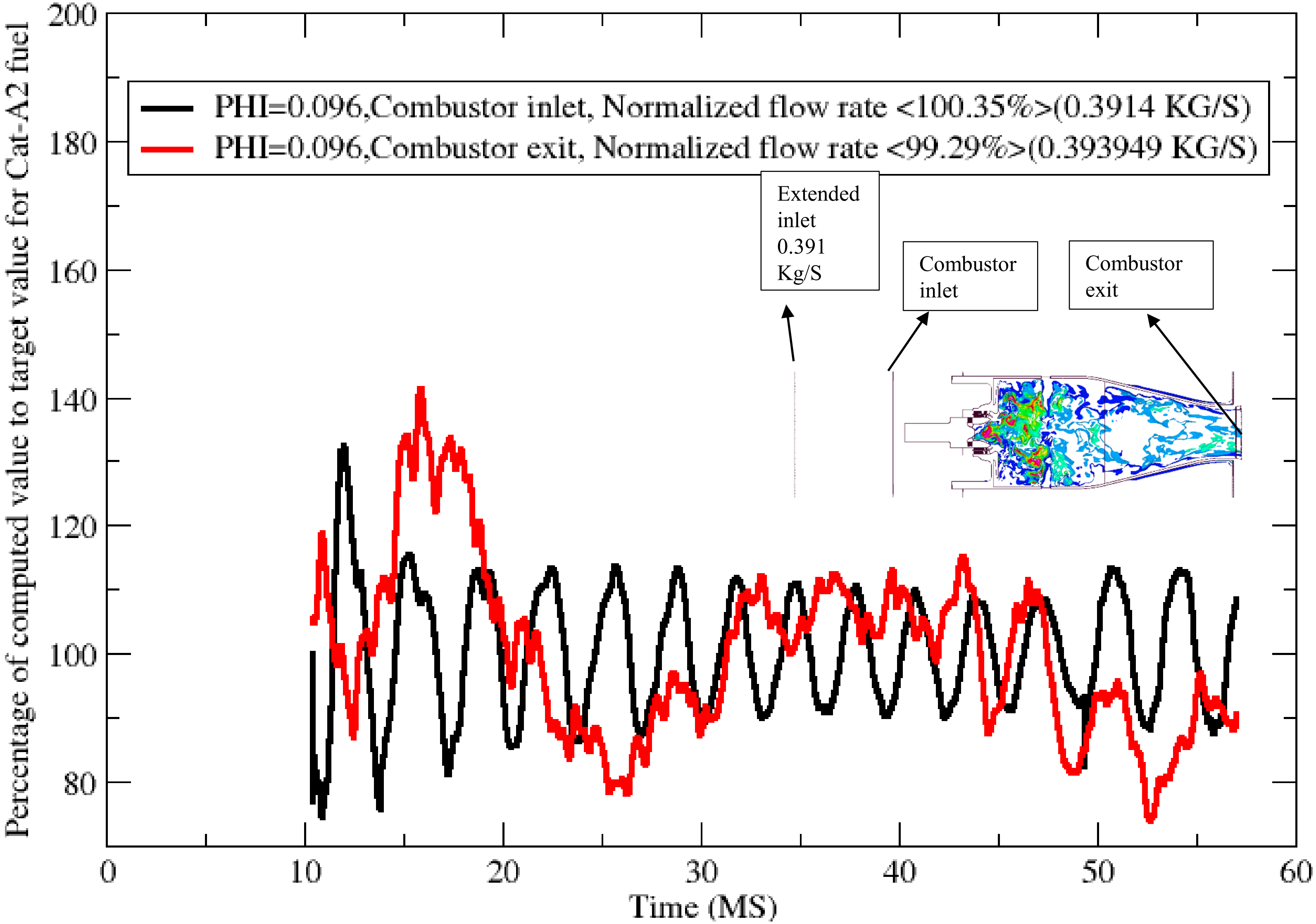
Cat-A2


Exp. Cat-A2, OH* ϕ=0.096,
chemiluminescence image
Time-averaged OH mass fraction,
A2, Red31, PHI=0.096
8.854e-51
0.0002373
0.0004745
0.0007118
0.0009491
0.001186

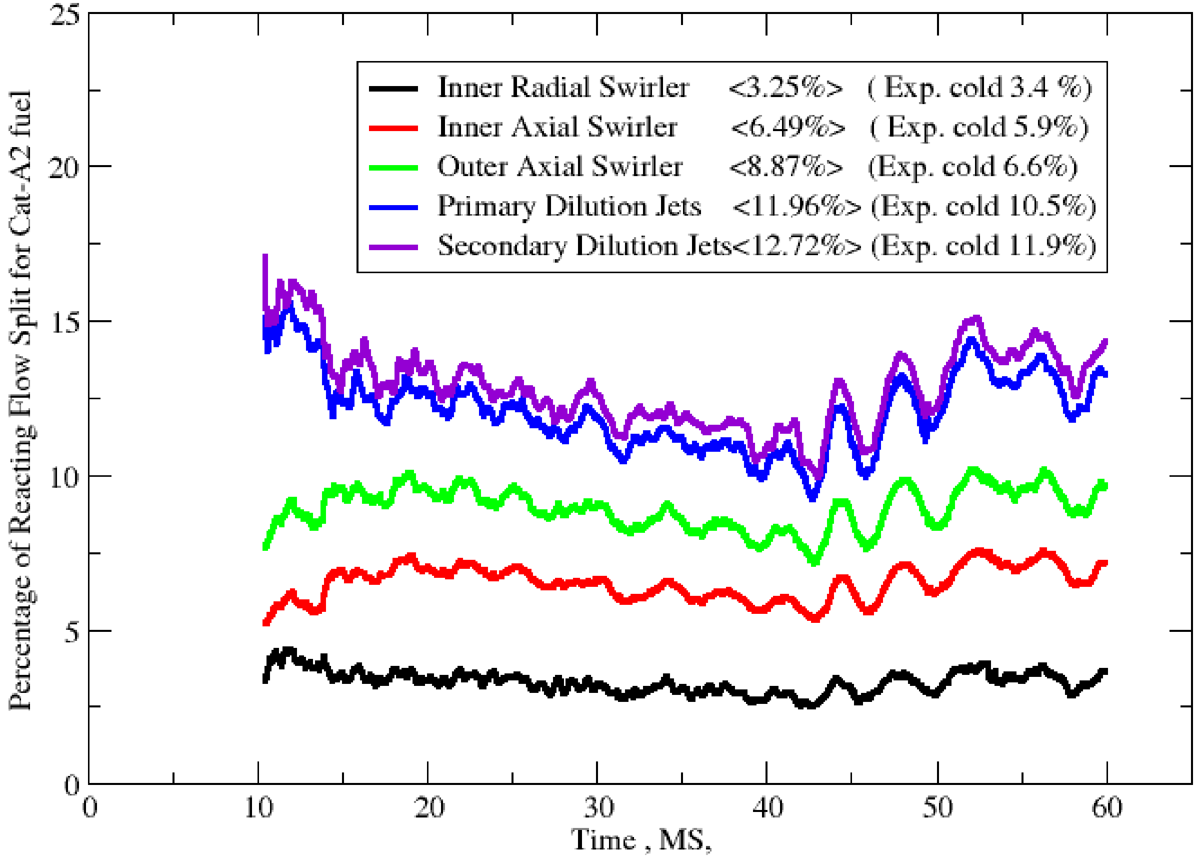
Cat-A2

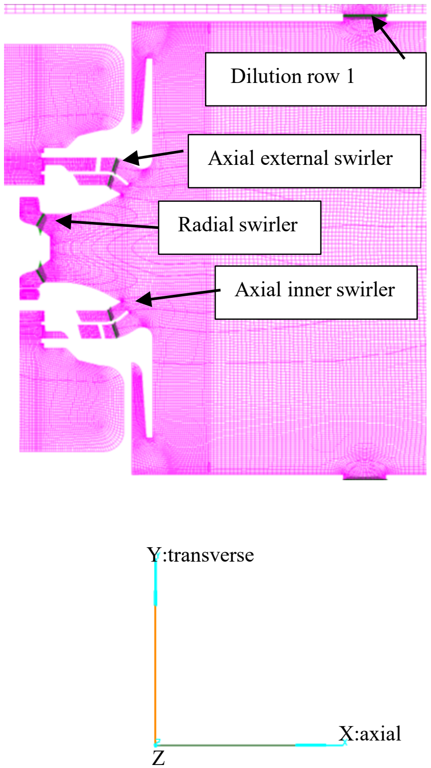

PHI=0.096, Normalized rate of evaporation<83%>(0.002549 KG/S)
PHI=0.096, Normalized heating rate<81%>(111 KJ/S)
PHI=0.096, Normalized exit temperature<79%>(659K)
Ratio of computed value to target value for A2 fuel
Time (MS)
0
0.5
1
1.5
2
2.5
3
0
10
20
30
40
50
60

Cat-A2

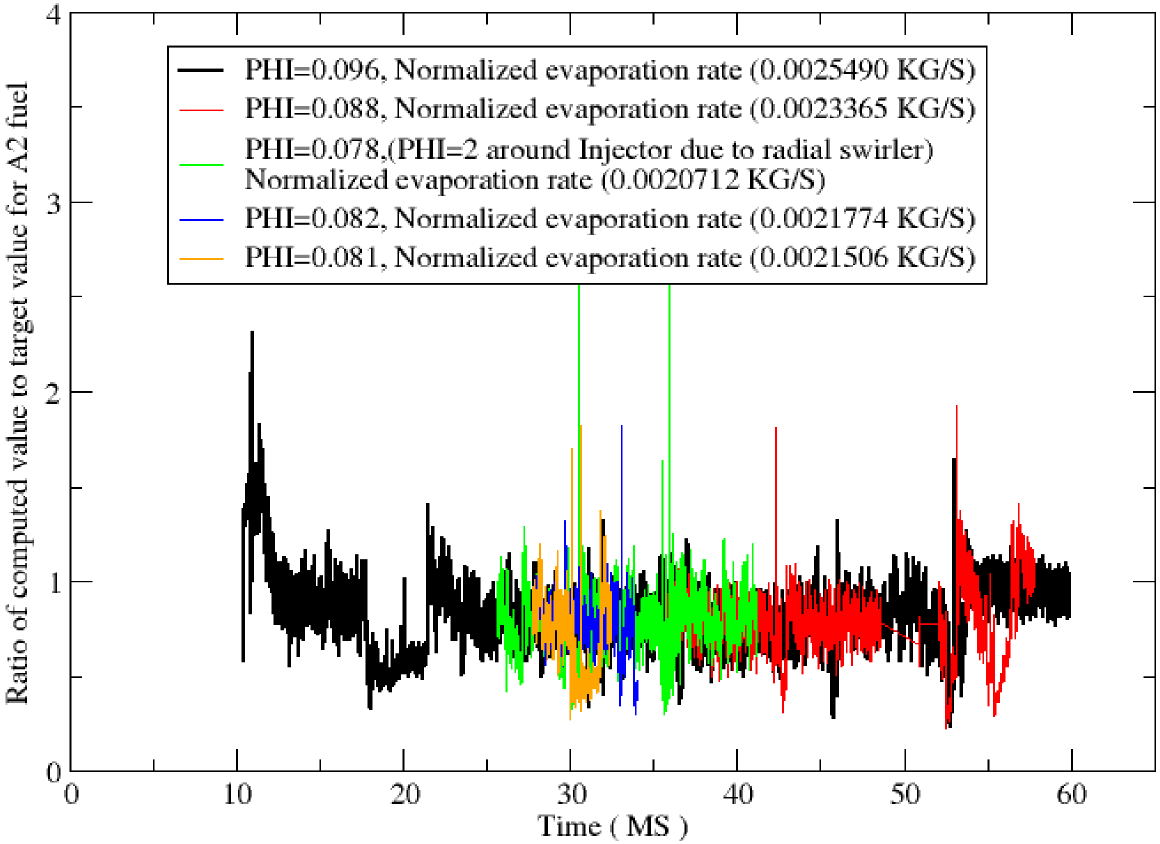

PHI=0.096,Combustor inlet, Normalized flow rate <100.35%>(0.3914 KG/S)
PHI=0.096,Combustor exit, Normalized flow rate <99.29%>(0.393949 KG/S)
Extended inlet 0.391 Kg/S
Combustor inlet
Combustor exit
Percentage of computed value to target value for Cat-A2 fuel
Time (MS)
200
180
160
140
120
100
80
0
10
20
30
40
50
60

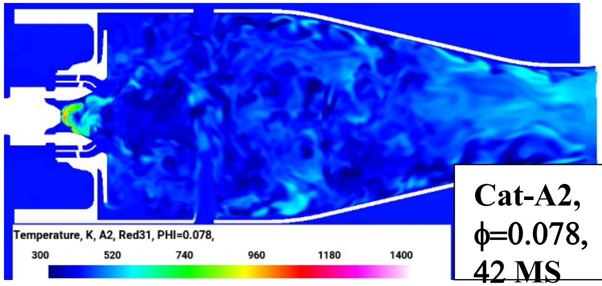
Cat-A2


Inner Radial Swirler <3.25%> (Exp. cold 3.4 %)
Inner Axial Swirler <6.49%> (Exp. cold 5.9%)
Outer Axial Swirler <8.87%> (Exp. cold 6.6%)
Primary Dilution Jets <11.96%> (Exp. cold 10.5%)
Secondary Dilution Jets<12.72%> (Exp. cold 11.9%)
Percentage of Reacting Flow Split for Cat-A2 fuel
Time , MS,
0
5
10
15
20
25
0
10
20
30
40
50
60


Dilution row 1
Axial external swirler
Radial swirler
Axial inner swirler
Y:transverse
X:axial
Z

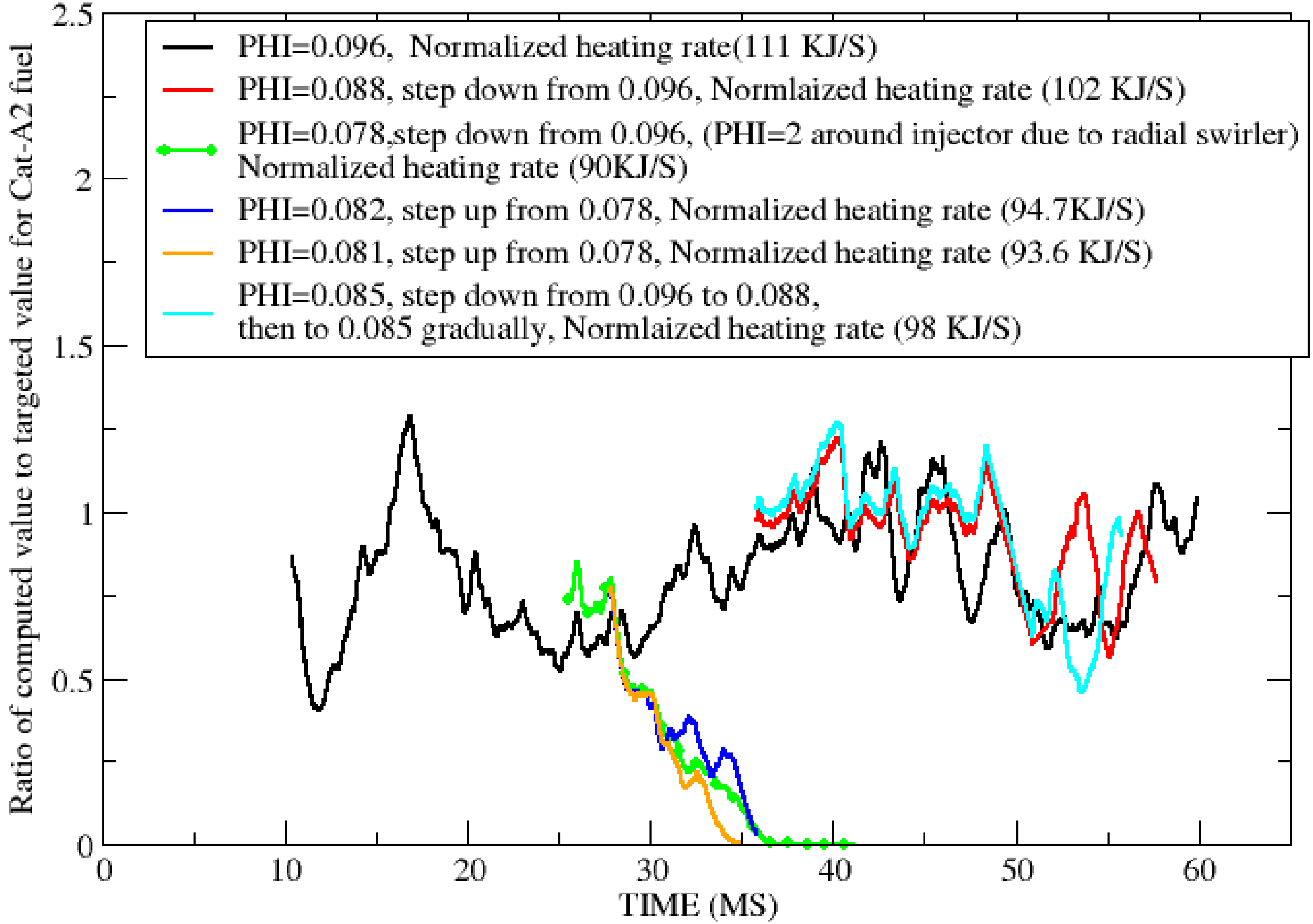
Cat-A2, Φ=[0.078↔0.096]





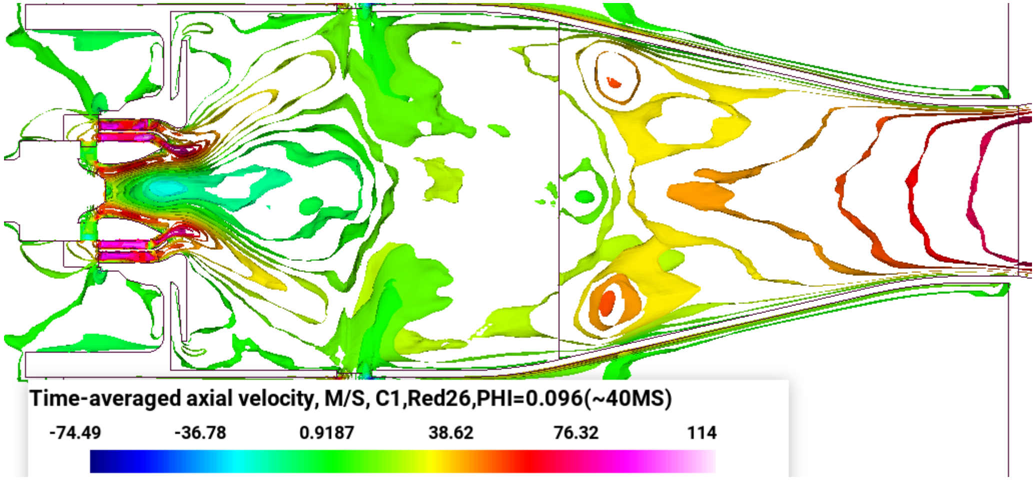
Cat-A2, ϕ=0.078, 42 MS

Cat-A2, Φ=[0.078↔0.096]

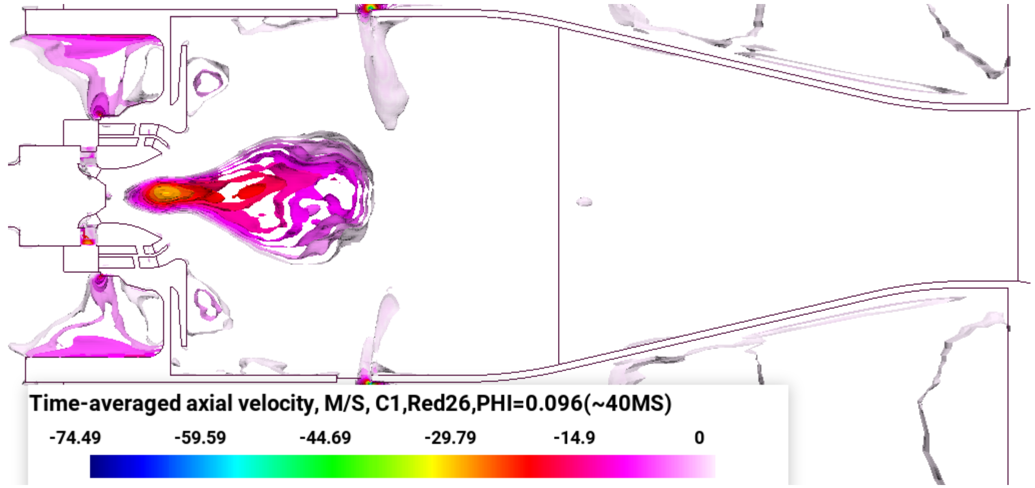


Cat-C1(two-component alcohol-to-jet (ATJ) fuel)

Axial velocity

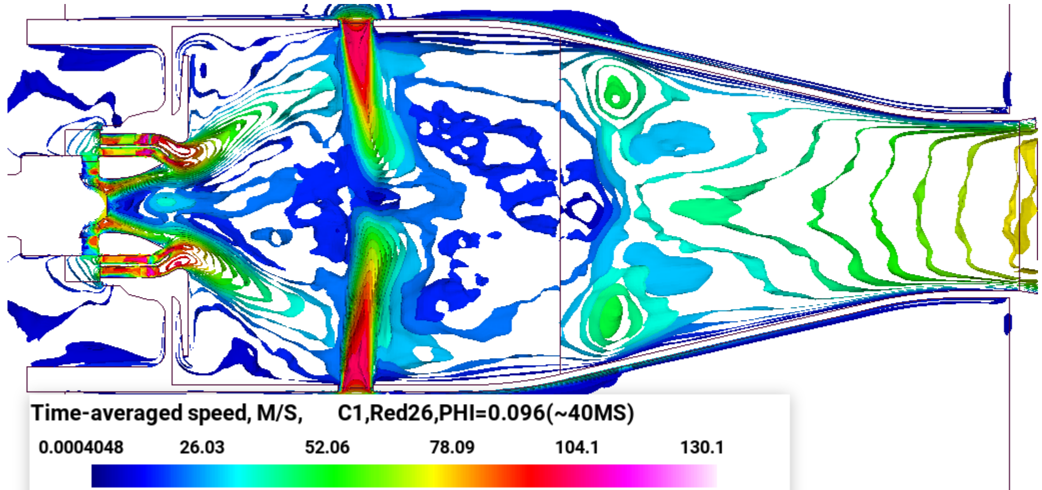


CRZ-
Central Recirculation
Zone

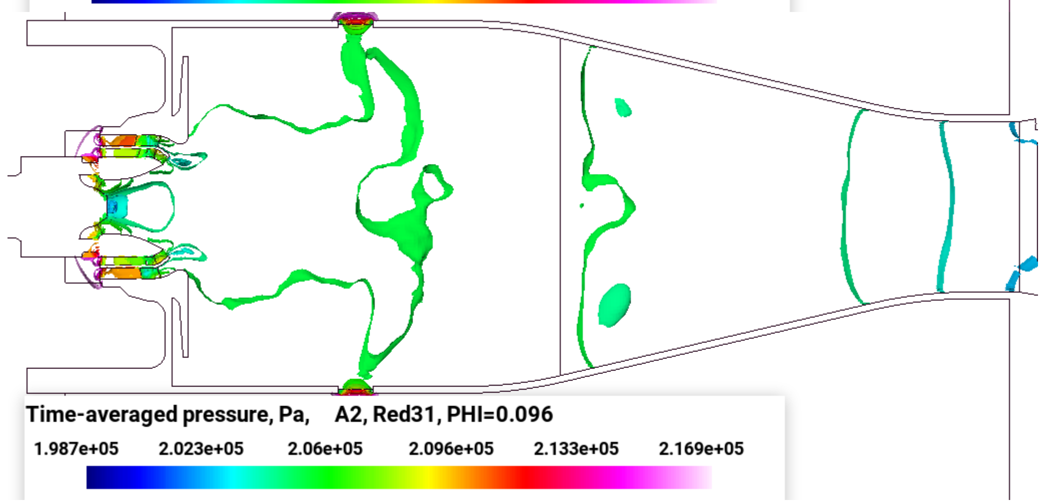


Cat-C1

Speed

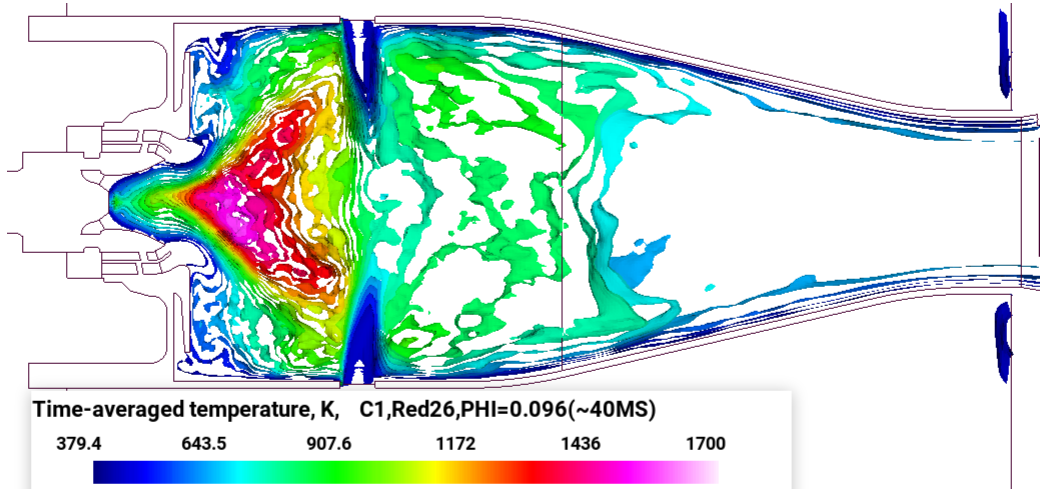


Pressure

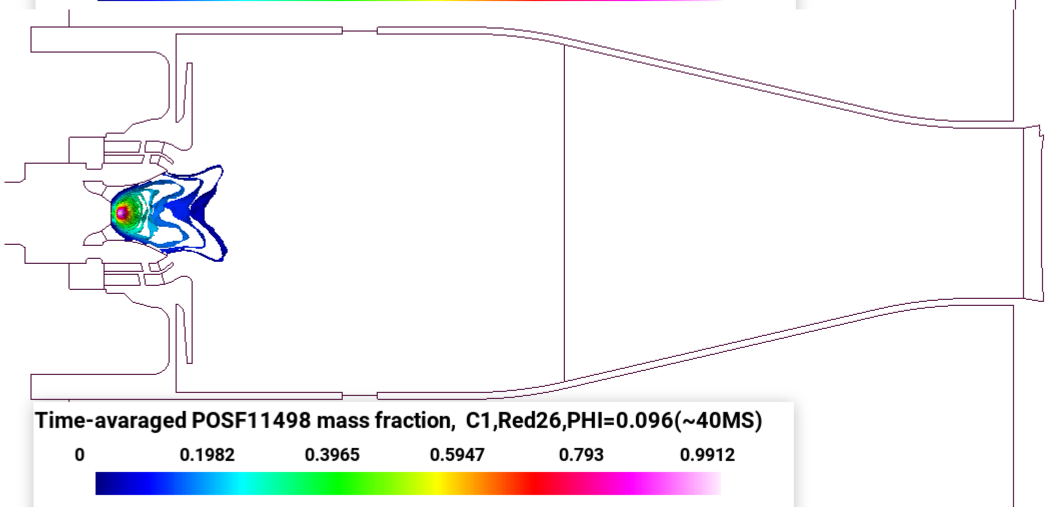


Cat-C1

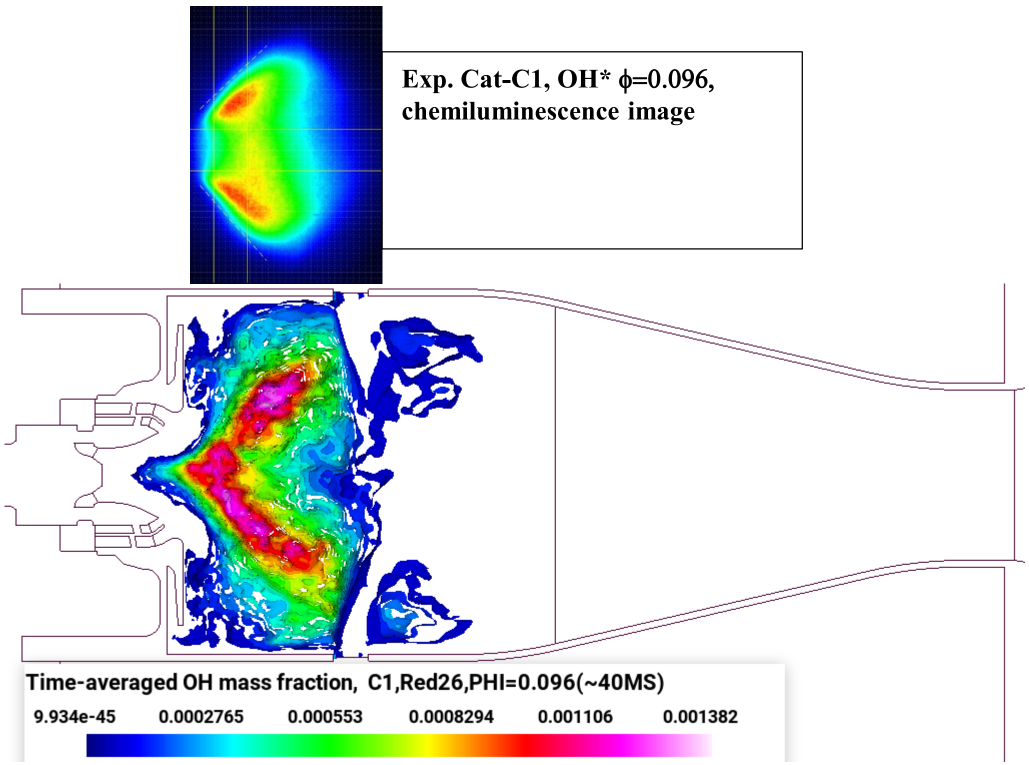
Temperature



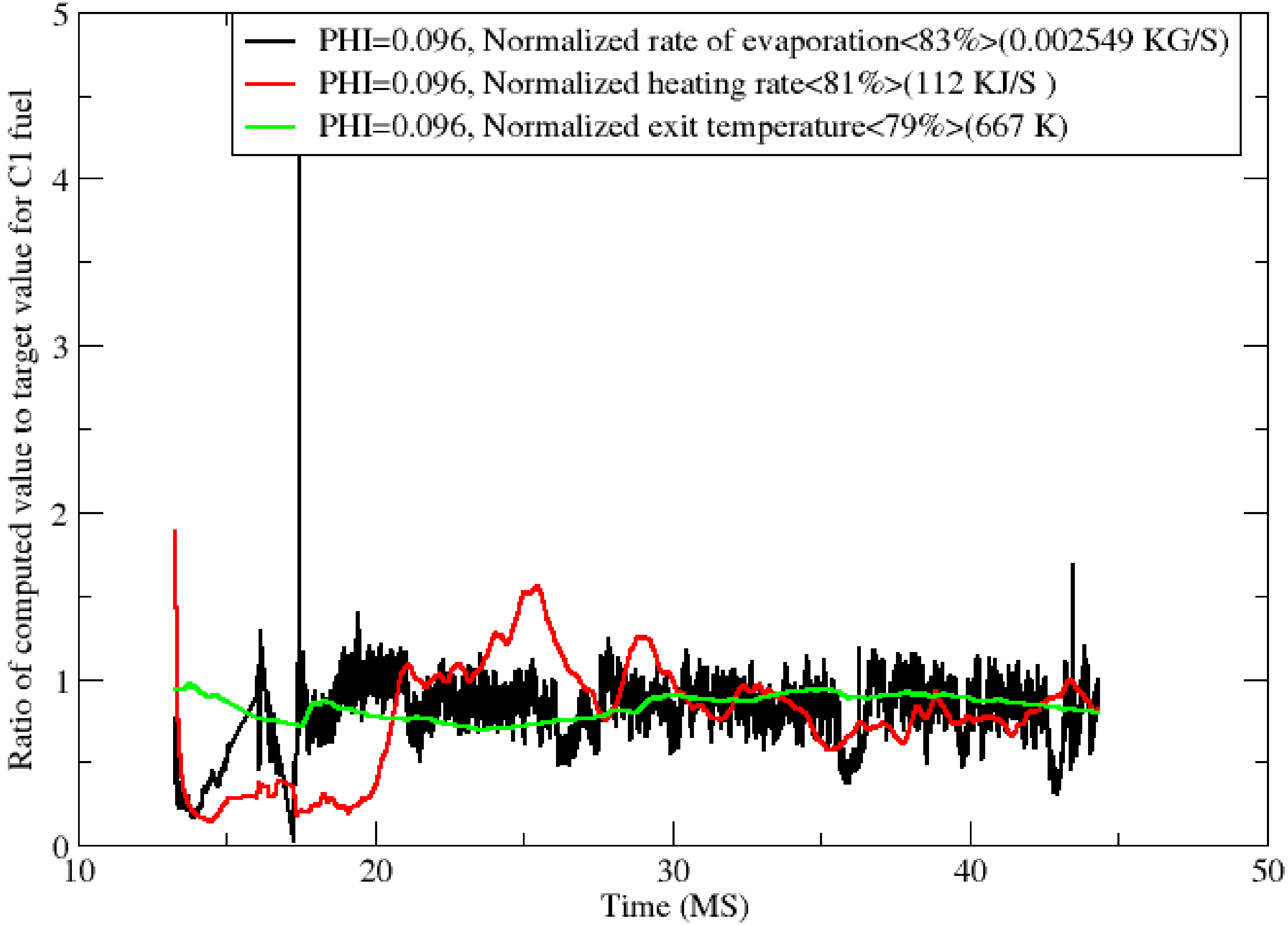
C1 mass fraction



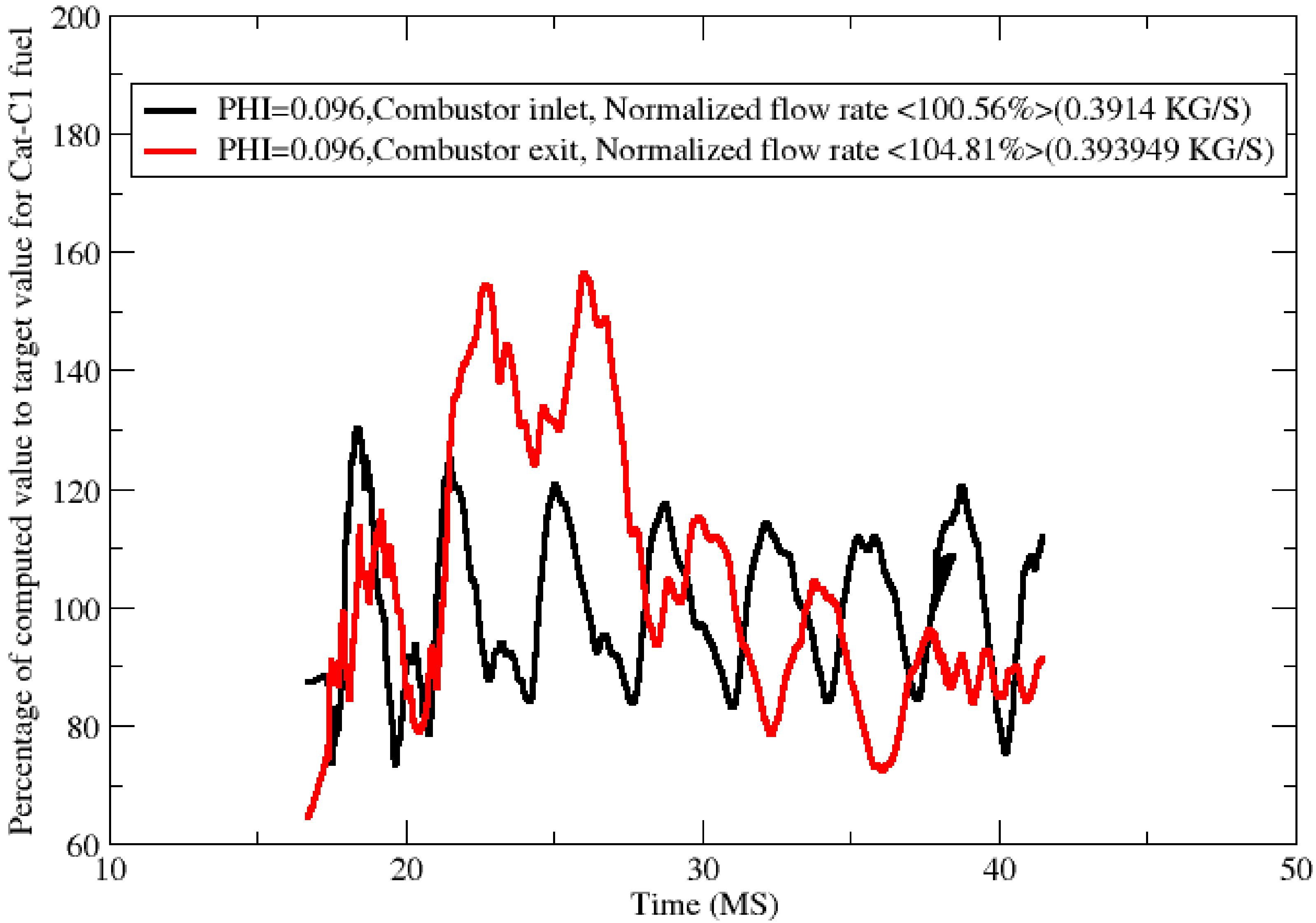
Cat-C1


Exp. Cat-C1, OH* ϕ=0.096,
chemiluminescence image
Time-averaged OH mass fraction, C1,Red26,PHI=0.096(~40MS)
9.934e-45
0.0002765
0.000553
0.0008294
0.001106
0.001382

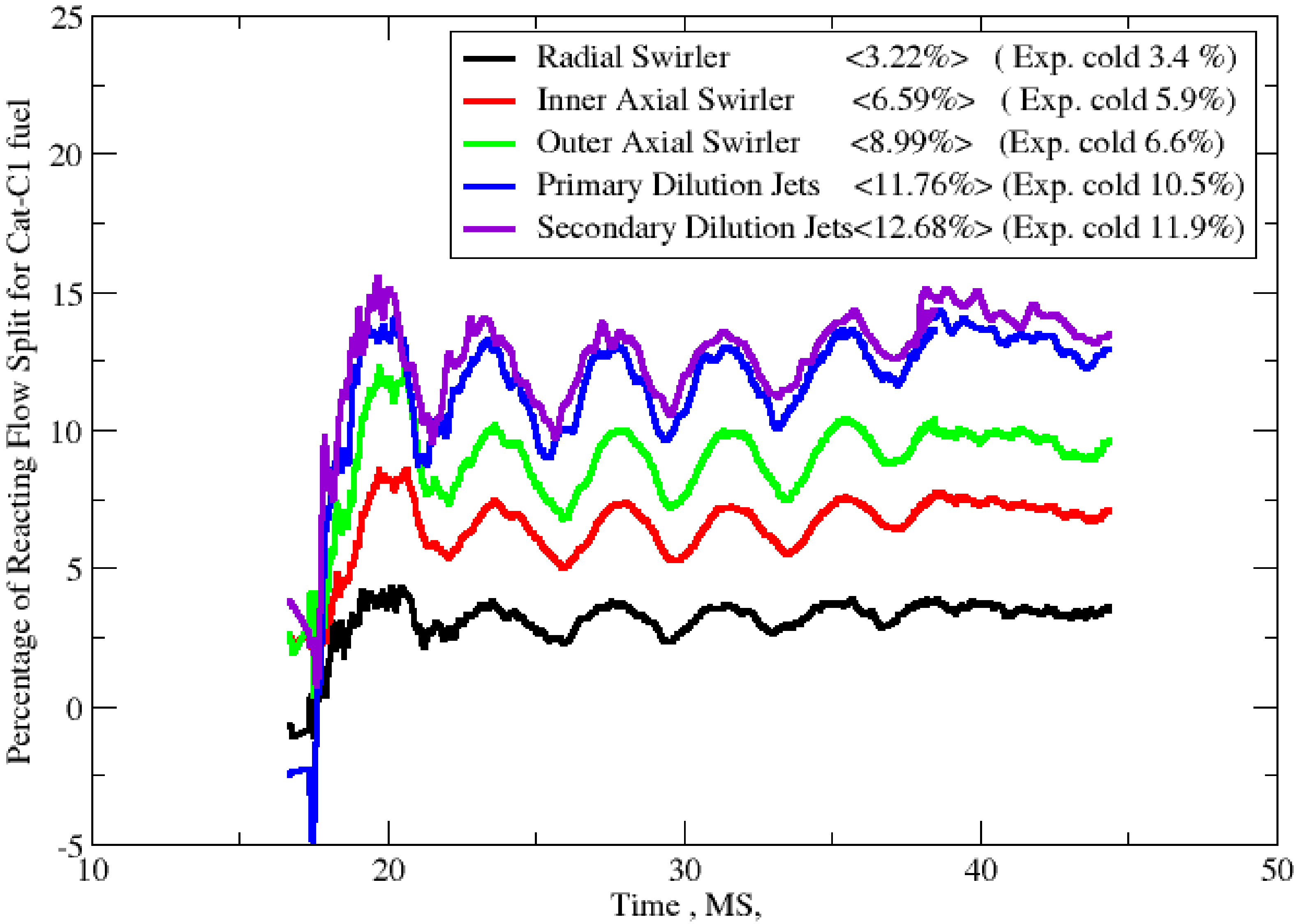
Cat-C1


PHI=0.096, Normalized rate of evaporation<83%>(0.002549 KG/S)
PHI=0.096, Normalized heating rate<81%>(112 KJ/S)
PHI=0.096, Normalized exit temperature<79%>(667 K)
Ratio of computed value to target value for C1 fuel
Time (MS)
0
1
2
3
4
5
10
20
30
40
50

Cat-C1

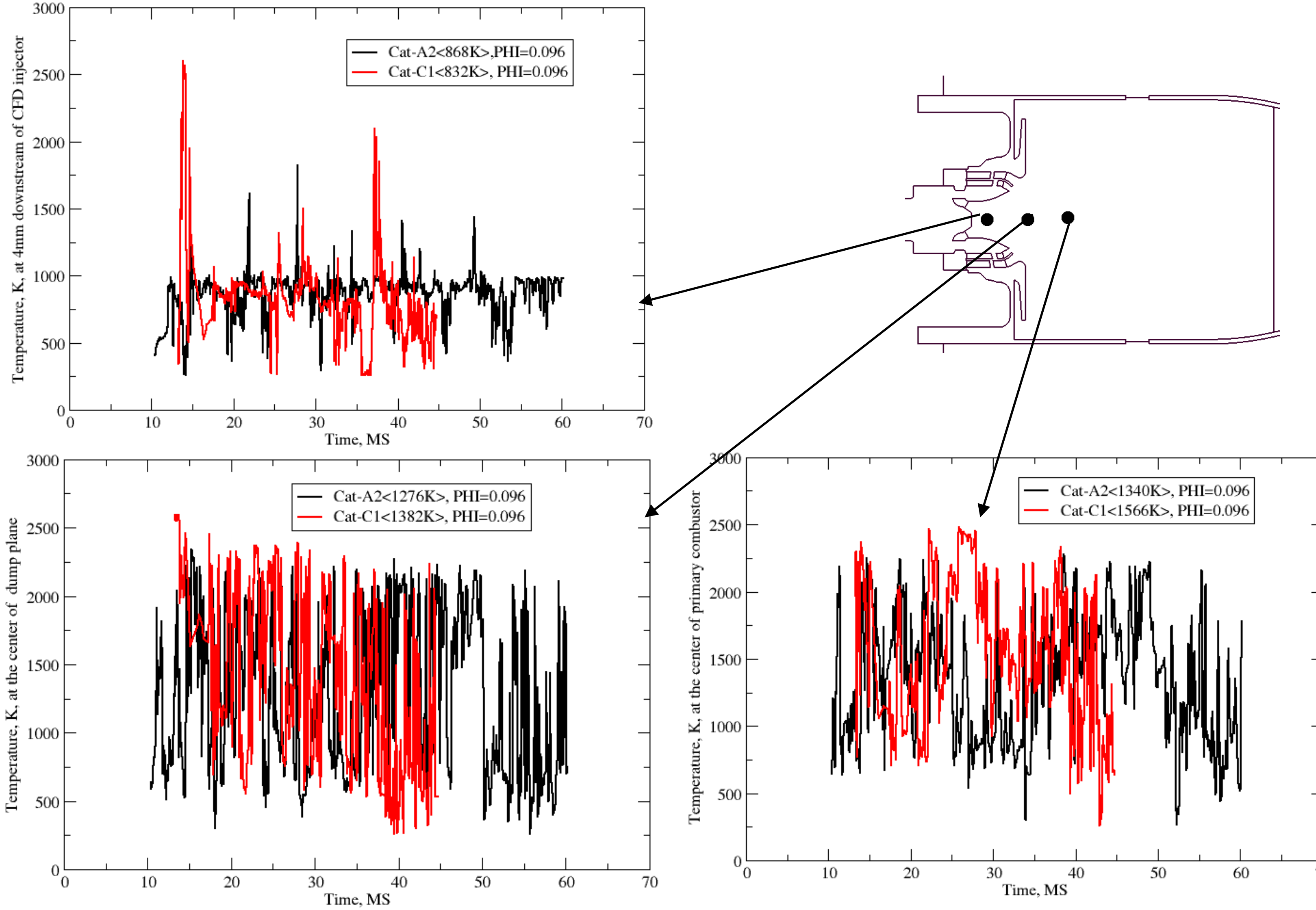

PHI=0.096,Combustor inlet, Normalized flow rate <100.56%>(0.3914 KG/S)
PHI=0.096,Combustor exit, Normalized flow rate <104.81%>(0.393949 KG/S)
Percentage of computed value to target value for Cat-C1 fuel
Time (MS)
200
180
160
140
120
100
80
60
10
20
30
40
50

Cat-C1



25
20
15
10
5
0
-5
10
20
30
40
50
Time , MS,
Percentage of Reacting Flow Split for Cat-C1 fuel
Radial Swirler <3.22%> (Exp. cold 3.4 %)
Inner Axial Swirler <6.59%> (Exp. cold 5.9%)
Outer Axial Swirler <8.99%> (Exp. cold 6.6%)
Primary Dilution Jets <11.76%> (Exp. cold 10.5%)
Secondary Dilution Jets<12.68%> (Exp. cold 11.9%)

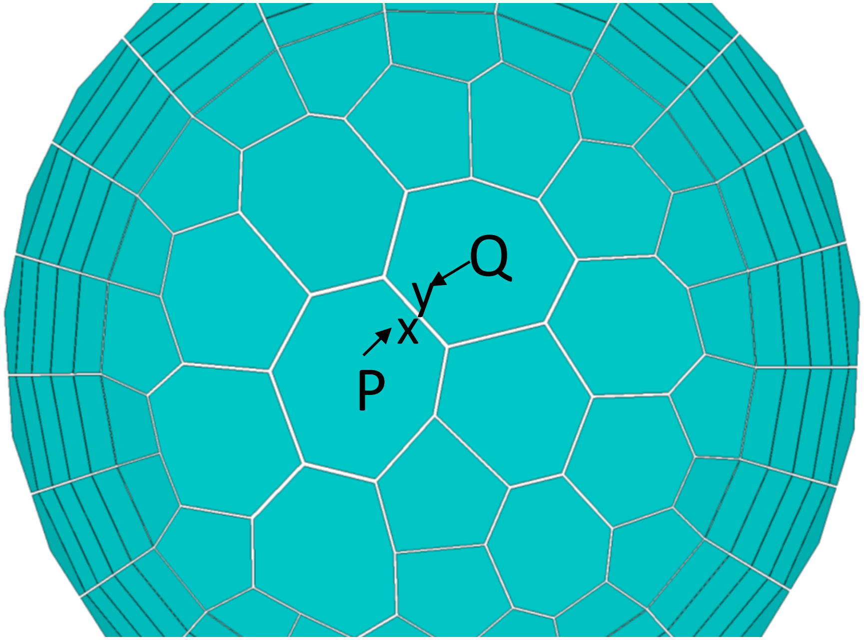
Time history of temperatures at three points Φ=0.096



A stable flame can sustain itself at Φ=0.096.

Higher than 2nd order scheme for inviscid fluxes

A three-dimensional third-order Taylor series Expansion formula is applied to **x** from **P** to Compute all necessary variables at one side of the Integration face for the fluxes computations. Similarly, the same formula is applied to **y** from **Q** at the other side of the integration face. In general, the values at **x** and **y** are ***different*** and ***discontinuous***. Higher than 2nd order SLAU2 schemes for inviscid fluxes can be achieved by utilizing Taylor series expansion formula.

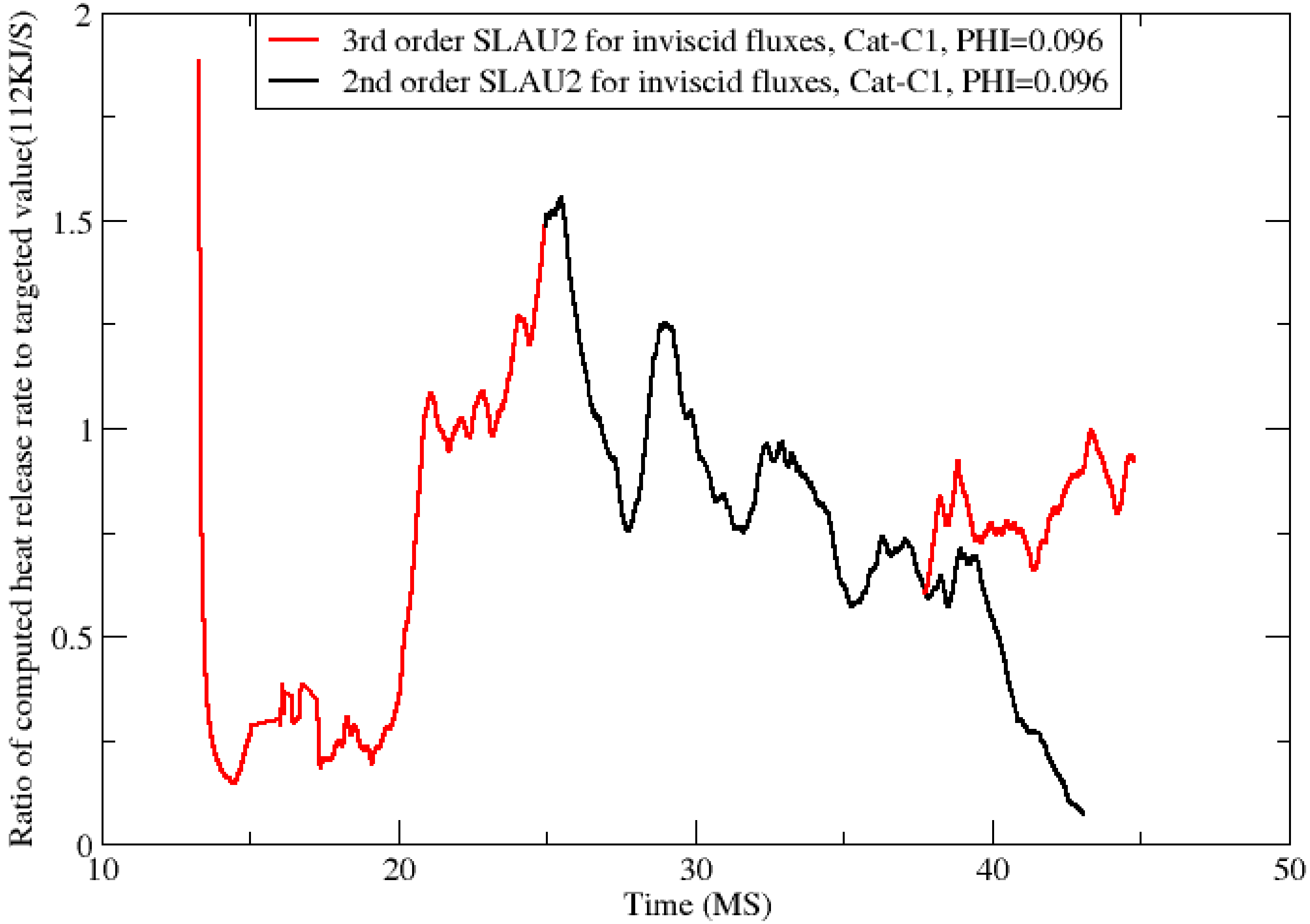


$$U(\vec{x})=U(\vec{P}) + U'(\vec{P})(\vec{x}-\vec{P})+\frac{1}{2}U''(\vec{P})(\vec{x}-\vec{P})^2+\frac{1}{6}U'''(\vec{P})(\vec{x}-\vec{P})^3$$

Similarly, a second-order Taylor series expansion for any variable at **x** and **y** will look like:(The integration of the inviscid fluxes will be 3rd order accurate)

$$U(\vec{x})=U(\vec{P}) + U'(\vec{P})(\vec{x}-\vec{P})+\frac{1}{2}U''(\vec{P})(\vec{x}-\vec{P})^2, \quad U(\vec{y})=U(\vec{Q}) + U'(\vec{Q})(\vec{y}-\vec{Q})+\frac{1}{2}U''(\vec{Q})(\vec{y}-\vec{Q})^2$$

Effect of high order scheme on heating rate of Cat-C1 fuel



The speed of simulation with 3[rd] order SLAU2 is up to 35% slower than that of 2[nd] order SLAU2.

Concluding Remarks

- In this paper, the strategy of using reacting K-LES in analyzing the sensitivity of two aviation fuels in a referee combustor rig was developed.
- For the reacting cases, an average jet fuel (denoted as "Cat-A2" in the NJFCP) and a test fuel (Cat-C1) were selected for the sensitivity study.
- Five simulations for Cat-A2 fuel with consecutive decreased equivalence ratios were performed to examine the combustion characteristics starting at stable conditions near lean blow-out to lean blow-out in order to understand the trend of the stabilization processes.
- One simulation for Cat-C1 fuel was performed due to the constraint of the time. The simulation of Cat-C1 fuel indicated that at Φ= 0.096 the temperature field was sustainable with 3rd SLAU2 scheme for the inviscid fluxes.
- The simulations of Cat-A2 fuel indicated that at Φ=0.096 and Φ=0.088 the temperature fields were at sustainable conditions. At Φ =0.078, which was stepped down from Φ =0.096, the values of the unsteady heat release rate reduced to near zero in roughly 10 MS. After 2 MS, the equivalence ratio was stepped up from 0.078 to 0.082 and 0.081. After another 8 MS, both the 0.082 and 0.081 cases approached the blow out, i.e. the unsteady heat release rates were almost zero. **It is projected that the threshold of the near blow out and lean blow for the Cat-A2 fuel would be between Φ =0.088 and = Φ 0.082 based on the value of the unsteady heat release rate.**
- All the simulations for both Cat-A2 and Cat-C1 at multiple equivalence ratios with different Hychem mechanisms will be performed continuously until the trends of the NBO and LBO are captured.

Acknowledgements

This work was supported by the NASA Transformational Tools and Technologies (TTT) project under the Transformative Aeronautics Concepts (TACP) program.