Jet Propulsion Laboratory
California Institute of Technology

CFD Analysis of Hybrid Rocket Motors for Interplanetary CubeSats

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Agenda

- Introduction
- Chemistry
- CFD Hybrid Rocket Motor Model
- Chemical Model Validation
- Boundary layer: comparison to theory
- Thermal Analysis Validation
- Motor Design and CFD Results
- Conclusion

Goal: Investigate the behavior of the internal fluxes to inform the final design of an hybrid rocket motor

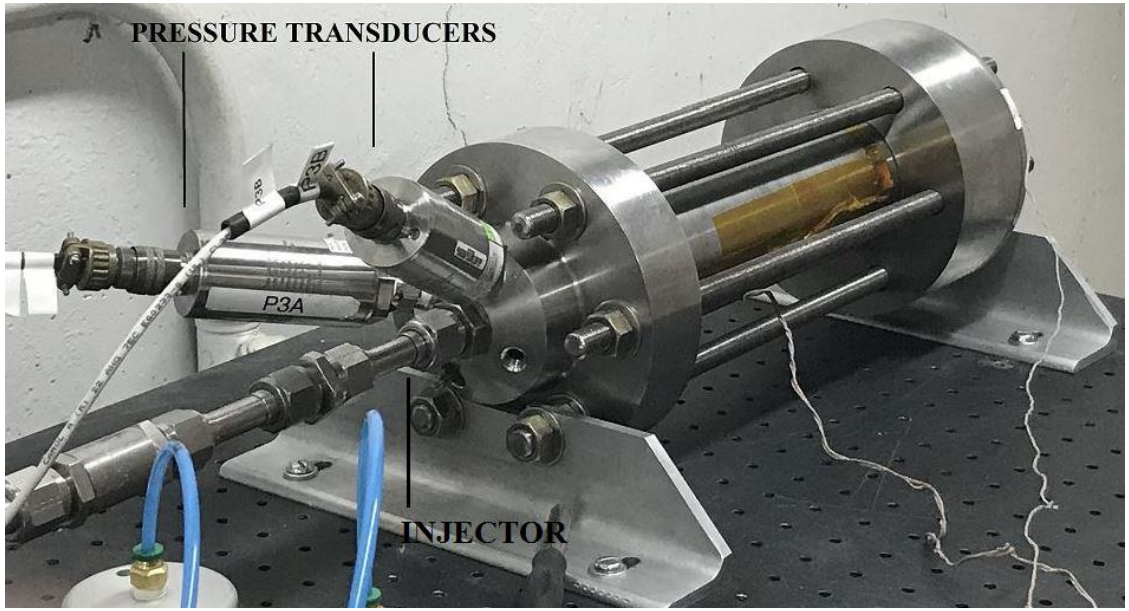
This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

- Hybrid rocket motors represent a promising alternative to conventional propulsion systems
- PMMA/GOX were determined to be the best propellant combination for the interplanetary cubesat application
- Numerical simulations of hybrid rocket motor internal fluid dynamics were carried out on STAR-CCM+ to understand the effect of design variations on performance
- A parallel thermal study has been also performed at Jet Propulsion Laboratory to evaluate the temperature in the motor, especially in the post-combustion chamber

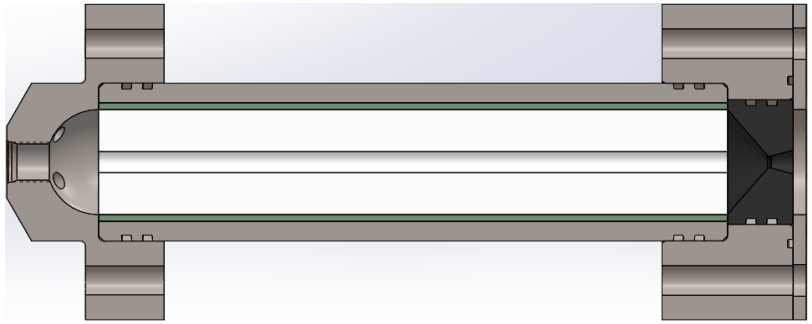
Hybrid Rocket Motor Design

System Constraints

- fuel grain outer diameter (0.051 m)
- max operating chamber pressure (2.4 MPa)
- max oxidizer upstream pressure (6.89 MPa)

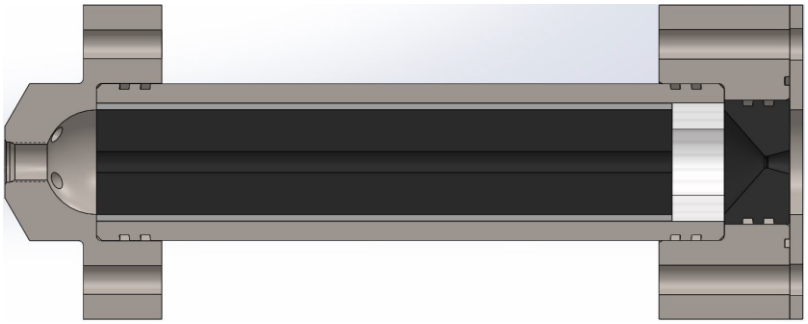


Motor configurations



Nominal configuration: Test #50

Polymethyl methacrylate fuel grain



Configuration post-combustion chamber: Test #59

Blackened polymethyl methacrylate fuel grain with Nylatron post-combustion chamber

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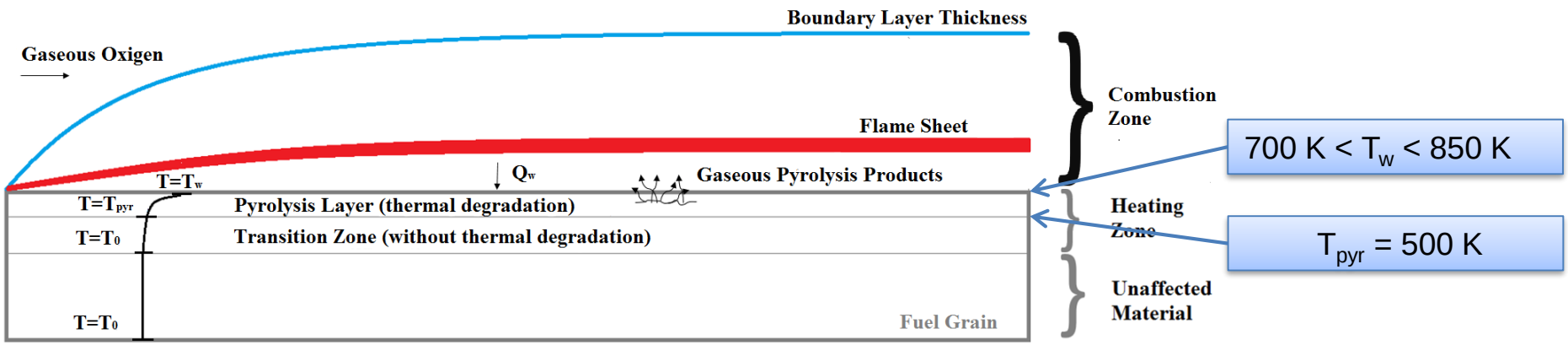
Chemistry

Main products of Decomposition of PMMA

- Methane
- Methanol
- Formaldehyde
- Acetylene

PMMA Pyrolysis Process



CFD Chemical model

The pyrolisis of the fuel is simplified for the CFD model

- Only the chemical process outside the fuel surface, in the gas phase, are modeled
- Assumption: the polymeric fuel completely pyrolyzes into methane, methanol, formaldehyde and acetylene

Selection of Products of PMMA/GOX combustion with a mass fraction grater than 10^{-5} from CEA and implementation of a balanced reaction in STAR-CCM+

$$\nu_F F + \nu_O O \longrightarrow \nu_{P_1} P_1 + \nu_{P_2} P_2 ... + \nu_{P_j} P_j$$

The Standard Eddy Break-Up Model is used in STAR-CCM+ for predicting the chemistry

$$R_{F,mix} = -\frac{\rho}{M_F}\left(\frac{1}{\tau_R}\right)\tilde{A}min\left[\tilde{Y}_F, \frac{\tilde{Y}_O}{s_O}, \tilde{B}\left(\frac{\tilde{Y}_O}{s_O} + \frac{\tilde{Y}_{P1}}{s_{P1}} + \frac{\tilde{Y}_{P2}}{s_{P2}} + ... + \frac{\tilde{Y}_{Pj}}{s_{Pj}}\right)\right], s_O = \frac{\nu_O M_O}{\nu_F M_F}, s_{P_i} = \frac{|\nu_{P_i}| M_{P_i}}{\nu_F M_F}$$

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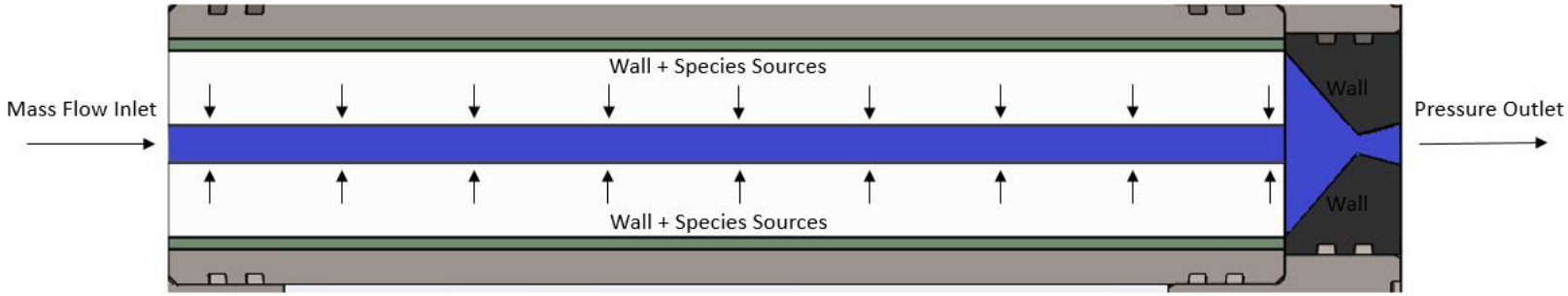
CFD Hybrid Rocket Motor Model

Internal working volume (Nominal configuration)



Boundary conditions

- Mass Flow Inlet
- Wall + Species Source
- Wall
- Pressure Outlet

Other requirements

- Field function
- Damping factor applied to wall in contact with fuel

Initial conditions

- Fuel Surface Temperature = 800K

	Test #50	Test #59
	Nominal Configuration	Configuration with $pcc^{\wr}$
$\dot{m}_o[g/s]$	16.709	19.351
$t_b[s]$	20	20
$p_c\ [MPa]$ ‡	1.379	1.420
$\dot{r}[mm/s]$	0.477	0.433
OF_{test} *	1.665	2.223

* $OF_{stoic} = 1.92$
‡ Mean chamber pressure.
$\wr$ pcc: post-combustion chamber.

CFD Model Set-Up in STAR-CCM+

Models

- Space: Three dimensional study of internal fluxes
- Time: Implicit Unsteady
- Material: Multi-component gas
- Reaction Regime: Reacting
- Reacting Species Model: Standard Eddy Break-Up
- Flow: Coupled Flow
- Viscous Regime: Turbulent
- Reynold-Averaged Turbulence: k-Epsilon Turbulence

Fuel Surface Regression Model

The consumption of the fuel is simulated through an expansion of the internal working volume

- A mesh morphing redistributes mesh vertices in response to the movement of control points

The fuel surface regression is simulated through a specified time dependent function that reproduces experimental results

Boundary vertices are control points for the selected boundary conditions:

- Displacement (fuel surface)
- Constrained (surfaces in contact with the fuel surface)
- Fixed (all the other surfaces)

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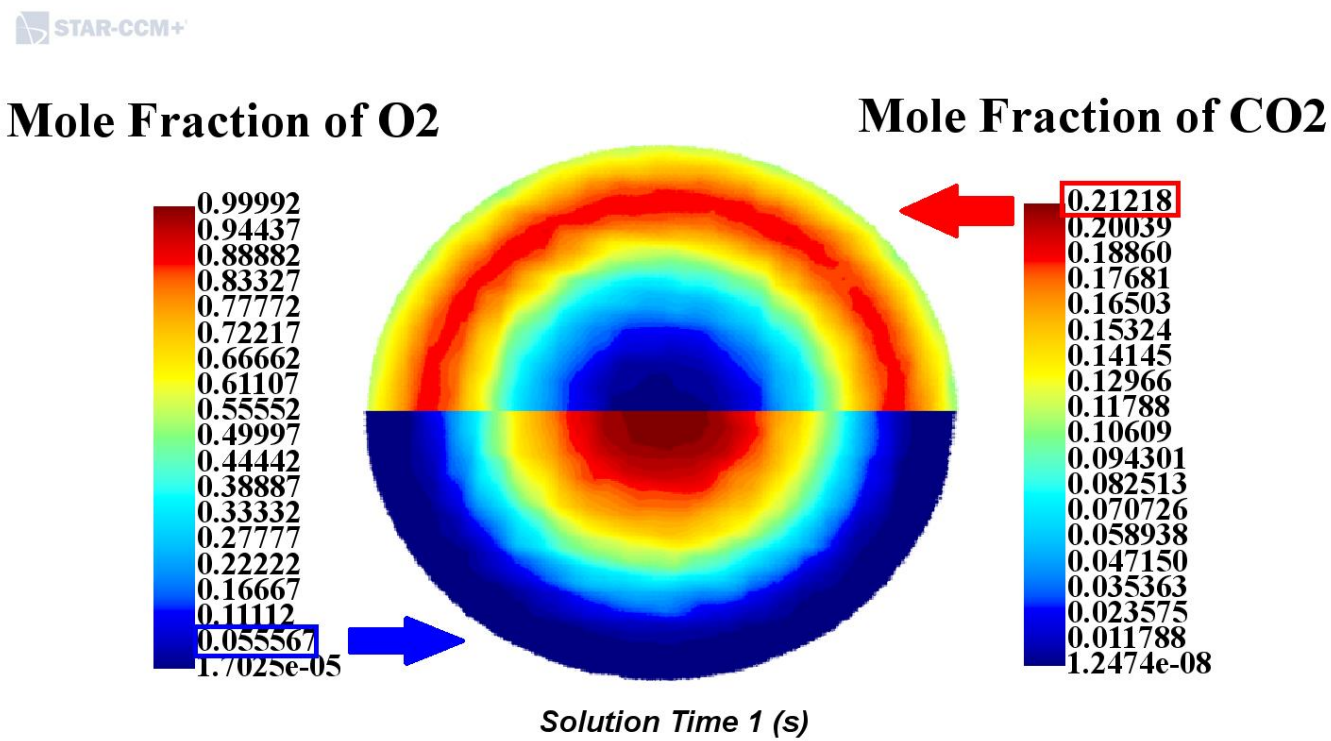
Chemical Model Validation

Mole fractions of O_2 and CO_2 from STAR CCM+ Standard Eddy Break-Up Model



Comparison of PMMA/O2 combustion results from CEA and STAR-CCM+

	CEA •	EDM *
OF	1.665	1.665
p_c [MPa]	1.379	1.379
		t = 1s
T_c [K]	3360	3253 †
Mole Fractions		
H_2O	0.29529	0.29049
CO_2	0.21913	0.21234
CO	0.26647	0.20181
H	0.02416	0.03663
H_2	0.04454	0.04092
O	0.02165	0.04515
OH	0.07303	0.04523
O_2	0.05560	0.05557

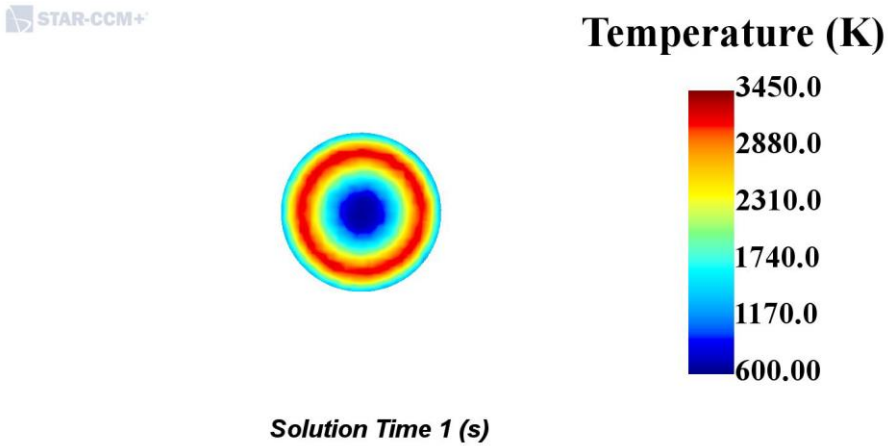
• Chemical Equilibrium with Application.

* Standard Eddy Break-Up Model in STAR-CCM+.

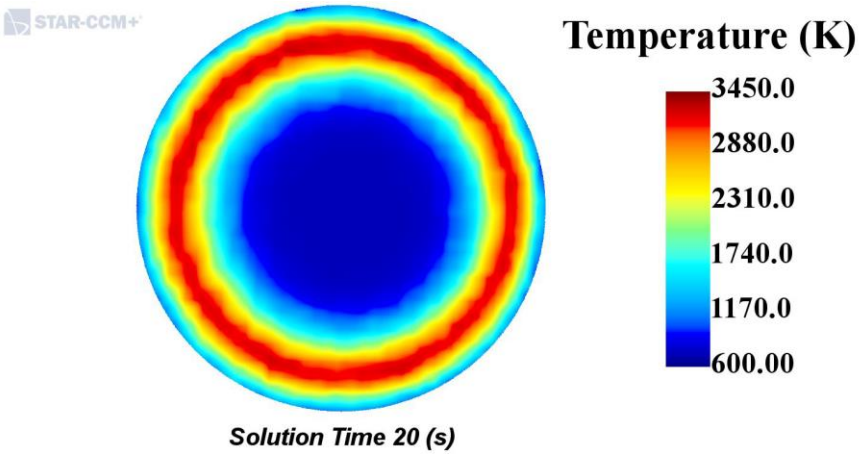
† Maximum value.

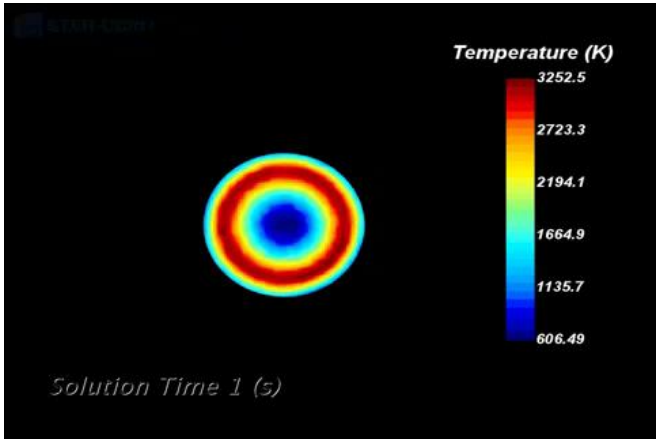
Temperature trends from STAR-CCM+ Standard Eddy Break-Up Model at the aft end of the fuel grain.

Time = 1 (s)

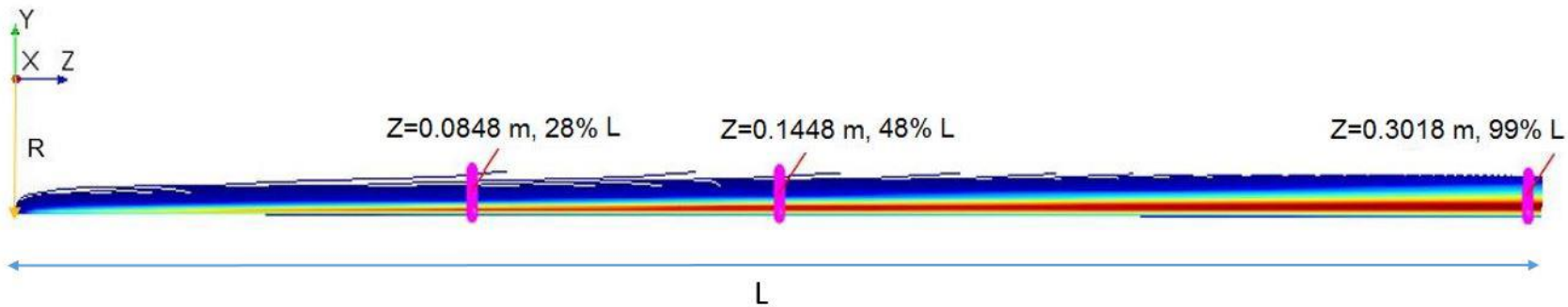


Time = 20 (s)

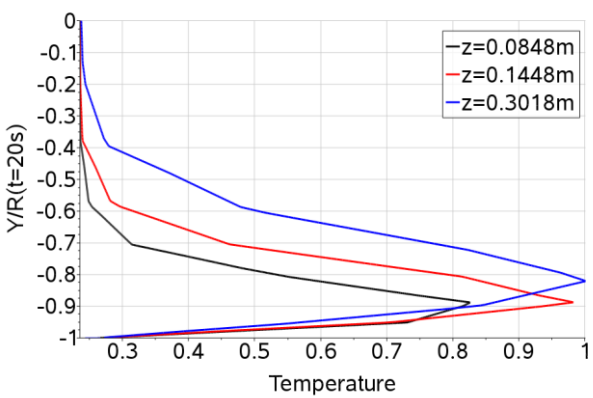




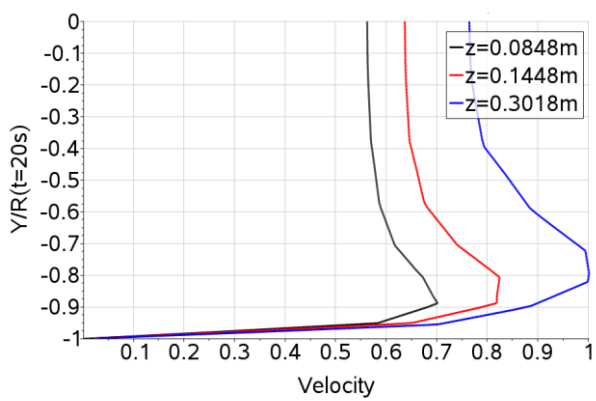
Non dimensionalized temperature, velocity and density profiles after 20 seconds of combustion



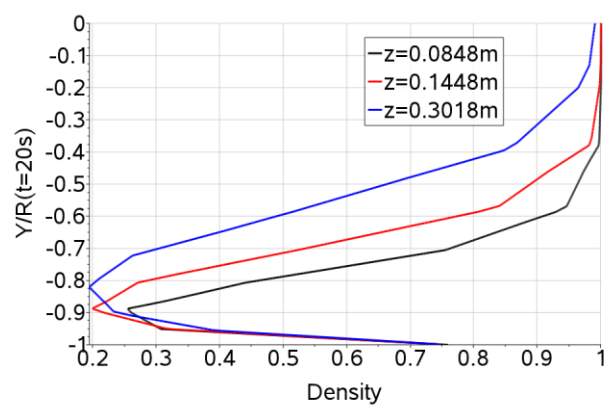
Temperature



Velocity



Density



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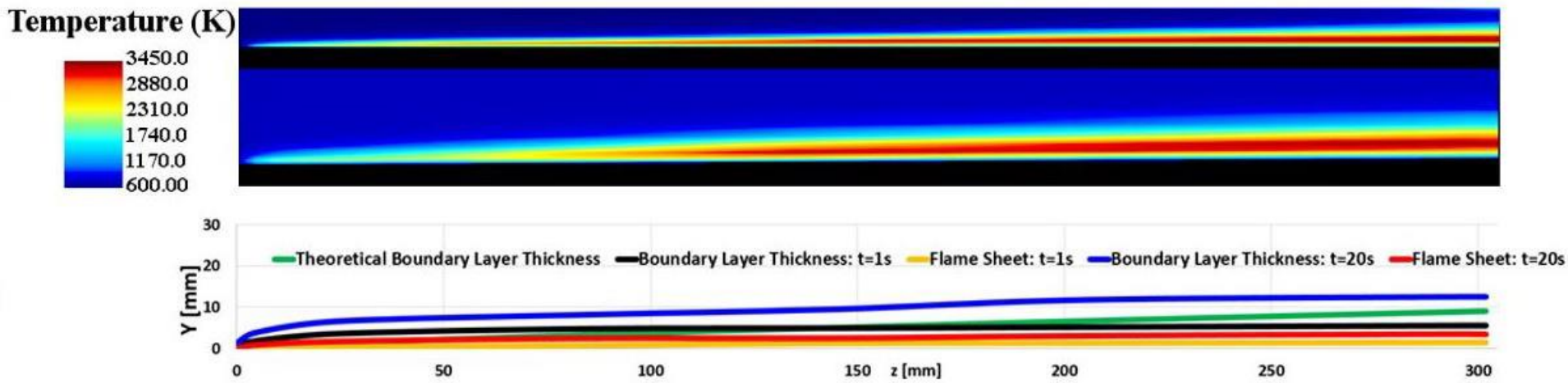
Results Verification CFD Analisys

Boundary Layer and Flame Location



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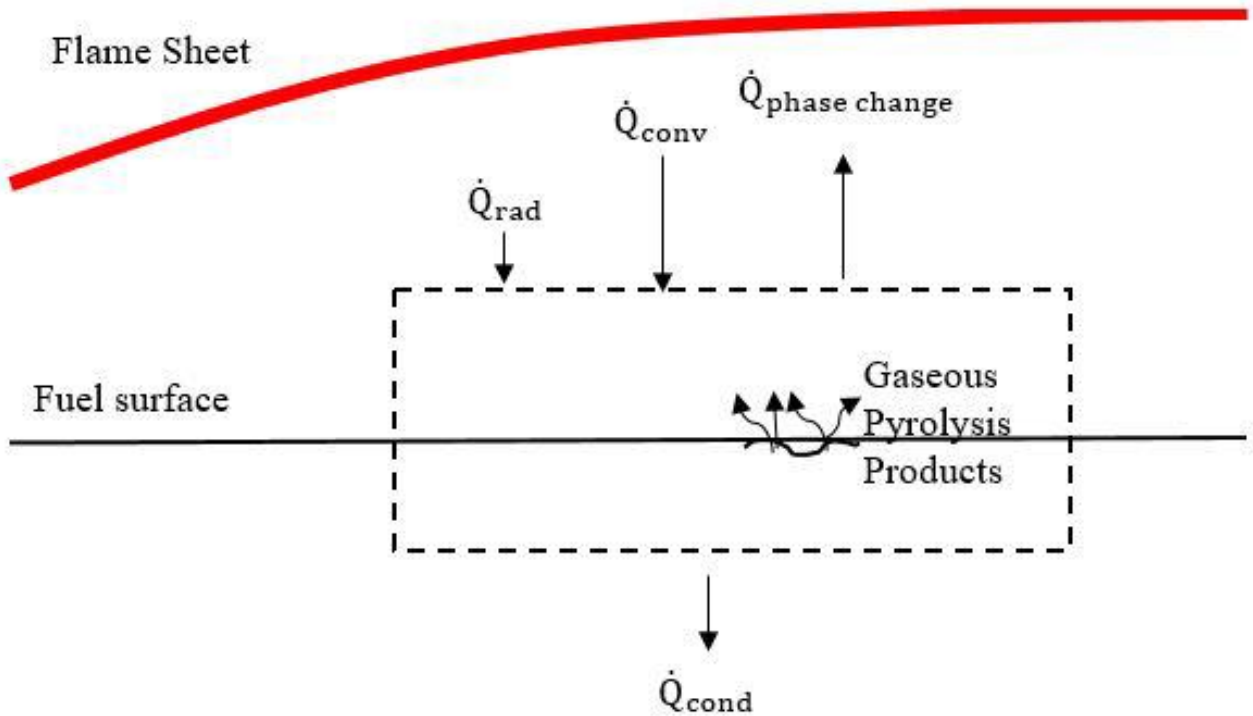
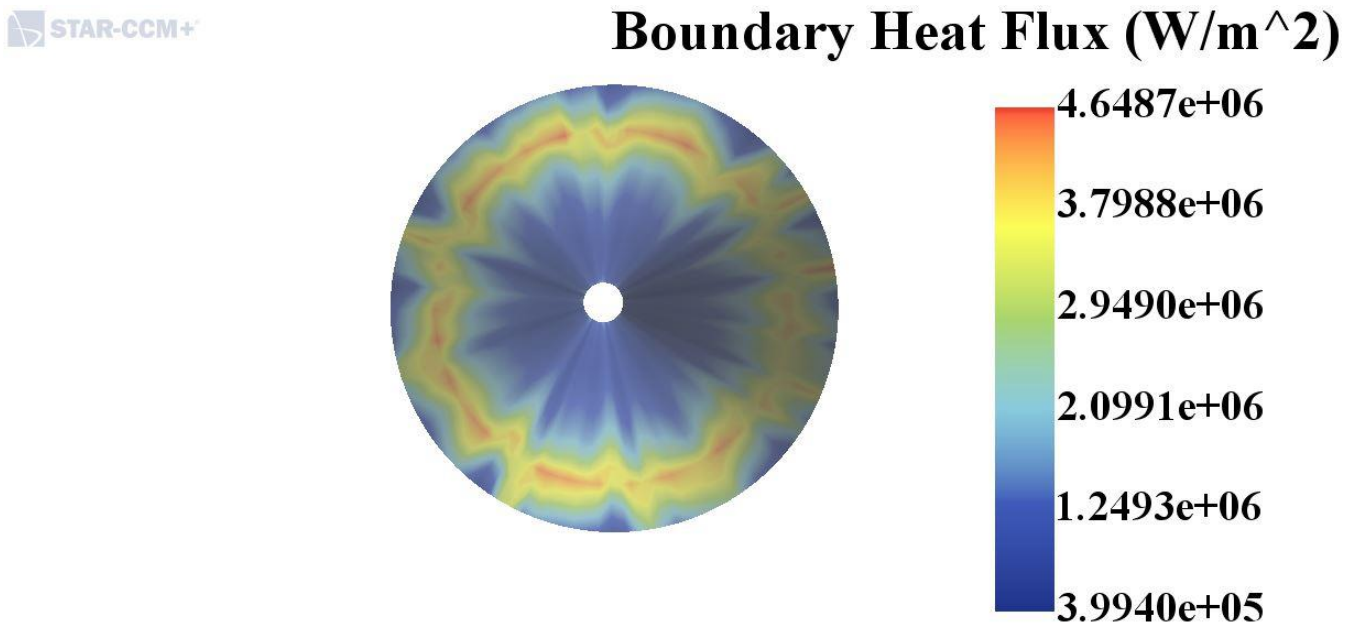
Thermal Analisys Validation

Heat transfer model

$$\dot{Q} = \dot{Q}_{conv}\left[\left(\frac{\dot{Q}_{rad}}{\dot{Q}_{conv}}\right) + e^{-\frac{Q_{rad}}{Q_{conv}}}\right]$$



Boundary heat flux from STAR-CCM+ after 1 second of combustion



Heat Flux comparison

$$\begin{cases} \dot{Q} = 1{,}01 \cdot 10^6 \frac{W}{m^2} & \rightarrow theoretical \\ 3{,}99 \cdot 10^5 \frac{W}{m^2} < \dot{Q} < 4{,}65 \cdot 10^6 \frac{W}{m^2} & \rightarrow CFD\ analysis \end{cases}.$$

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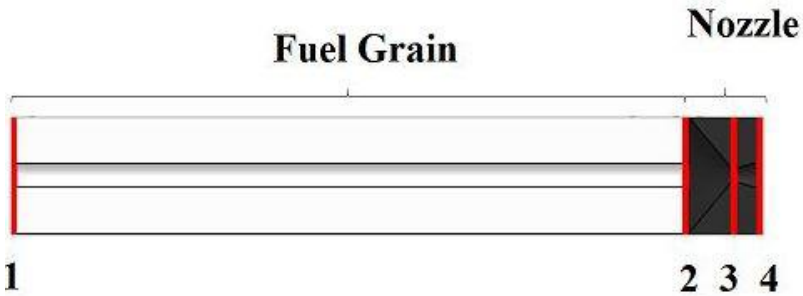
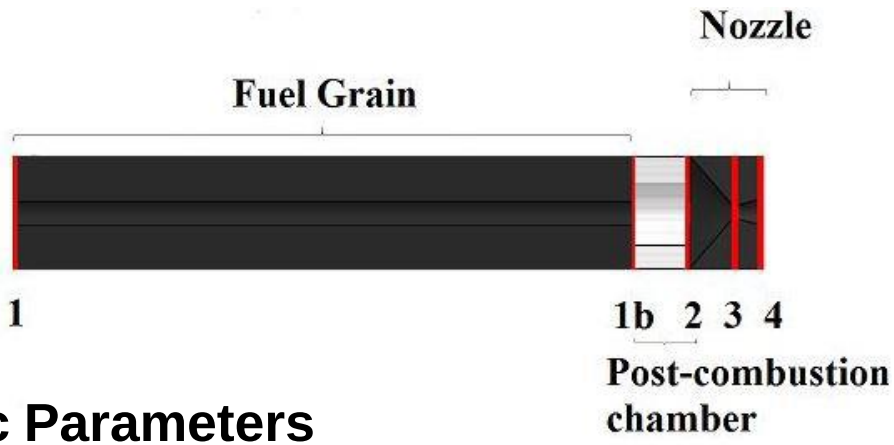
Design

Test #50



Test #59



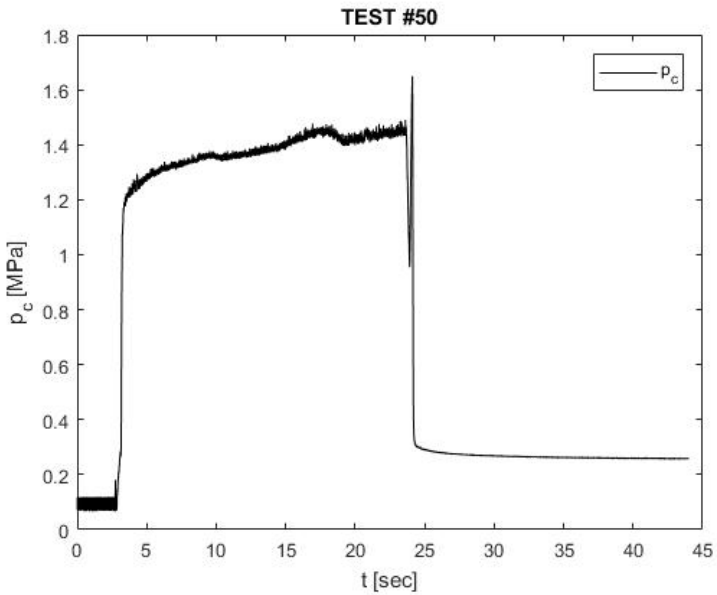
Geometric Parameters

	Test #50	Test #59
	Nominal Configuration	Configuration with pcc^{l}
L_{fuel} [m] †	0.305	0.279
L_{pcc} [m]^{l}	-	0.025
$D_{i_{pcc}}$ [m]^{l}	-	0.032
$L_{fuel}/D_i^{\ddagger}$	30.284	27.060
L_{fuel}/D_f	10.387	10.139
$A_3/A_1^{\bullet}$	0.328	0.312
A_3/A_4	0.249	0.251

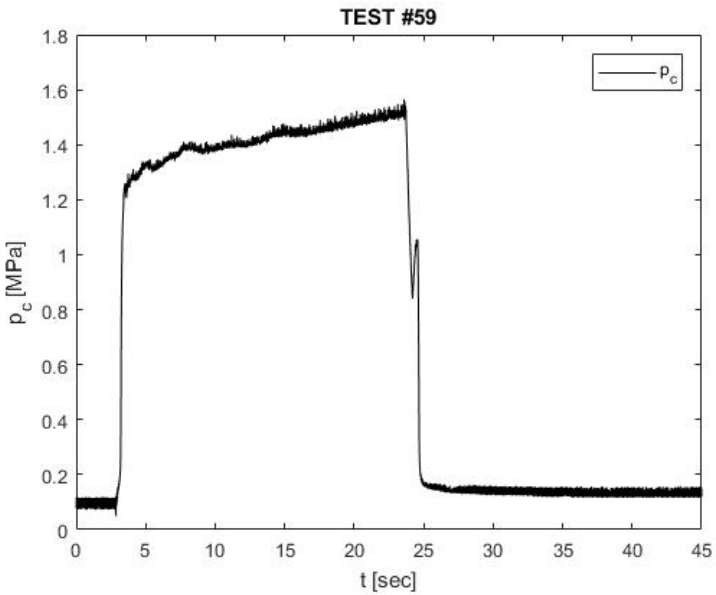
^{l} *pcc*: post-combustion chamber.
† *L*: fuel length.
‡ *D*: fuel diameter.
$^{\bullet}$ *A*: cross section area.

Tests Performances and CFD Analysis

Test #50



Test #59



$$\dot{r} = aG_{ox}^{n} \qquad \eta = \frac{p_{t_2} A_t \dot{m}}{C^*_{ideal}}$$

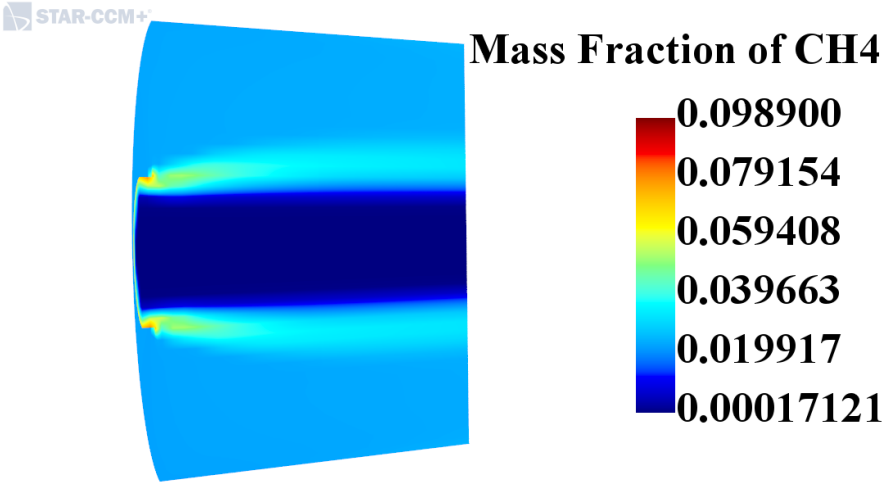
	Test #50	Test #59
	Nominal Configuration	Configuration with $pcc^{\wr}$
a/a_{lit}^{*}	1.83	1.55
$\dot{r}$ [mm/s]	0.477	0.436
$p_c[MPa]^{\ddagger}$	1.379	1.420
η	0.81	0.84

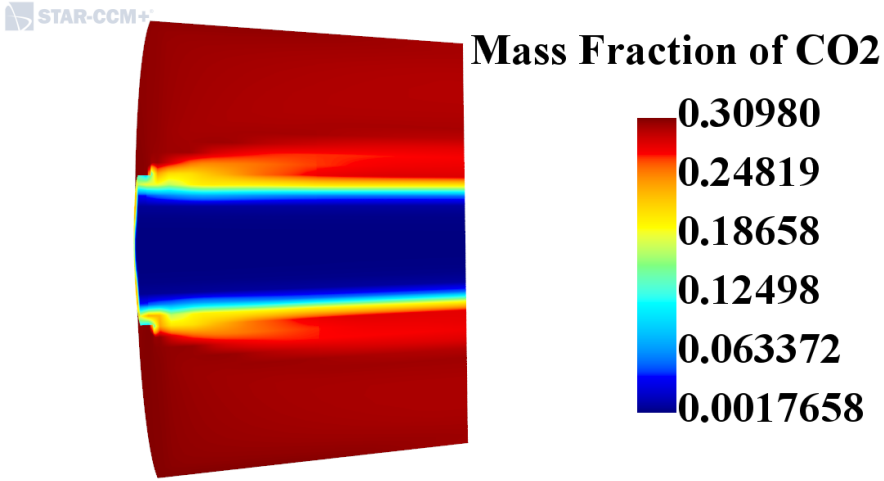
$^{\wr}$ *pcc*: post-combustion chamber
* *lit*: literature
‡ Mean chamber pressure.

$a_{lit} = 2.11\text{x}10^{-05}$
$n_{lit} = 0.62$

Tests Performances and CFD Analysis

Mass Fractions after 1 second of combustion
Post-combustion chamber cross section

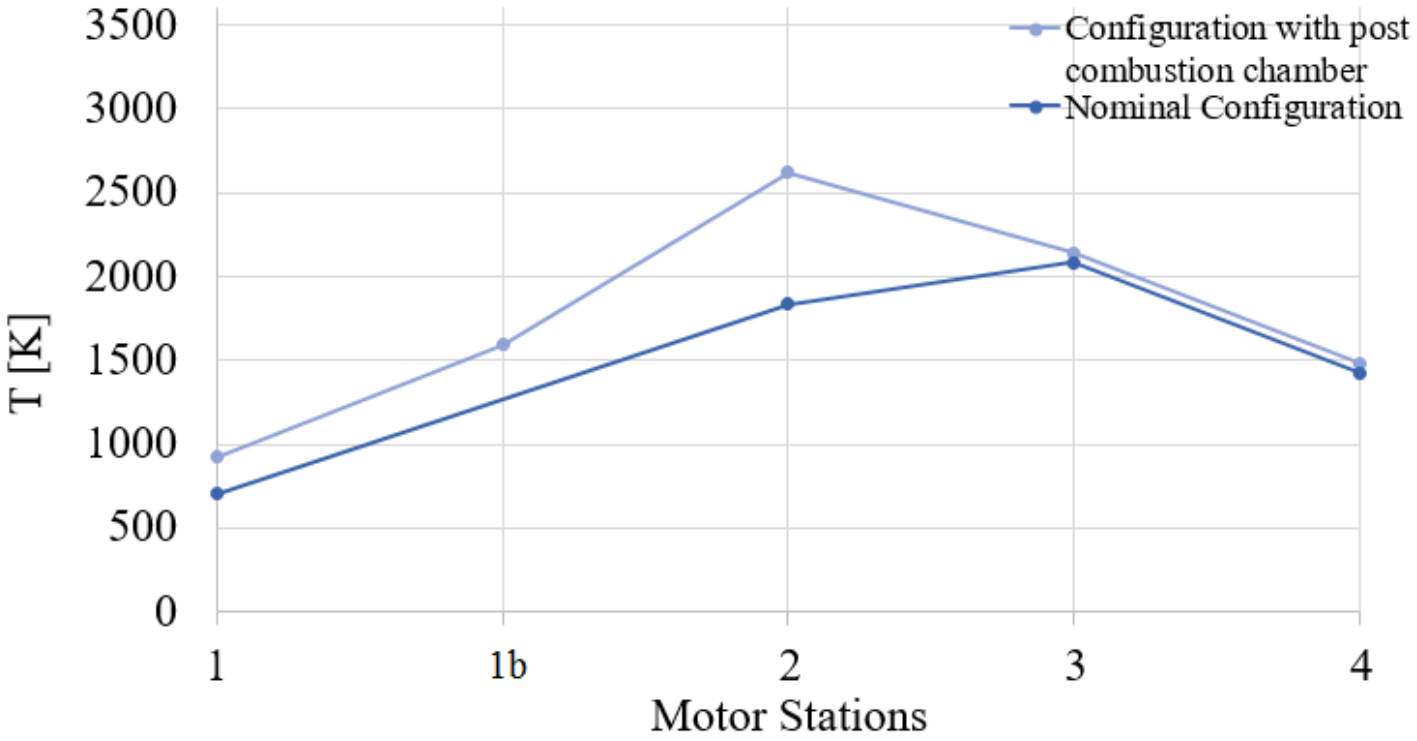




	Test #59	CFD
η	0.84	0.87

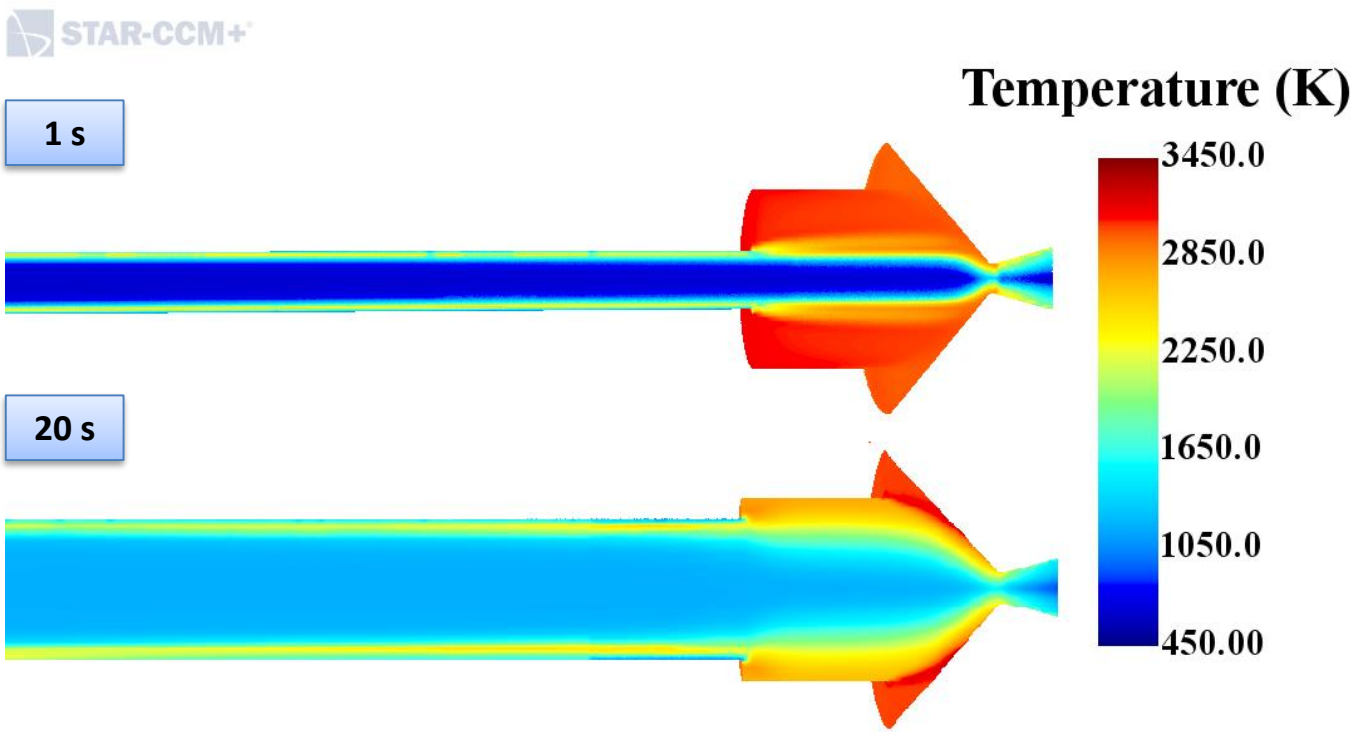
Tests Performances and CFD Analysis

Temperature trends along the motor length



Tests Performances and CFD Analysis

Temperature
Post-combustion chamber cross section



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Conclusions

Trade Study

- A CFD analysis has been conducted to investigate the behavior of internal fluxes during the combustion process and determining the effect of new flow altering devices in an attempt to improve performance
- An unsteady combustion model has been implemented and PMMA/GOX combustion has been simulated
- The combustion model was validated and applied to model the internal fluid dynamics of two reference tests

Results

- CFD results shown that the addition of a post-combustion chamber enables more complete burning of the combustion products before they are expelled through the nozzle
- The effect of the post-combustion chamber is an increase of the mixing of the chemical species participating in the combustion process
- Better performance and higher efficiency have been observed by including this post-combustion chamber. However, the benefits of this addition may be outweighed by the increased mass of the insulation required and further studies are required.

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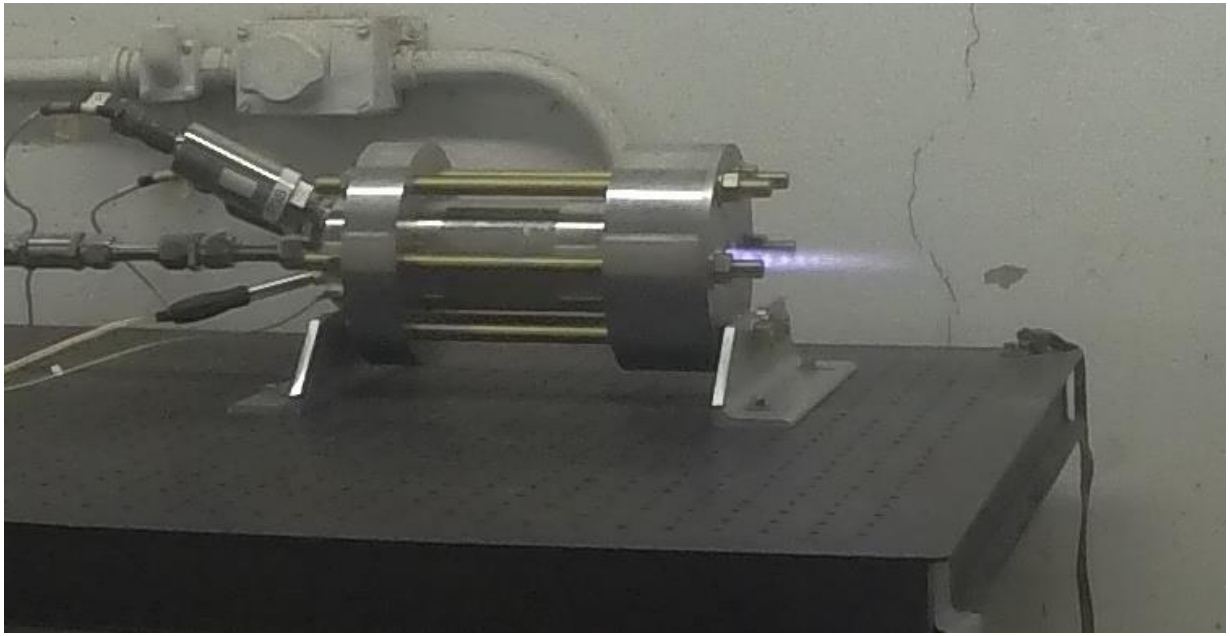
Questions?

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