Título Solid propellant rocket nozzle design and validation using Finite Difference Method and CFD technique

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"Solid propellant rocket nozzle design and validation using Finite Difference Method and CFD technique"

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Objectives

GENERAL

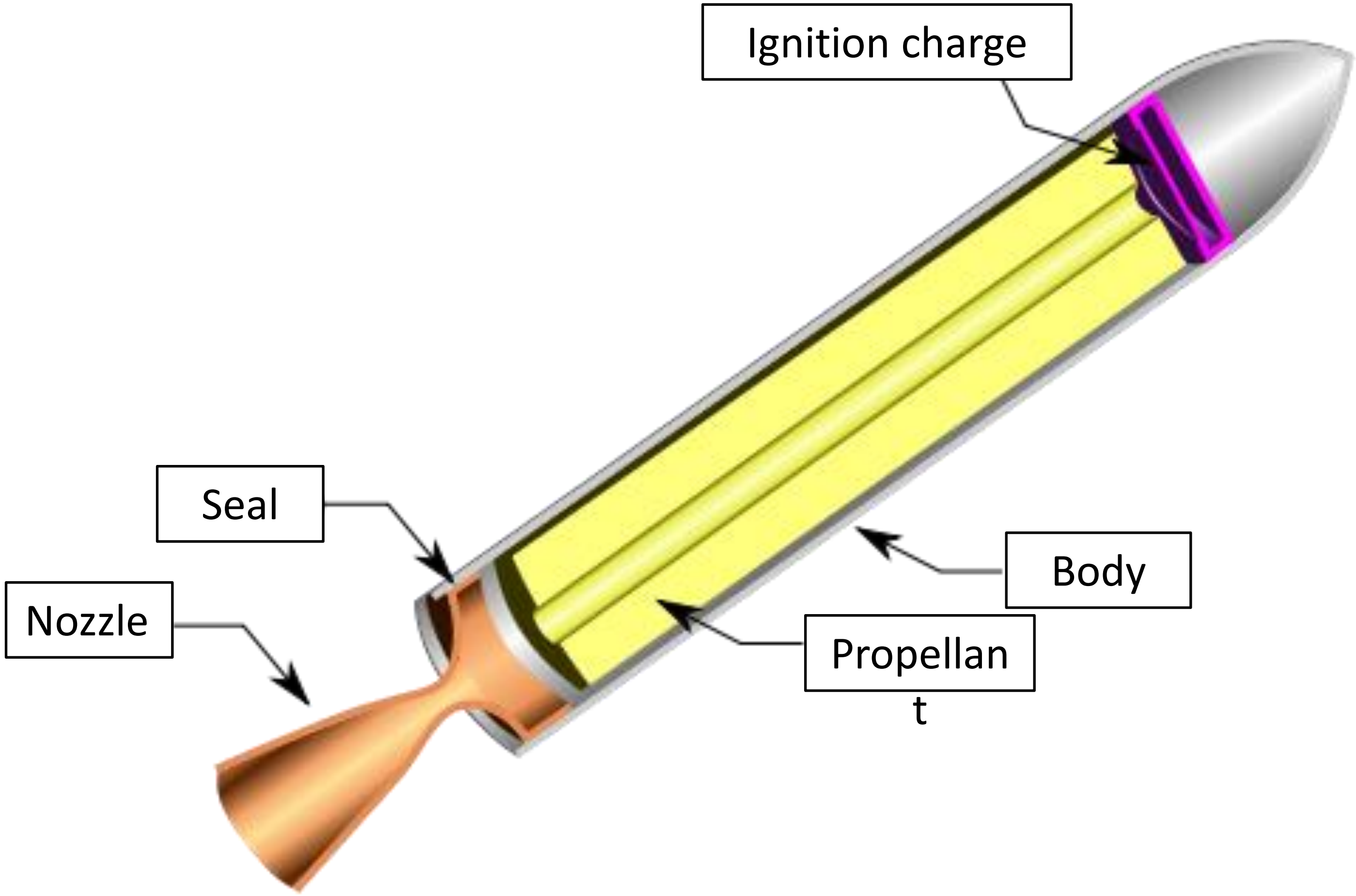
Develop capabilities to calculate and predict the behavior of a solid propellant rocket nozzle under certain conditions, using numerical methods.

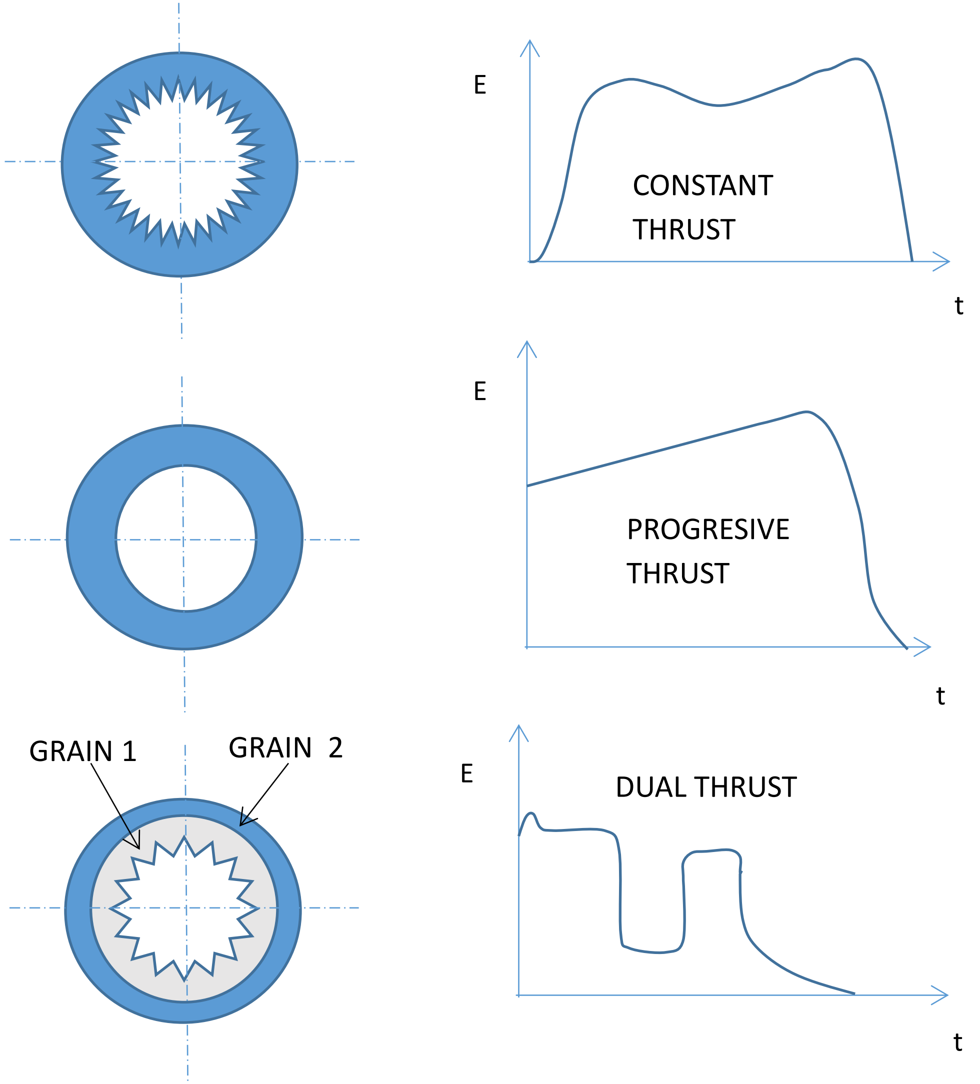
SPECIFICS

- Validate different ways of numerical nozzle study methods against experimental data from rocket test bench and against each other.
- Have a clear understanding about the influence of design and thermodynamic parameters over the nozzle performance.

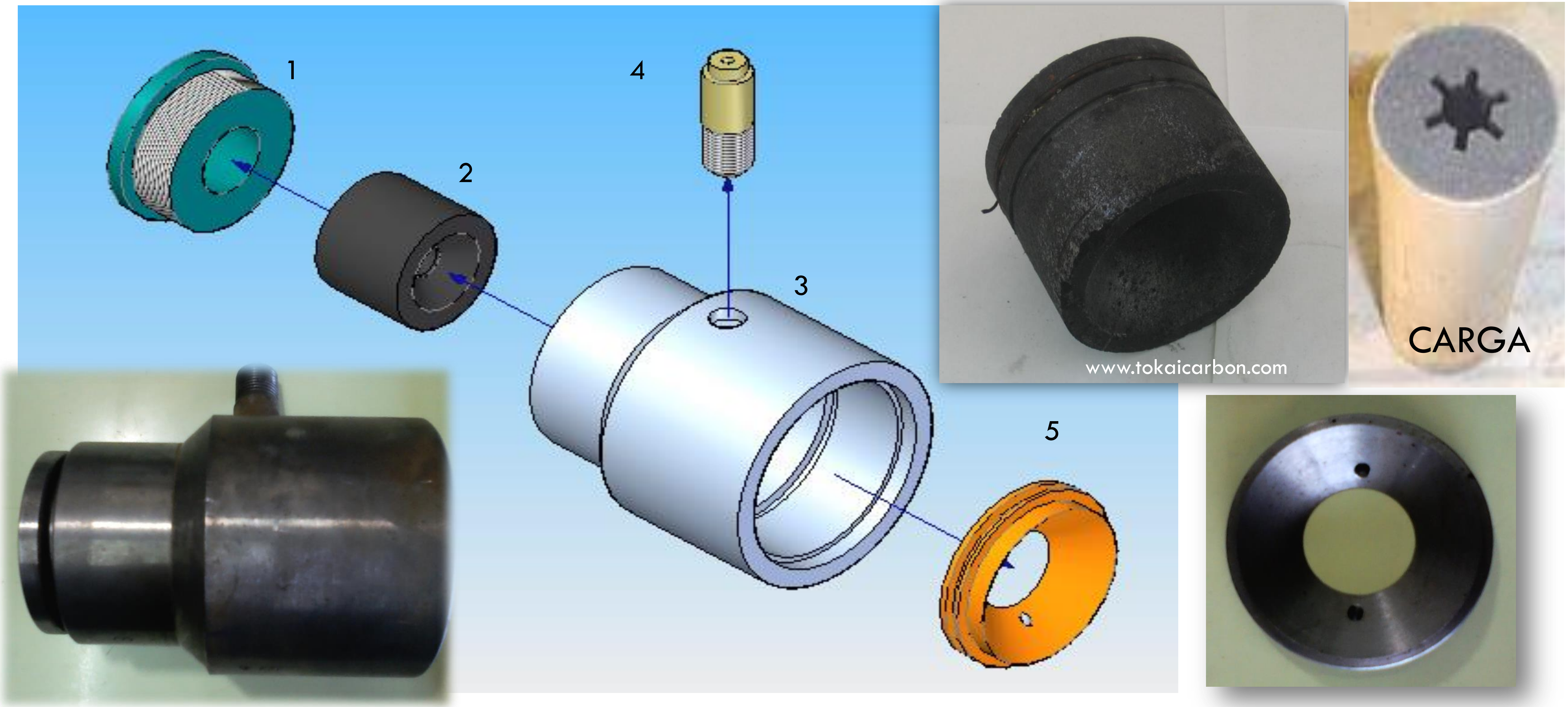
Solid Propellant Rocket

Basic Configuration

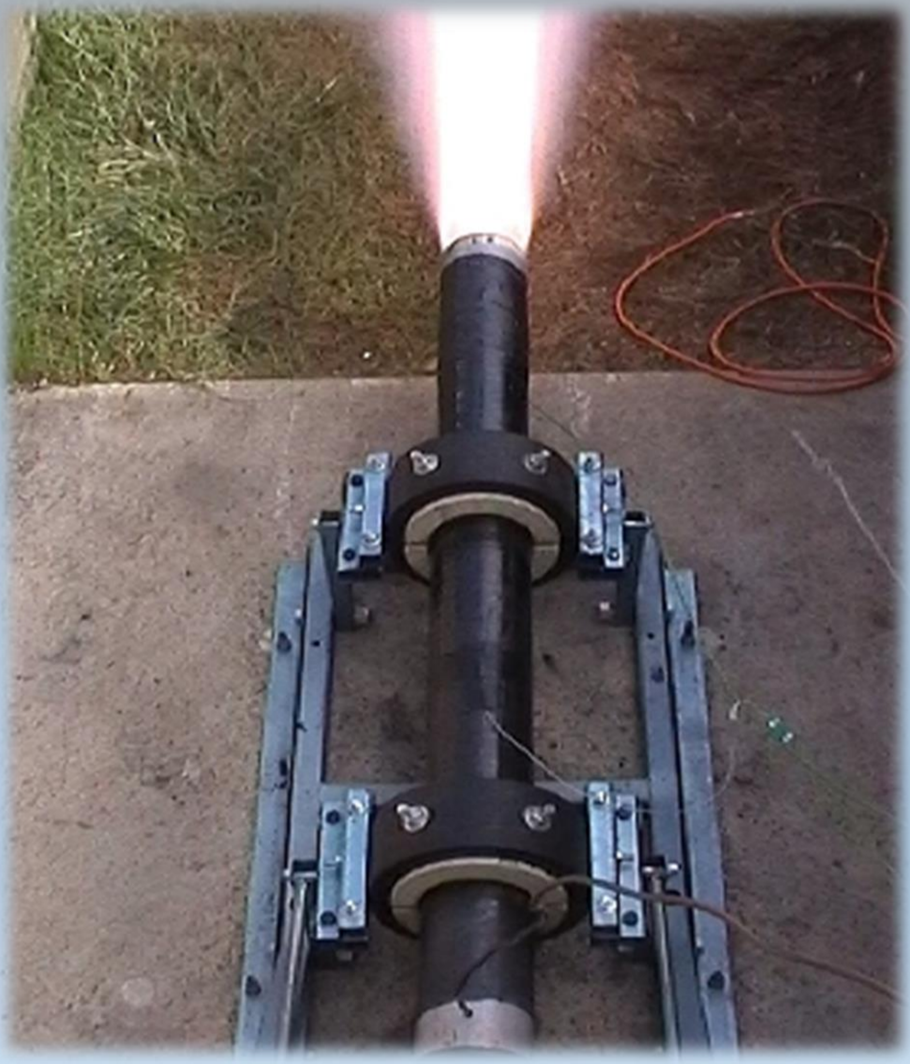




Experimental Set-up



Micro-engine Test Bench



Ensayo de un micromotor con sensores de presión y empuje colocados.
(La foto es ilustrativa) Imagen de http://www.teaklecomposites.com.au

Isentropic Relations

Departing from the nozzle design and the propellant data, Mach number at the exit was determined:

$$\frac{A_{out}}{A_{th}} = R_{out} = \frac{1}{M_{out}}\left[\frac{2\left(1+\frac{k-1}{2}{M_{out}}^2\right)}{k+1}\right]^{\frac{k+1}{2\,(k-1)}}$$

$$M_{out}$$

$$Rho_{out} = Rho_{in}\left[1+\frac{k-1}{2}{M_{out}}^2\right]^{-1}$$

$$P_{out} = P_{in}\left[1+\frac{k-1}{2}{M_{out}}^2\right]^{\frac{-k}{(k-1)}}$$

$$T_{out} = T_{in}\left[1+\frac{k-1}{2}{M_{out}}^2\right]^{-1}$$

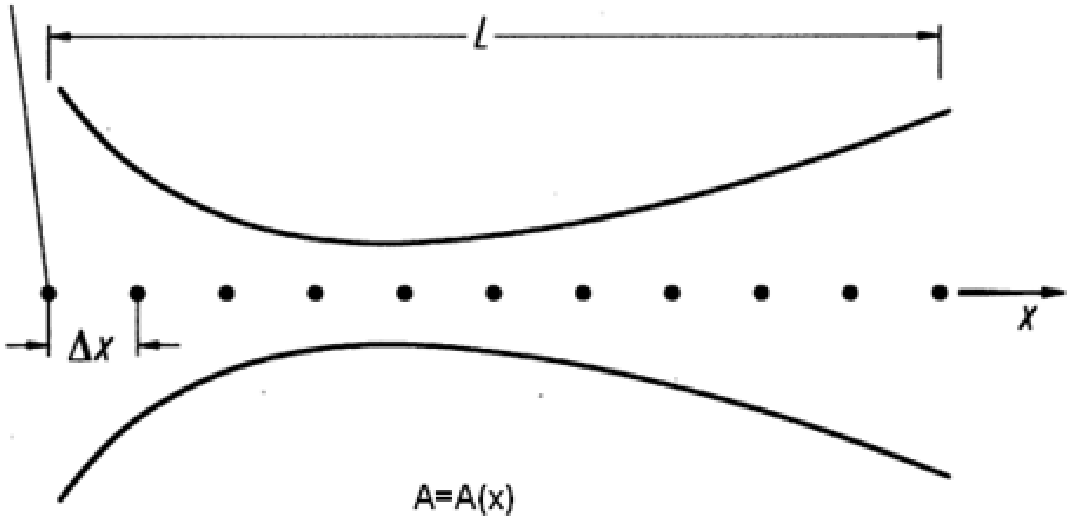
$$V_{out} = M_{out} * \sqrt{k * R_{gas} * T_{out}}$$

$$F = Rho_{out} * A_{out} * {V_{out}}^2 + A_{out} * (P_{out} - Patm)$$

Finite Difference Method:
Lax-wendroff Equations 1D

The Lax-Wendroff method is based in the Taylor series expansion to second order in time for a fixed *X*.

• Time derivatives are replaced by the partial differential equation.
• Central differences method is used to approximate the resulting spatial derivative to second order.



Continuity equation:

$$\frac{\partial \rho}{\partial t} = -\frac{1}{A}\left(\frac{\partial (A\rho u)}{\partial x}\right)$$

Momentum equation:

$$\frac{\partial u}{\partial t} = -\left(u\frac{\partial u}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x}\right)$$

Energy Equation:

$$\frac{\partial e}{\partial t} = -\frac{1}{\rho}\left(u\rho\frac{\partial e}{\partial x} + p\frac{\partial u}{\partial x} + \frac{pu}{A}\frac{\partial A}{\partial x}\right)$$

CFD Analysis

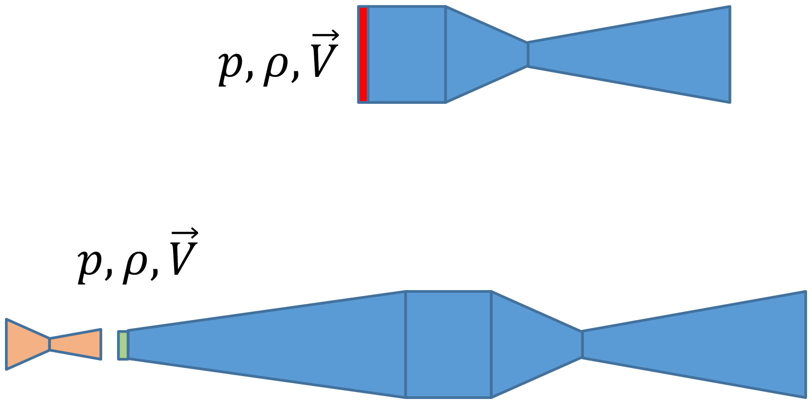
- Conducted using the **OpenFOAM©** Suite
- ***rhoCentralFoam*** *(van Leer limiter)*
- *Showed accurate results in test cases analyzed by L.F. Gutierrez Marcantoni et al., and was proven more accurate and faster tan sonicFoam, also included in the OpenFOAM suite.*

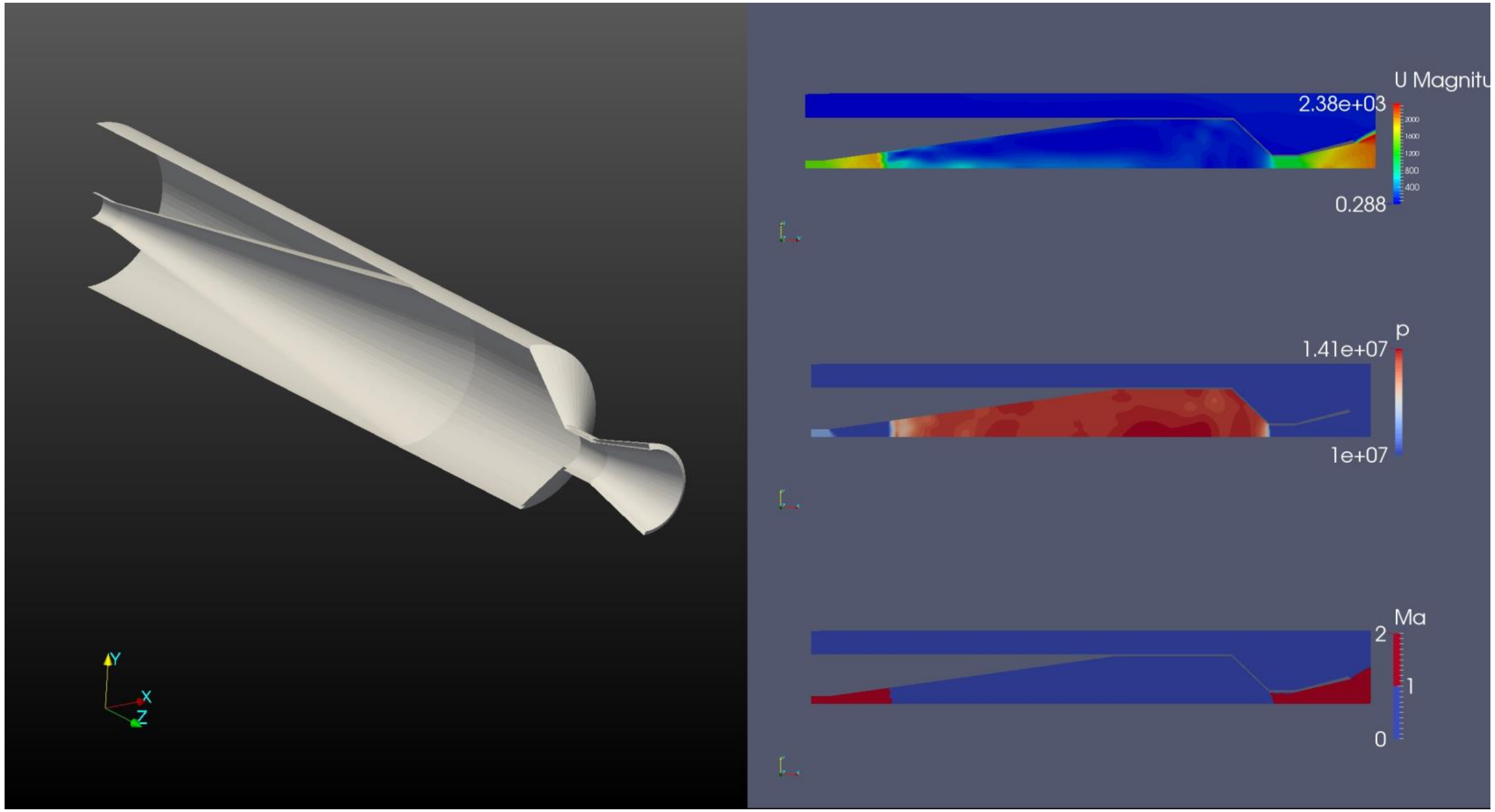
CFD Analysis

Boundary Conditions:

$p, \rho, \vec{V}$

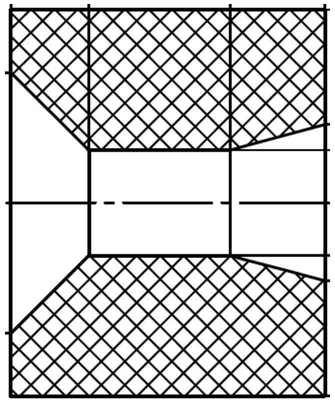
$p, \rho, \vec{V}$

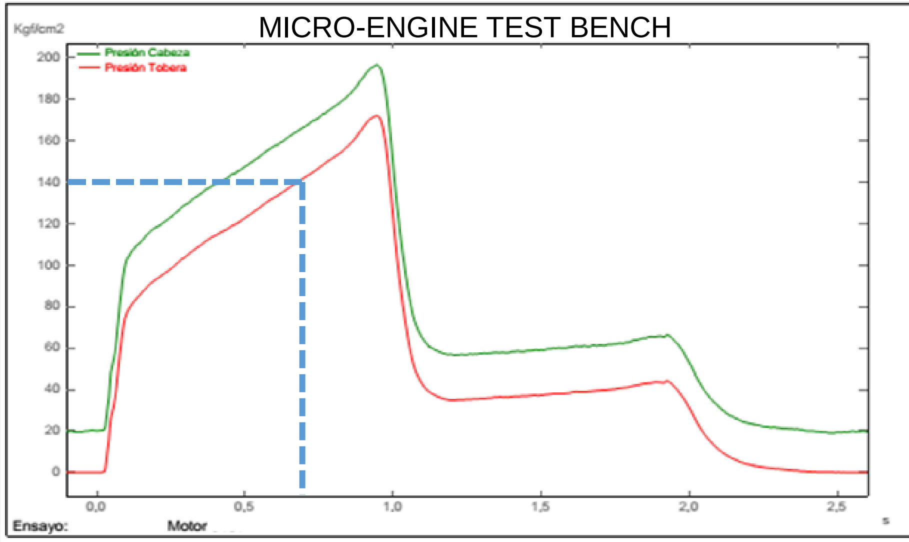




Study case: t1

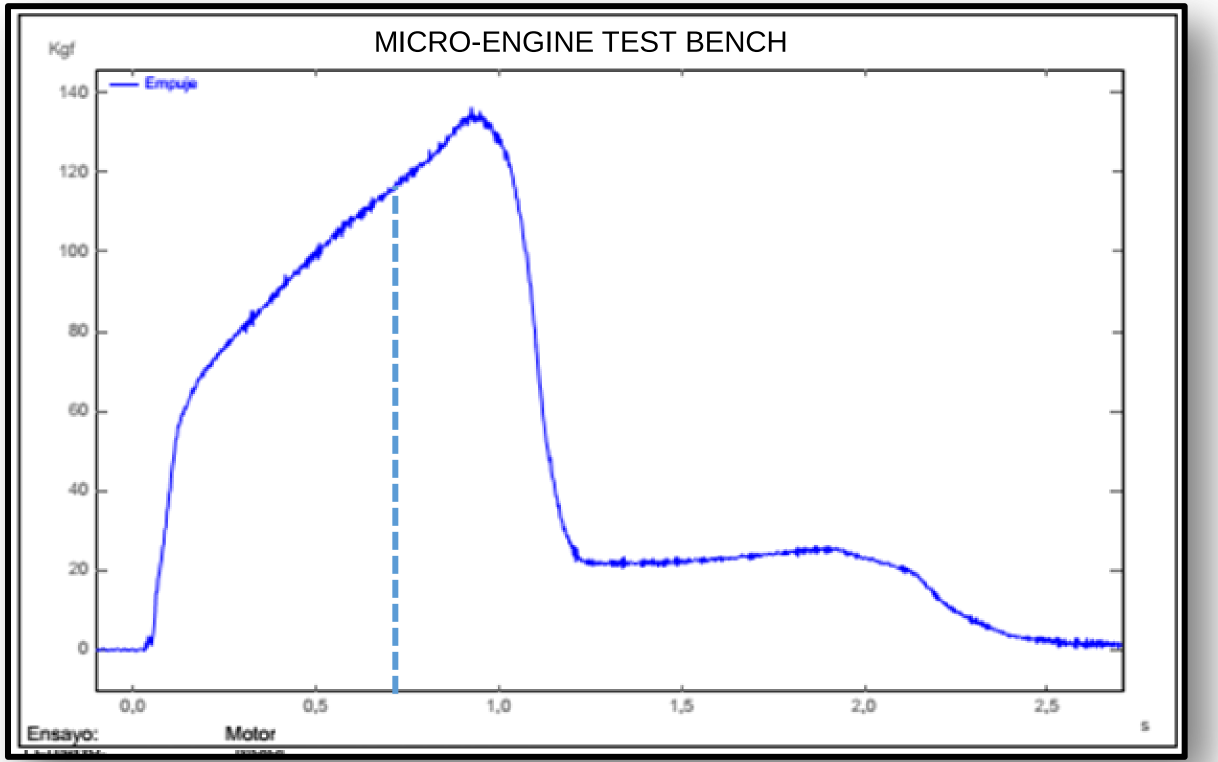
PARAMETER	Isentropic	Finite Difference Method	CFD	Unit	Δ Ise. Vs Finite Difference	Δ CFD. Vs Finite Difference
Uin	25.36	25.36	28.95	m/s	0.00%	-14.17%
Min	0.024	0.024	0.027	-	0.00%	12,5%
Pin	140.00	140.00	139.95	Pa	0.00%	0.03%
Tin	2582.08	2582.08	2634.10	K	0.00%	-2.02%
Rhoin	15.66	15.66	18.15	kg/m3	0.00%	-15.92%
Uth	984.6	989.4	1004.0	m/s	-0.49%	-1.48%
Mth	1.00	1.00	1.12	-	0.00%	-11.91%
Pth	7652219.90	7568684.92	6238344.97	kgf/cm2	1.09%	17.58%
Tth	2308.00	2301.77	2448.99	K	0.27%	-6.40%
Rhoth	9.77	9.69	9.24	kg/m3	0.81%	4.65%
Vout	2198.00	2185.16	1813.54	m/s	0.58%	17.01%
Mout	3.06	3.05	2.53	-	0.24%	16.83%
Pout	281468.80	284058.34	431022.81	kgf/cm2	-0.92%	-51.74%
Tout	1226.00	1224.21	1445.03	K	0.15%	-18.04%
Rhoout	0.68	0.68	0.983	kg/m3	-1.11%	-43.89%





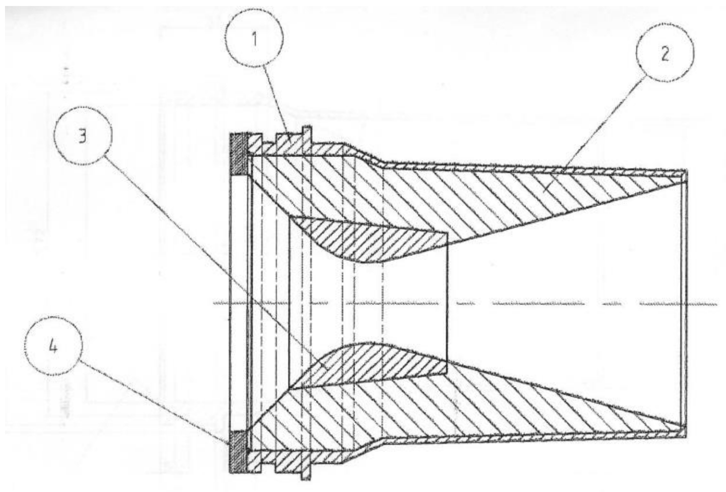
Thrust Comparisson: T1

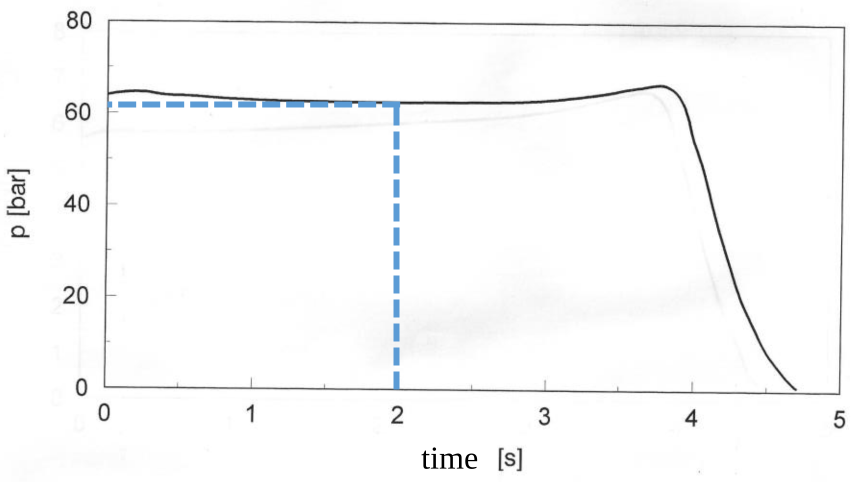
Test Bench	Isentropic	Finite Difference Method	CFD	Unit	Δ Ise. Vs Test Bench	Δ Finite Difference Vs Test Bench	Δ CFD. Vs Test Bench
1177	1761	1762	1823	N	33.17%	33.18%	35.43%



Study case: t2

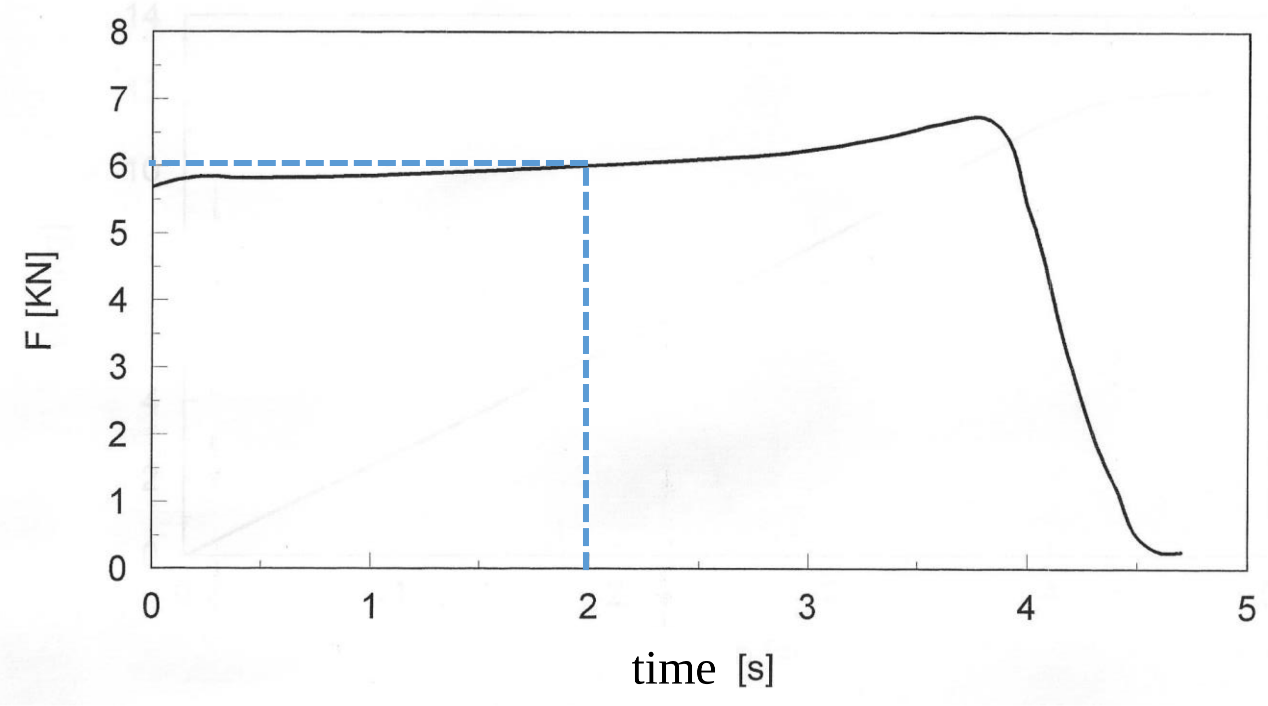
PARAMETER	Isentropic	Finite Difference Method	CFD	Unit	Δ Ise. Vs Finite Difference	Δ CFD. Vs Finite Difference	Δ Ise. Vs CFD
Uin	64.33	64.33	55.18	m/s	0.00%	14.21%	-16.57%
Min	0.059	0.059	0.070	-	0.00%	-19.57%	16.37%
Pin	6328759.50	6328759.50	6434823.99	Pa	0.00%	-1.68%	1.65%
Tin	2538.00	2538.00	2516.77	K	0.00%	0.84%	-0.84%
Rhoin	7.683	7.68	8.90	kg/m3	0.00%	-15.85%	13.68%
Uth	930.79	936.40	844.22	m/s	-0.60%	9.84%	-10.25%
Mth	1.00	1.00	0.97	-	0.00%	2.91%	-2.99%
Pth	3469491.21	3633465.90	3123594.84	Pa	-4.73%	14.03%	-11.07%
Tth	2318.00	2321.00	2257.42	K	-0.13%	2.74%	-2.68%
Rhoth	4.765	4.983	4.83	kg/m3	-4.58%	3.09%	1.33%
Vout	2211.00	2194.00	2028.77	m/s	0.77%	7.53%	-8.98%
Mout	3.178	3.14	3.03	-	1.20%	3.41%	-4.78%
Pout	90742.50	101298.33	110019.56	Pa	-11.63%	-8.61%	17.52%
Tout	1295.00	1306.00	1387.56	K	-0.85%	-6.25%	6.67%
Rhoout	0.223	0.2468	0.276	kg/m3	-10.67%	-12.01%	19.33%



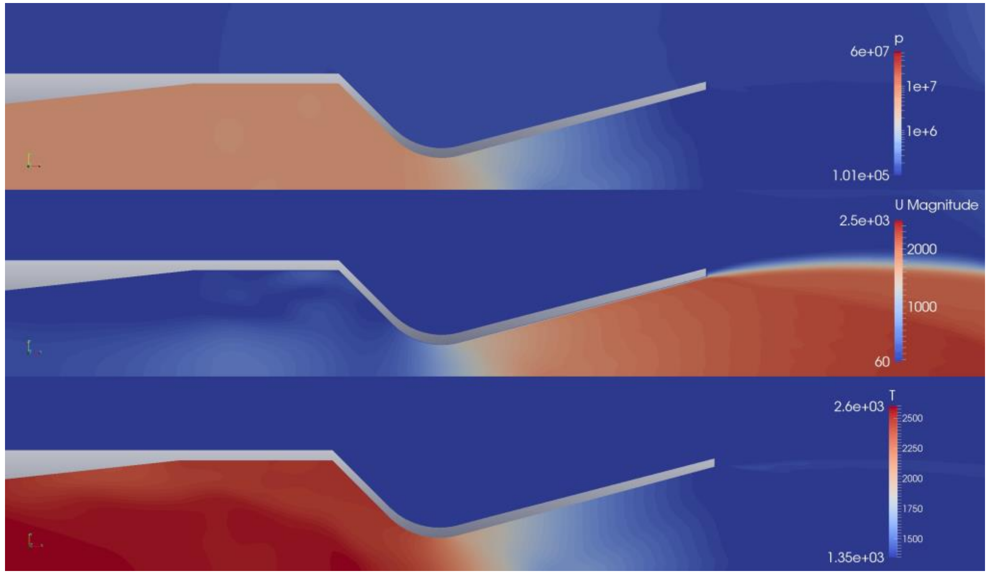


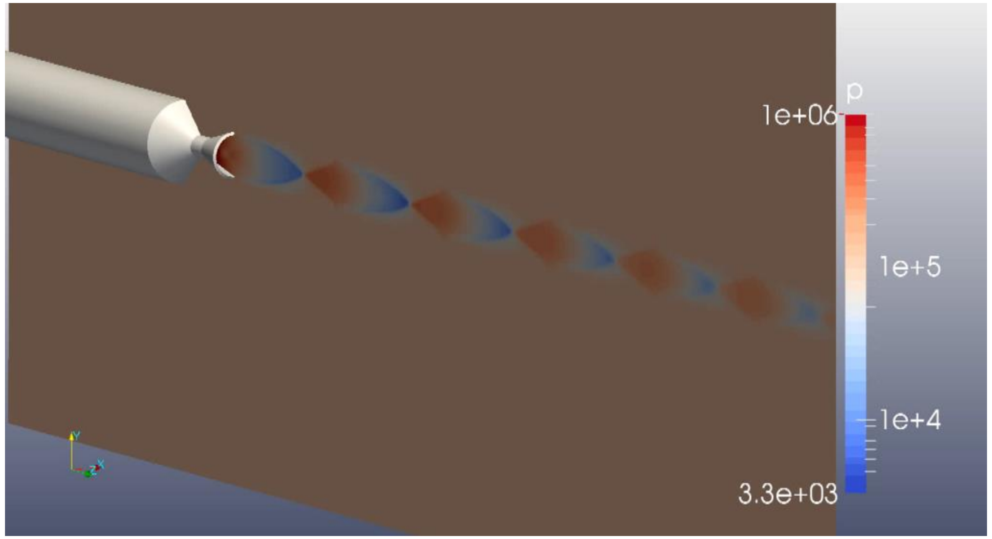
Thrust Comparisson: T2

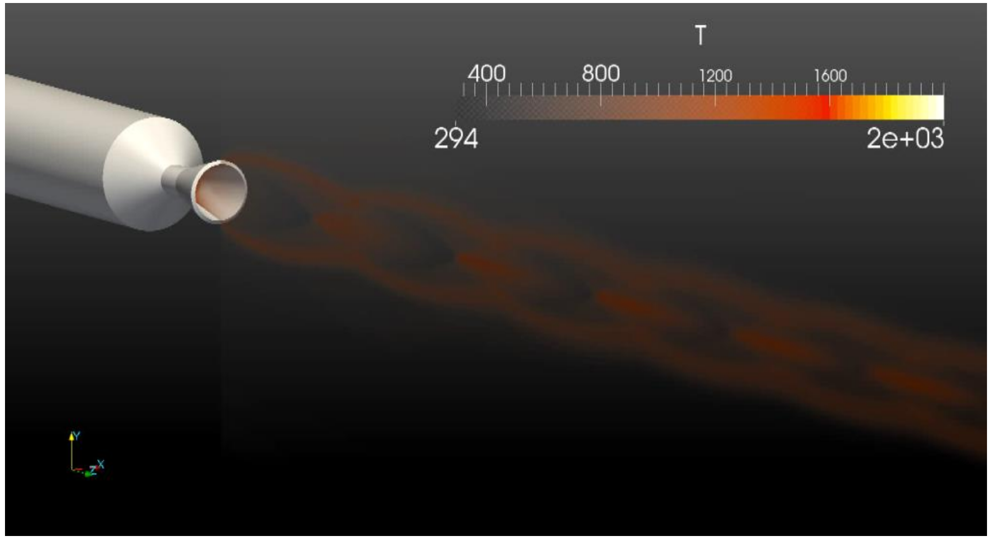
Test Bench	Isentropic	Finite Difference Method	CFD	Unit	Δ Ise. Vs Test Bench	Δ Finite Difference Vs Test Bench	Δ CFD. Vs Test Bench
6060	5877	6468	6243	N	-3.12%	6.31%	2.93%

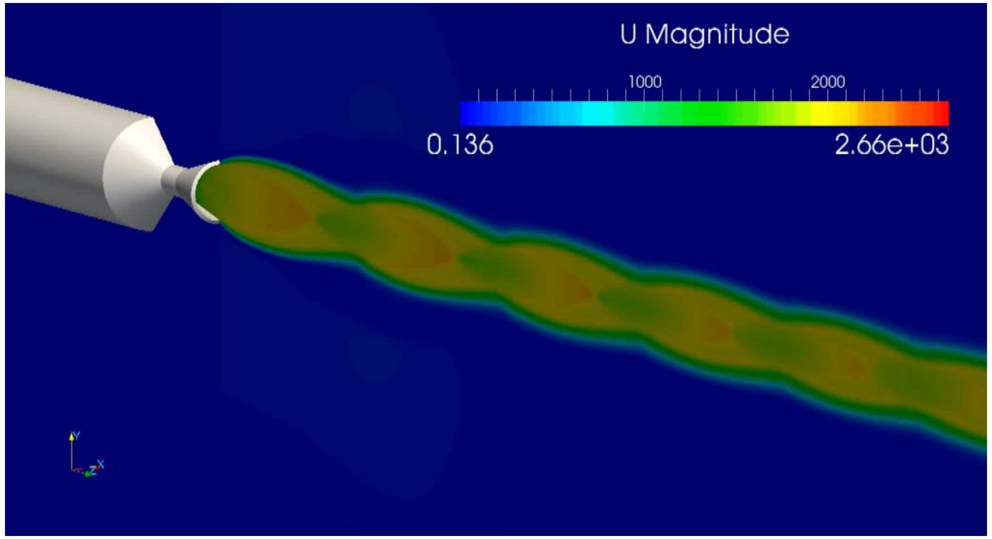


CFD: Results & Plume Overview









Conclusions & Future Work

- The 3 calculation techniques showed fair agreement between them.

- A re-design of the nozzle "T1" will be done aided by the presented methods.

- New experiments will be conducted in the rocket engine test bench to validate the simulations.

- A High speed camera will be used to capture the characteristics of the plume, in order to compare it with the CFD results and provide further information on the nozzle behaviour.

Acknowledgements

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…any questions?