Combustion optimisation of a passive pre-chamber motorcycle engine and of an innovative rotary engine using OpenFOAM

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Contents

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From Marmotors

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Stefano Rago	Engine Development Engineer
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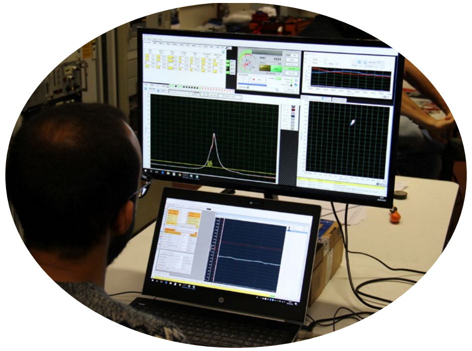
Marmotors at a glance

Marmotors is a small company based in Modena made up of 12 young development engineers.

It is a company specialized in design and development of high-performance engines:

- Computer Aided Design (CAD)
- Computer Aided Engineering (CAE)
  - Computational Fluid Dynamic (CFD): 1D and 3D simulations
  - Finite Element Analysis (FEM) simulations
  - Dynamic simulations
- Calibration and development of engines on dyno test
- Dedicated tests on the track with real-time analysis of indicating data

Why OpenFOAM?

Customization of numerical models for the simulation of:
- **unconventional combustion systems** (e.g. TJI, TCRCI, …)
- Different **fuel types** (e.g. heavy fuels for aviation, renewable fuels, …)

→ Open source tool for the development of **new combustion models**

Modeling of complex geometries and **unconventional engine architectures**

→ Automatic mesh generation and **tailored mesh management techniques**

Collaborative research between academic and industrial worlds

→ Open source tool = **exchange of ideas**

OpenFOAM currently used in Marmotors mainly for the simulation of:
- **Turbulent Jet Ignition** (TJI) combustion with passive pre-chamber
- **Rotary engine** fed by aviation heavy fuel

Combustion modeling

The Weller Combustion Model (flame area model) is adopted:

$$\underbrace{\frac{\partial \bar{\rho}\tilde{b}}{\partial t}}_{\text{Time Derivative}} + \underbrace{\nabla \cdot (\bar{\rho}\tilde{U}\tilde{b})}_{\text{Convective Term}} - \underbrace{\nabla \cdot (\mu_t \nabla \tilde{b})}_{\text{Diffusive Term}} = \underbrace{\bar{\rho}_u \tilde{S}_u \tilde{\Xi} |\nabla \tilde{b}|}_{\text{Reaction rate term}} + \underbrace{\dot{\omega}_{ign}}_{\text{Ignition Source term}}$$

Time Derivative — Convective Term — Diffusive Term — Reaction rate term — Ignition Source term

The computation of the regress variable b controls mixture combustion (1 = unburned, 0 = burned)

$$\Xi_{eq} = 1 - \frac{a_4 b_3^2}{2 b_1}\frac{L_t}{\delta_l} + \left[\left(\frac{a_4 b_3^2}{2 b_1}\frac{L_t}{\delta_l}\right)^2 + a_4 b_3^2 \frac{u'}{S_u}\frac{L_t}{\delta_l}\right]^{1/2}$$

Peters correlation to model laminar to turbulent flame transition

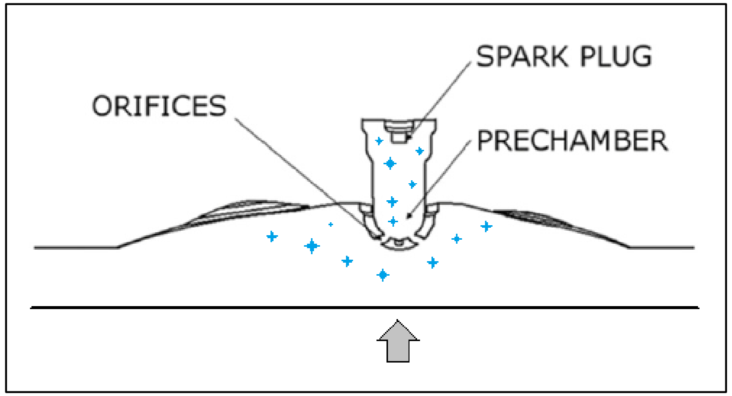
$$S_u = S_{u,ref}(\phi)\left(\frac{T_u}{T_{u,ref}}\right)^{\alpha}\left(\frac{p}{p_{ref}}\right)^{\beta}(1 - f\, Y_{EGR})$$

Gulder correlation to model to laminar flame speed development

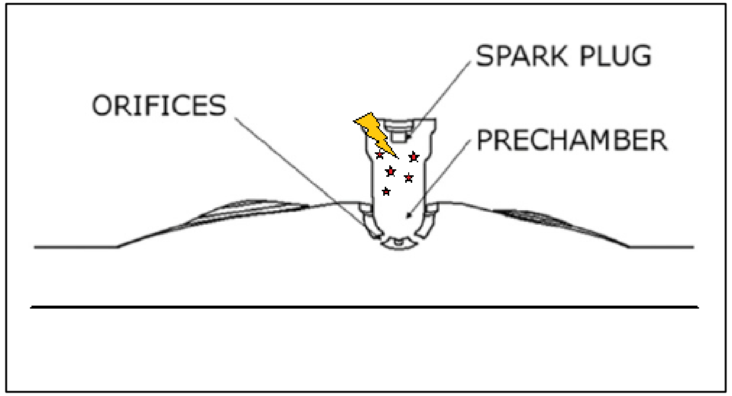
TJI combustion with passive pre-chamber

TJI combustion – Working principle

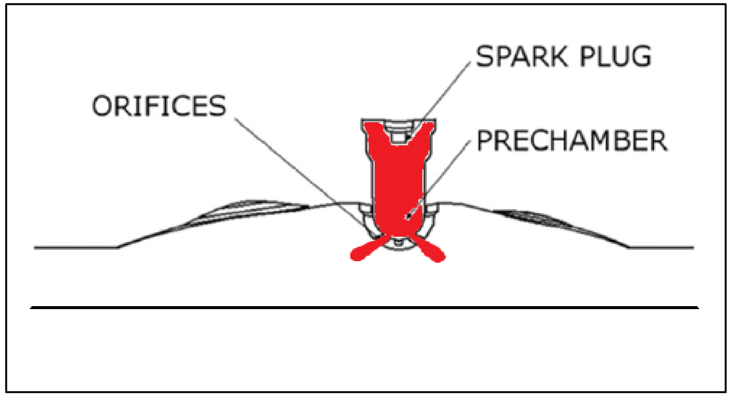
A pre-chamber combustion system i.e. TJI (Turbulent Jet Ignition) can be characterized by the following phases:



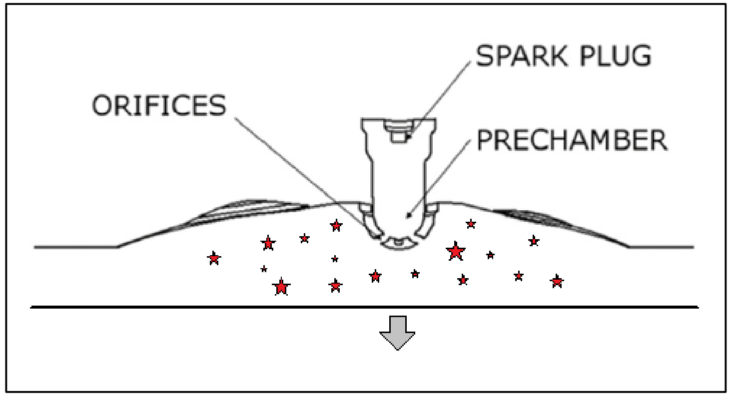
1. Pre-chamber filling process



2. Start of combustion in pre-chamber



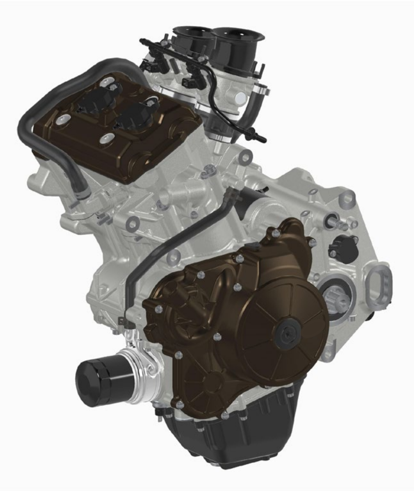
3. Hot turbulent jets ejection

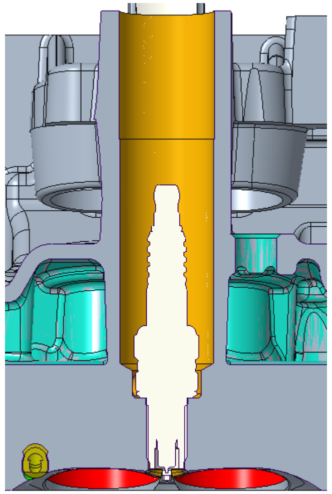


4. Main chamber combustion process

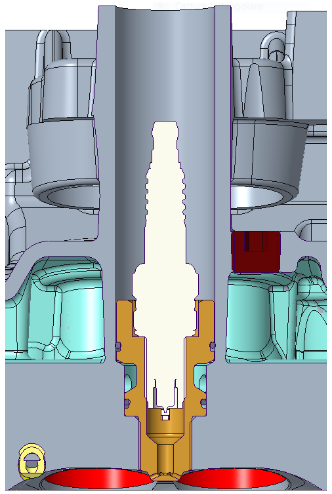
Engine specification: conversion to TJI technology

Definition	Value	Unit
Tipology	2 cylinders in-line, 4 stroke engine, 4 valves per cylinder	-
Displacement	659	cc
Bore	81	mm
Stroke	63.93	mm
CR	13,5 +/- 0,5 : 1	-
Maximum engine speed	10500 +/- 100	rpm
Pin Offset	7	mm





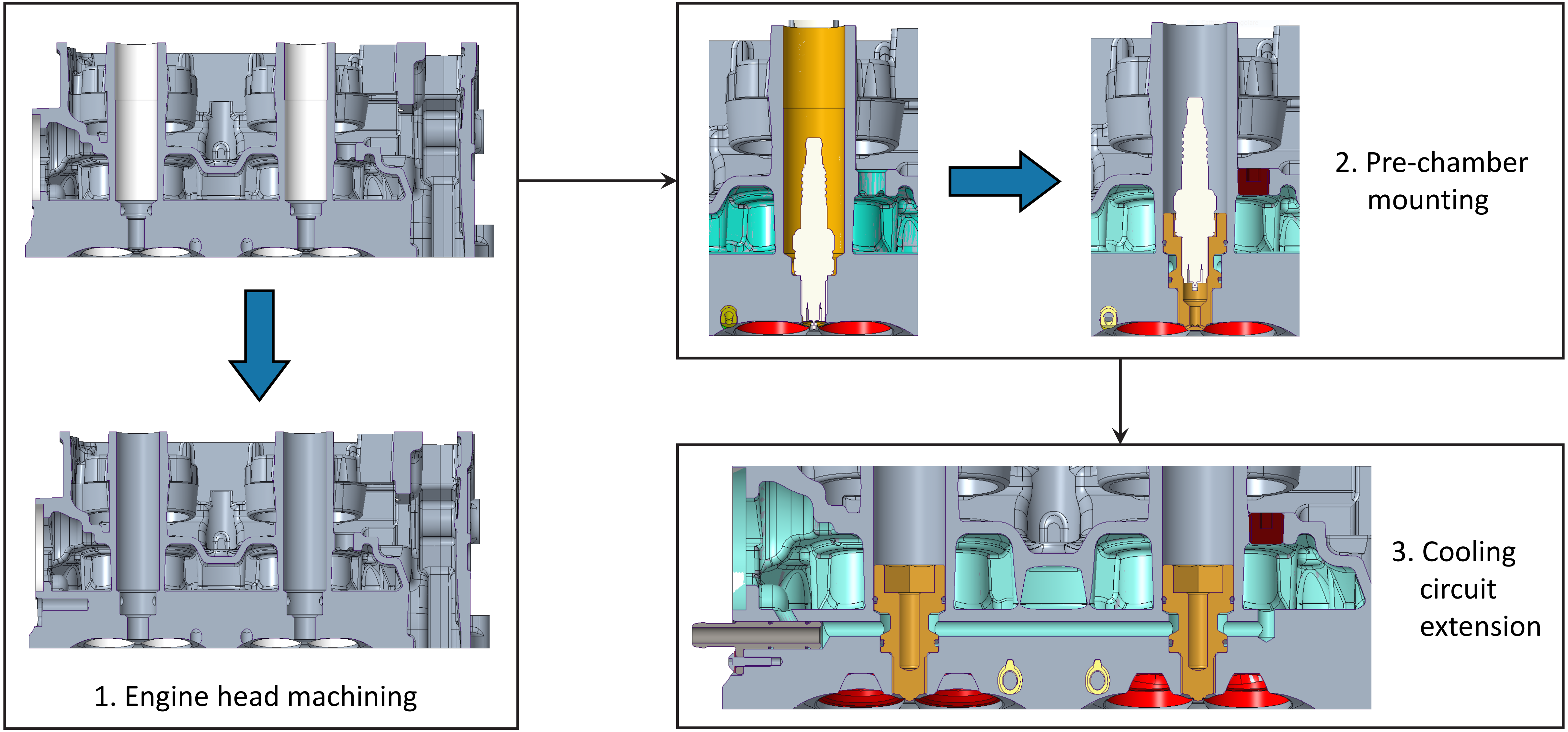
SI configuration (conventional engine)



TJI configuration (passive pre-chamber)

Pros ✚	Cons ▬
Lower combustion duration	Higher heat losses
Higher combustion stability	Pre-ignition risk in case of poor cooling
Lower knock risk	Possible misfires (cold start, low load)
Higher combustion efficiency	Additional machining
Higher CR achievable	
Leaner combustion achievable	
Less pollutant emission(CO, HC)	

Pre-chamber machining and mounting



Experimental test bench

The main focus of the experimental activity was the evaluation of the engine **performance** and **emissions**.
The dedicated sensors employed were the following:

- Kistler cylinder pressure sensor
- Kistler instrumented spark plug (to measure the pre-chamber pressure)
- Motor exhaust gas measuring system (Horiba MEXA-1600DEGR)

- The fuel used is a road **gasoline** (RON95)
- 4 operating points at different **throttle angles** (25% ,50%, 75% , 100%) for 4 different **regimes** (3500, 5000, 9000, 10500 rpm)
- **Pressure traces** in main chamber and pre-chamber for each operating point acquired by the indicating system at ≈180 kHz
- The measured data were used for the validation of the CFD model

Experimental activity

The experimental activity was done following a specific sequence of steps for each operating point:

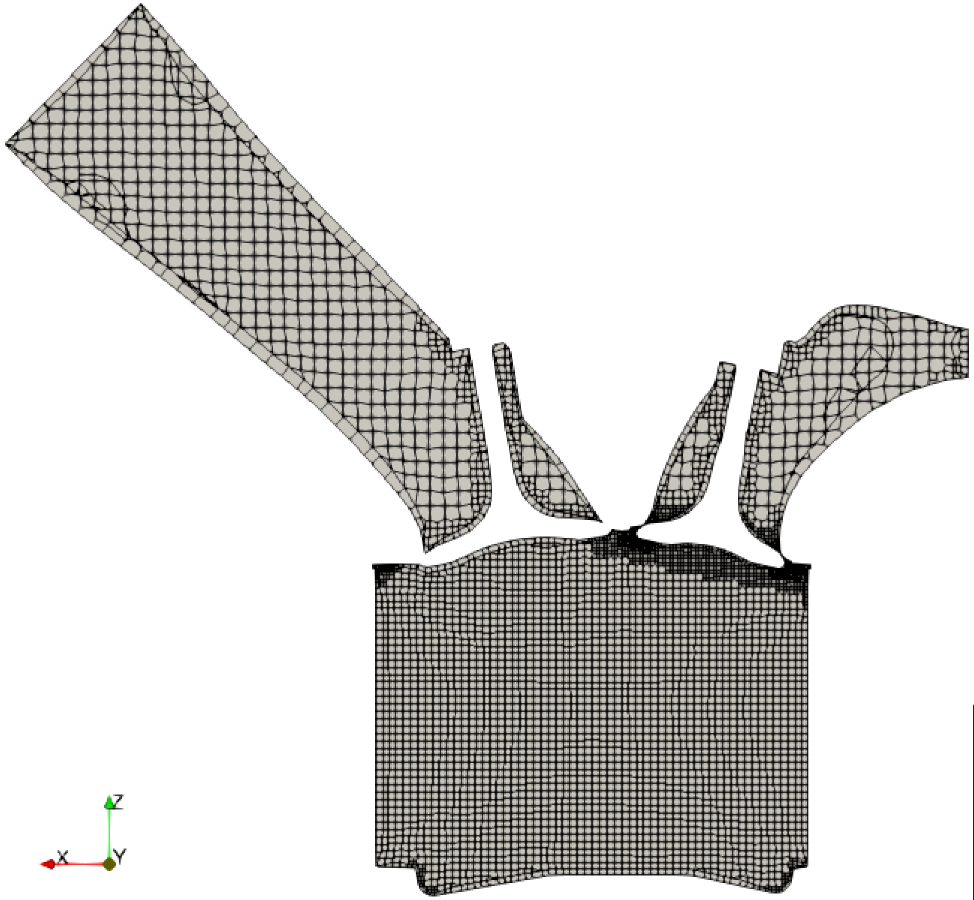
Operative Range	Throttle (load) [deg]	Lambda (%fuel)		Spark Advance (STD: MFB50=8)	
		Cyl 1	Cyl 2	Cyl 1	Cyl 2
Engine Speed: 10500 rpm	61,5 (75%)	STD	STD	STD	STD
		STD	STD	-2	-2
		STD	STD	-4	-4
		STD	STD	STD	STD
		x0,95	x0,95	*	*
		x0,95^2	x0,95^2	*	*
		x0.95^3	x0.95^3	*	*
		x0.95^4	x0.95^4	*	*

The procedure followed was:

- Two steps retarding the engine **spark advance**
- A back-to-back test returning the standard SA
- Four steps increasing the **lambda value**, trying to keep the standard SA

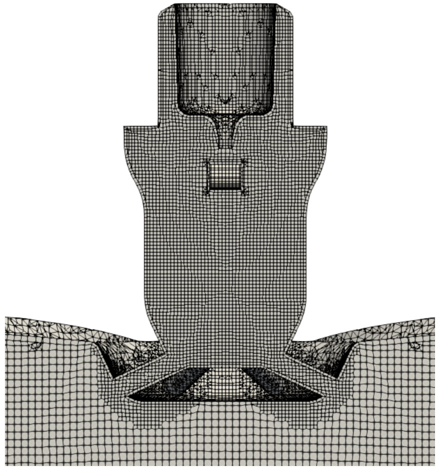
CFD simulation – 3D model setup

- Engine **full cycle** simulation handled with a **multi-mesh** approach
- Boundary and initial conditions taken from 1D model and experimental data
- Selected operating point: 10500 rpm, full load (max engine power)



Full cycle mesh motion

Pre-chamber mesh section

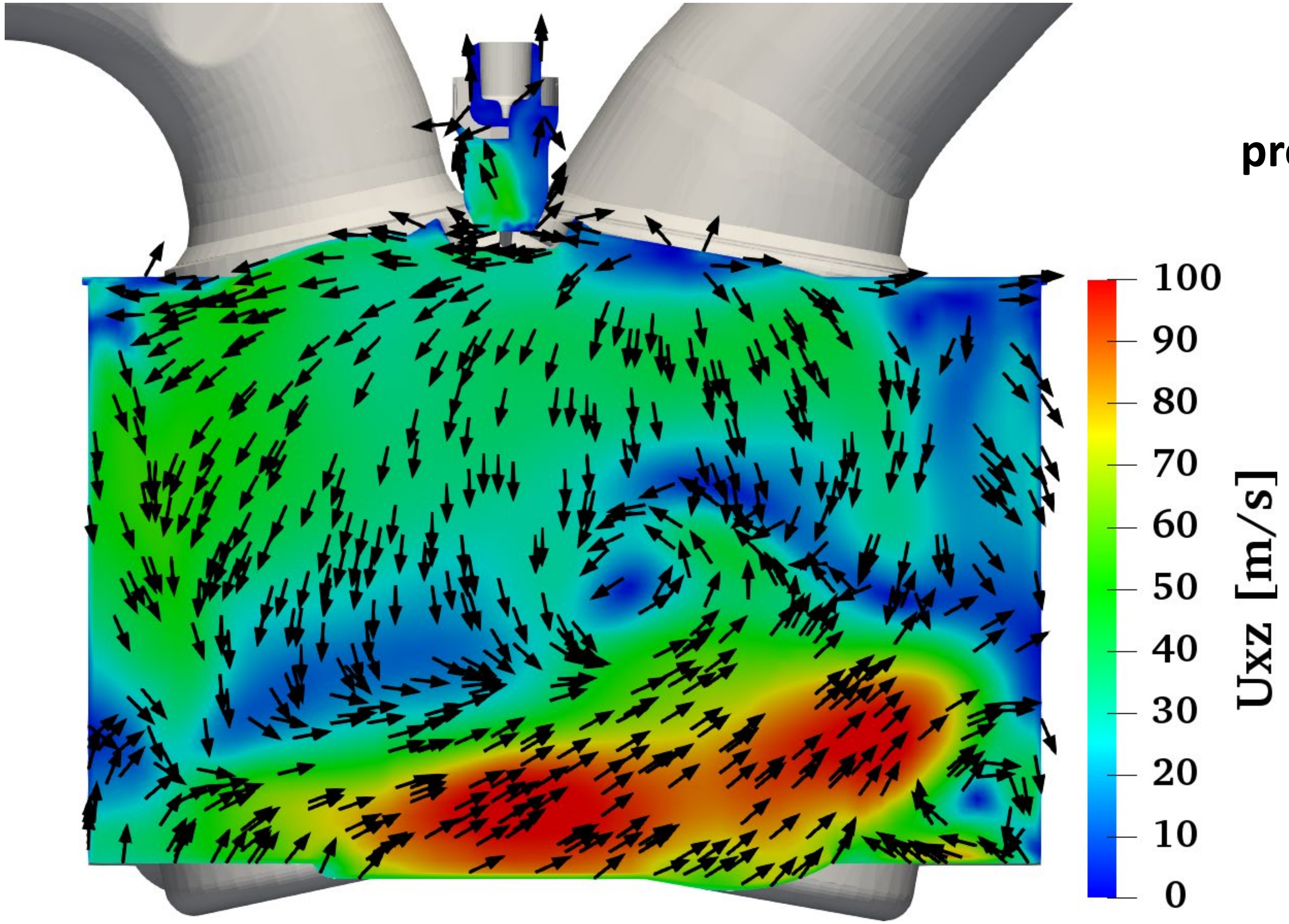


Computational grid cell size:

- Intake and exhaust ports: 2.5 mm
- Cylinder (gas exchange): 0.6 – 1.25 mm
- Cylinder (TJI combustion phase): 0.3 – 0.6 mm
- Pre-chamber: 0.15 mm
- Valves: 0.05 - 0.6 mm

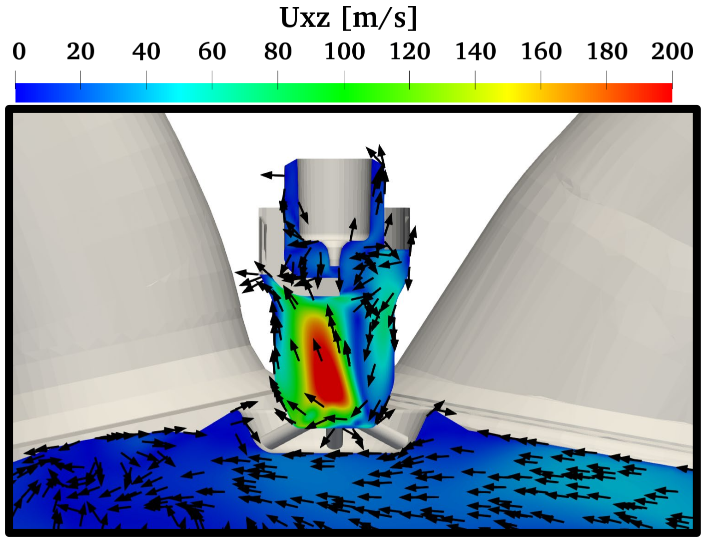
	EVO	EVC	IVO	IVC
CAD [°]	121.7	391.7	331.2	610.2

CFD simulation – Results: gas exchange

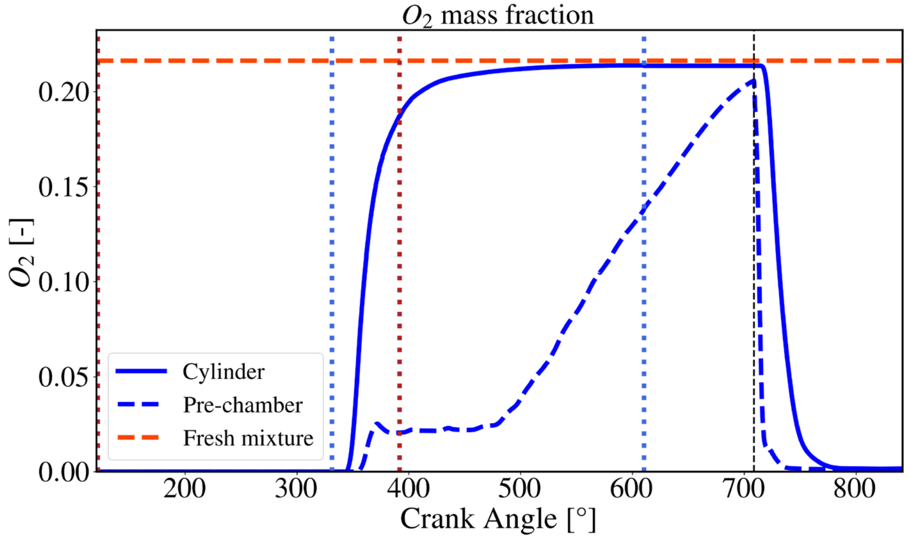


Flow field at IVC

Flow field in pre-chamber at SA:



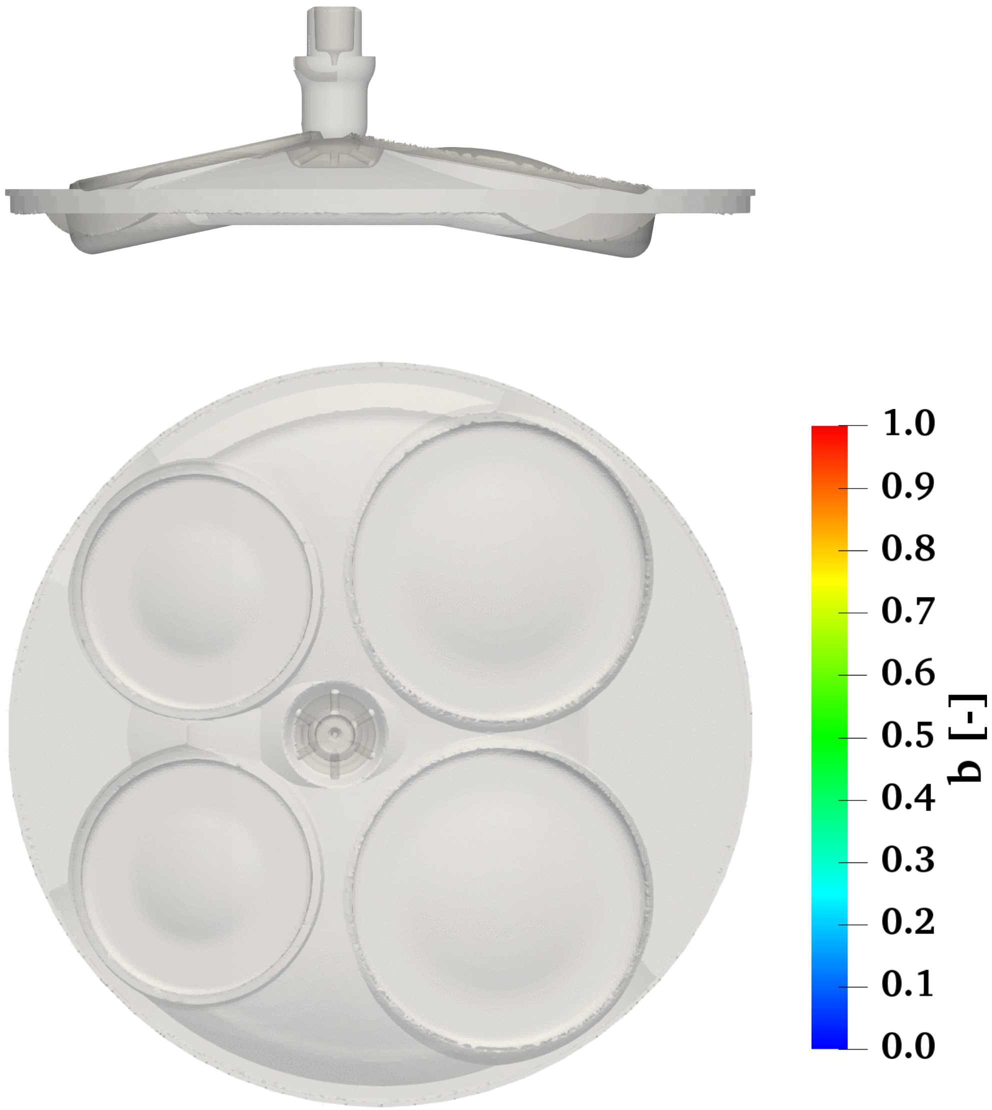
Main chamber and pre-chamber **scavenging:**

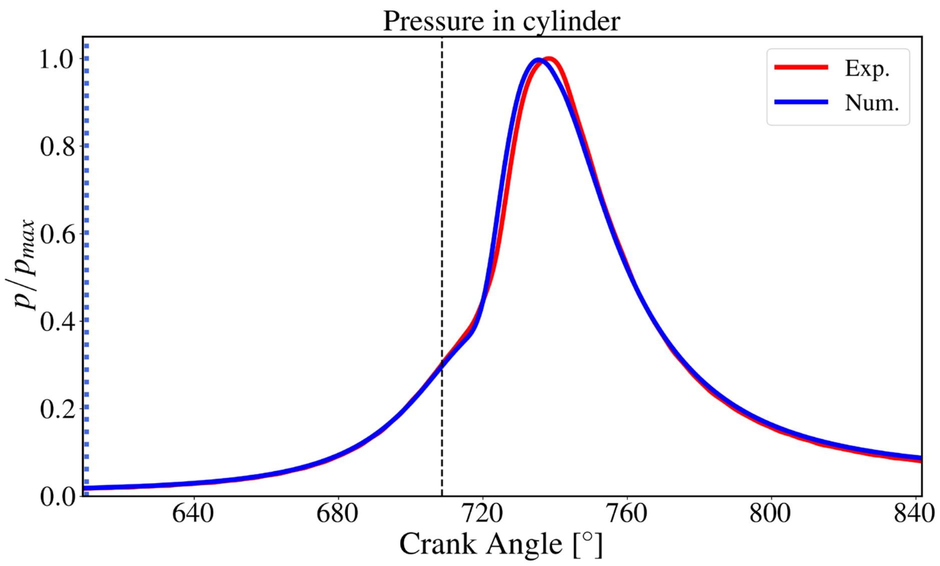


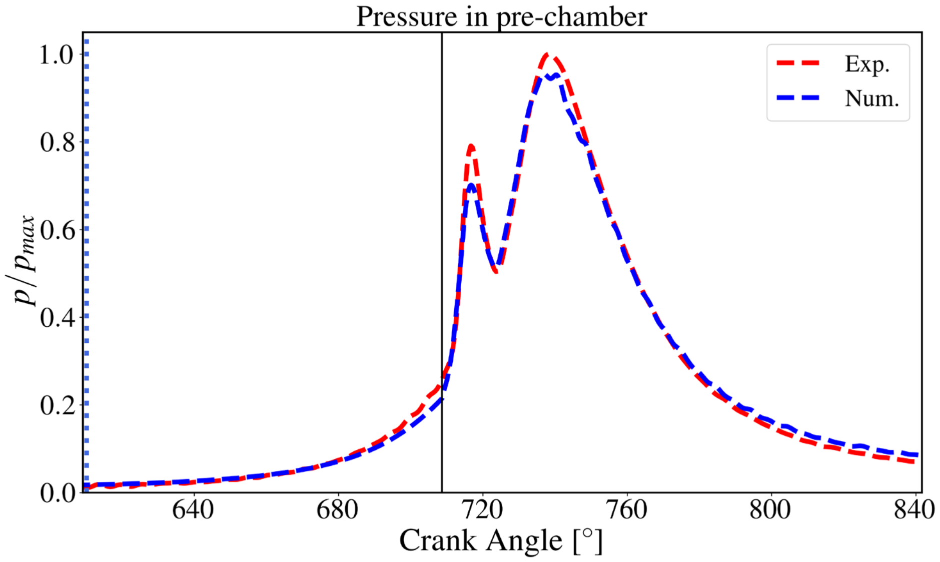
CFD simulation – Results: combustion

Front view

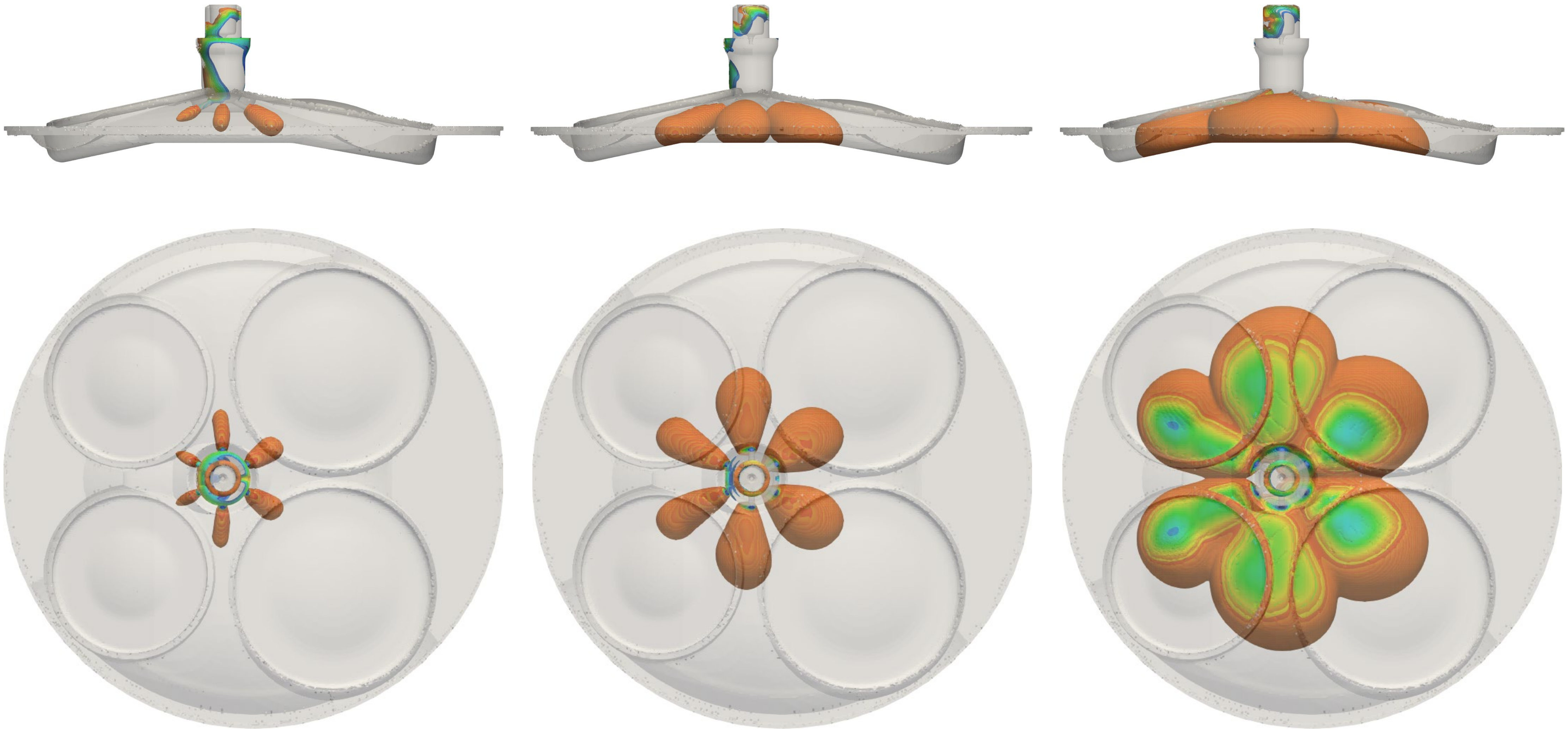
Top view







CFD simulation – Results: combustion



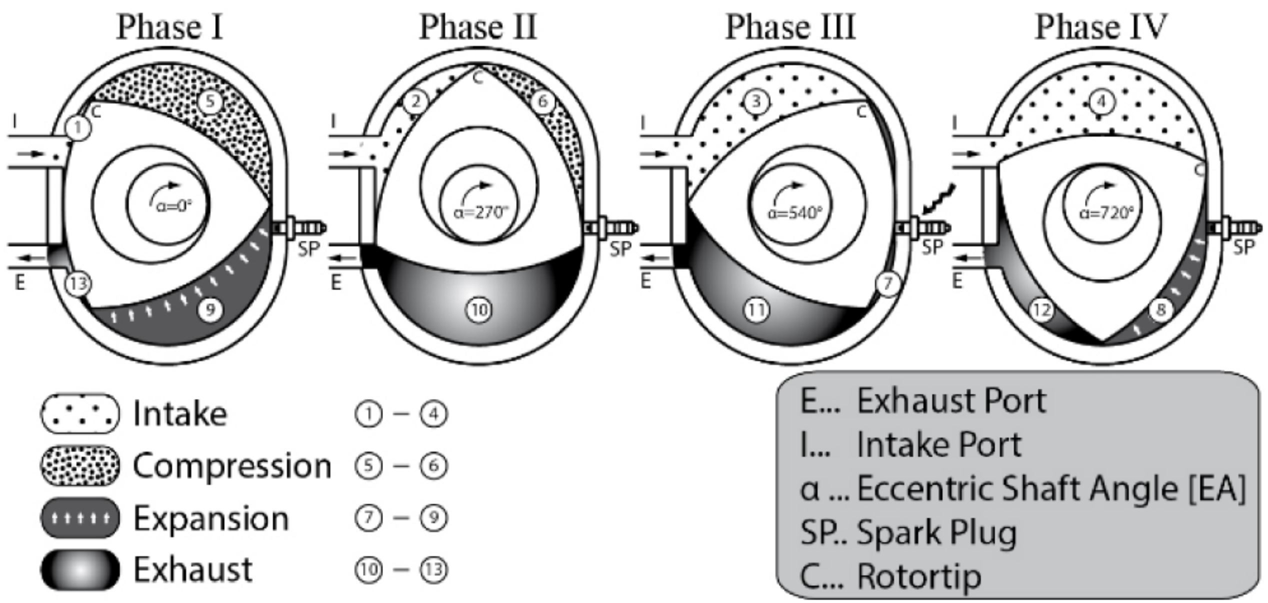
Flame front at 716 CA

Flame front at 720 CA

Flame front at 724 CA

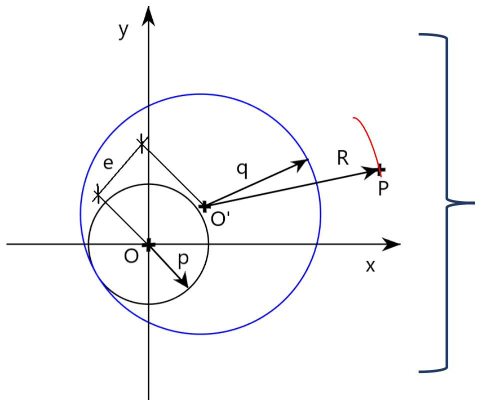
Rotary engine fed by aviation heavy fuel

The Rotary Engine – Working principle



Housing profile → peri-trochoid

Rotor flank profile → trochoid inner envelope

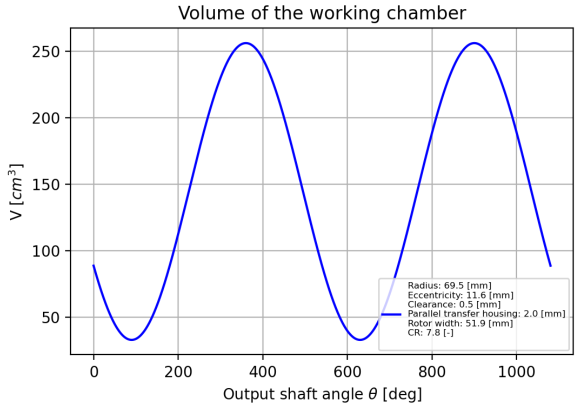


The **peri-trochoid** is the curve drawn by a point P at distance R from the center of the **revolving circle** (O') revolving over the **base one** (centered in O).

Volume law:

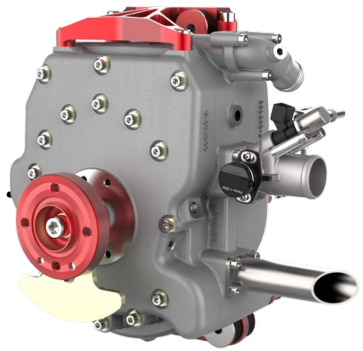
$$V = V_{min} + V_H \left(1 - \sin\left(\frac{2}{3}\alpha + \frac{\pi}{6}\right)\right)$$

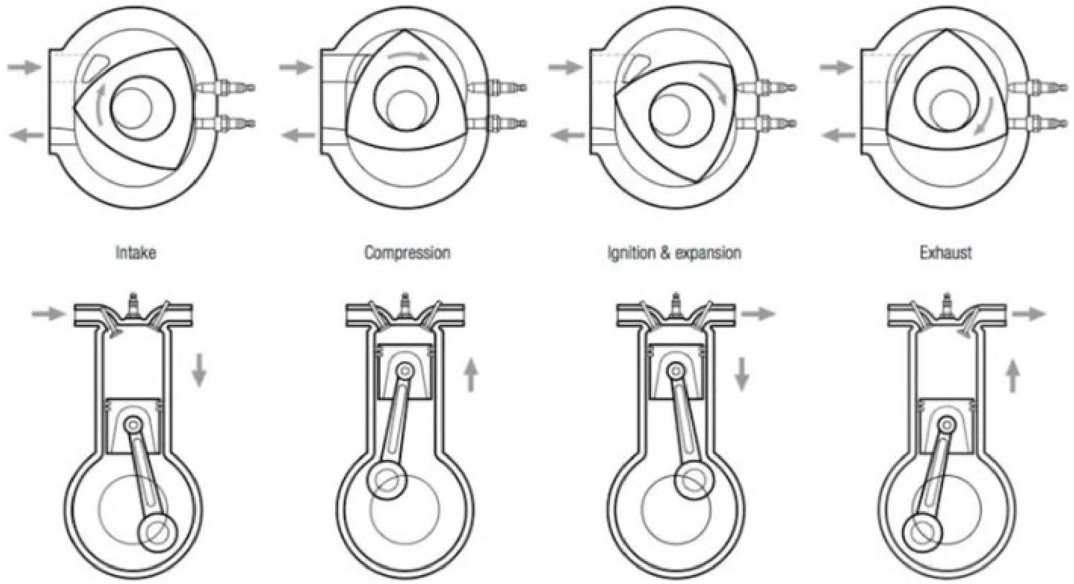
$$\begin{cases} V_{min} = f(R_1, R_2, e, \varphi_{max}) \\ V_H \triangleq \sqrt{3}\, e\, (2R_1 + R_2)\, b \\ R_1 \triangleq R + a', R_2 \triangleq R + a \end{cases}$$



Engine specification

Definition	Abbrev	Value	Unit
Generating Radius	R	69.5	mm
Eccentricity	e	11.6	mm
Offset housing	a	2	mm
Width of Rotor	b	51.941	mm
Offset rotor	a'	1.8	mm
Max angle oscillation	ϕmax	0.52443	rad
Radius 1	R1	71.5	mm
Radius 2	R2	71.3	mm
Stroke Volume	Vh	223.641	cc
Minimum Volume	Vmin	26.058	cc
Compression ratio	CR	7.8	-



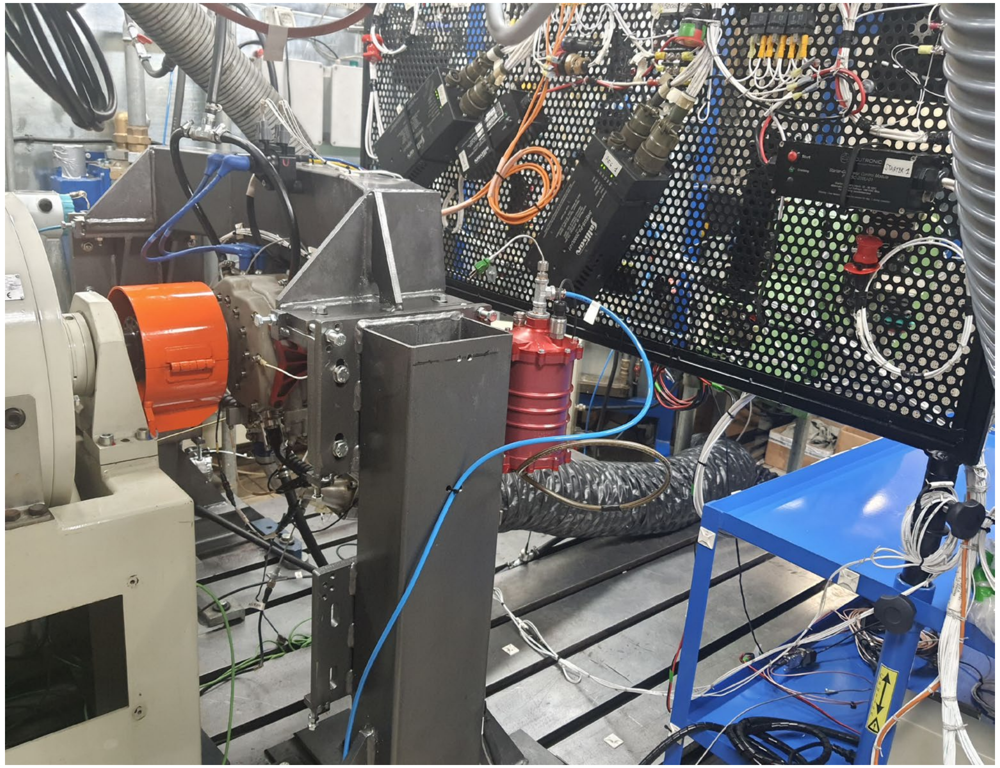


Pros ➕	Cons ➖
High power density	Oil consumption
Compactness	High pollutant emissions
Multifuel capability	Rapid wear of some parts
No reciprocating parts (low NVH)	Low efficiency (H.T. losses, low CR)
Construction simplicity	High CAPEX (machining, low # units)
Torque Regularity	

Experimental test bench

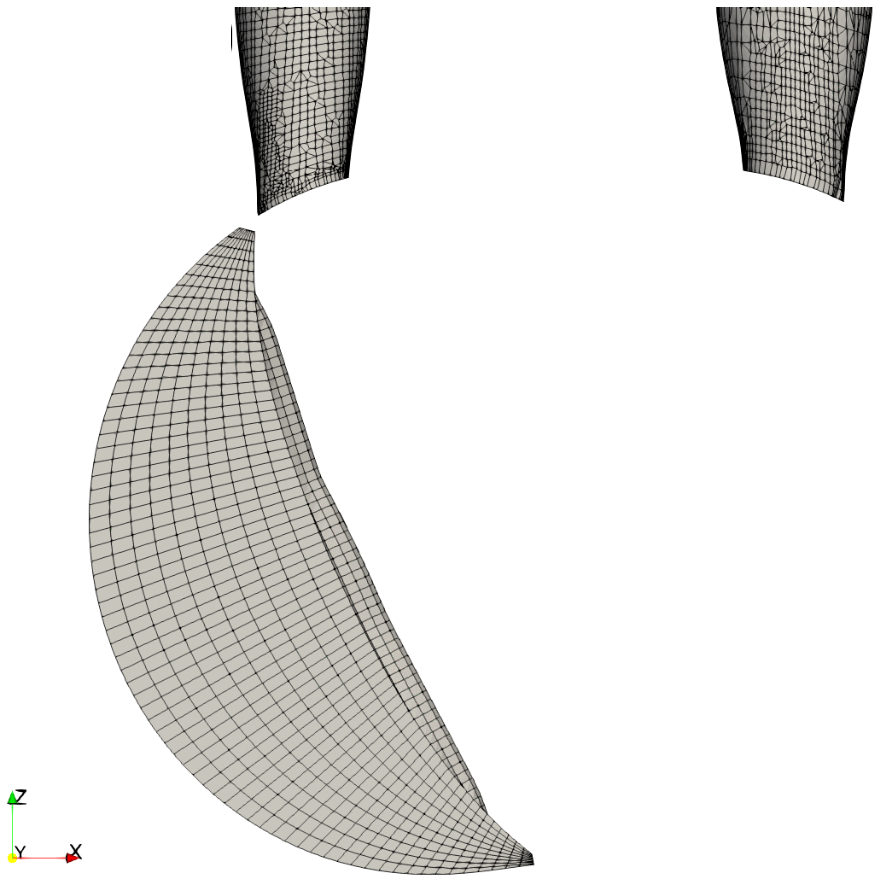
The test rig is equipped with several transducers to monitor in real time the main engine operating parameters such as:

- Intake air temperature (AIT)
- Manifold Air Pressure, downstream the throttle (MAP)
- Exhaust gases temperature (EGT)
- Temperature of blow-by gases (SPARCS) for rotor cooling (RAIT)
- Oil pressure (SPARCS)
- Fuel pressure and temperature
- Coolant temperature
- Shaft speed sensor
- Fuel mass flow rate (Coriolis) transducer
- Pressure transducer embedded within one spark plug
- Shaft speed sensor
- Relative A/F ratio (λ) probe (broad-band)



- ➢ The fuel used is a **kerosene** for civil aviation (jet-A1)
- ➢ 5 operating points at **different throttle angles** (32% , 42%, 52% , 76%, 98%), but **constant engine speed** (≈7500 rpm)
- ➢ **Pressure traces** at each operating condition acquired by the indicating system at ≈180 kHz
- ➢ The measured data were used for the validation of the CFD model

CFD simulation – 3D model setup



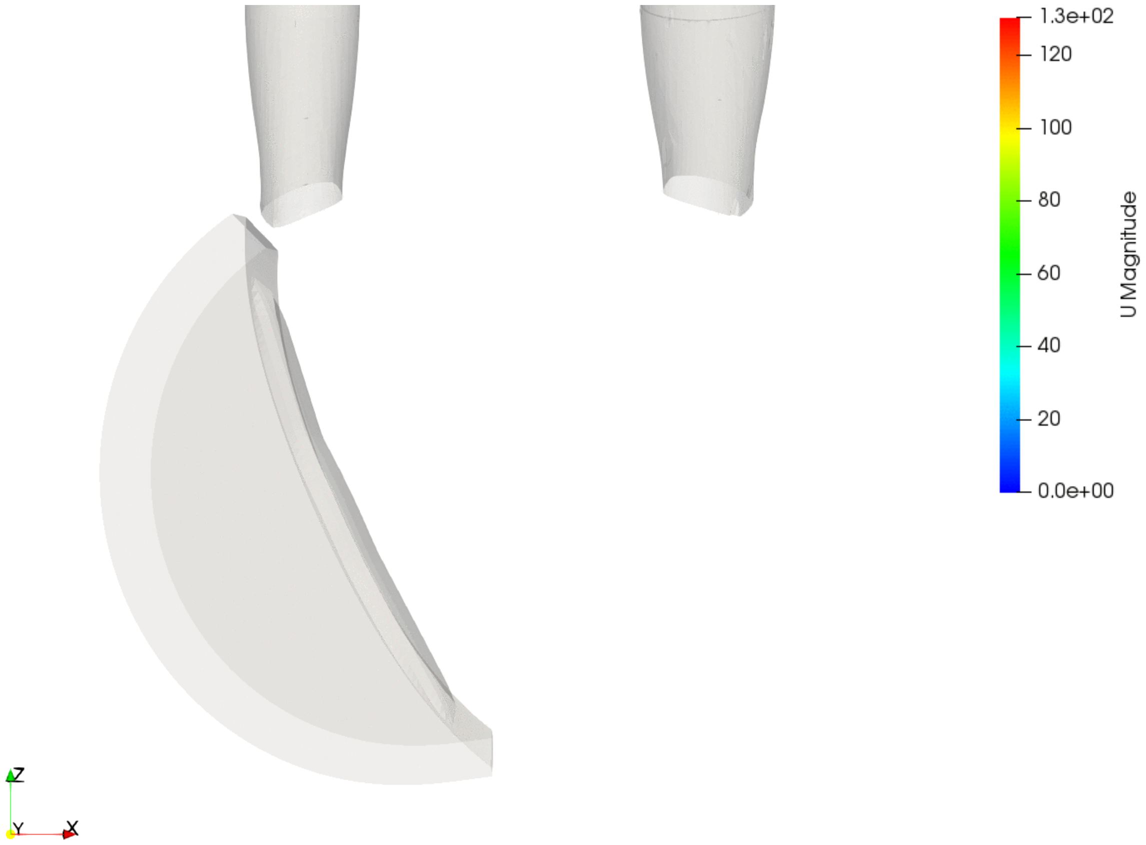
- Engine **full cycle** simulation handled by means of:
  - **Mesh deformation** approach
  - **Arbitrary mesh interfaces** for the gas exchange between combustion chamber and intake/exhaust ports
- Boundary and initial conditions taken from 1D model and experimental data
- Selected operating point: 7500 rpm, full and partial load conditions

Full cycle mesh motion

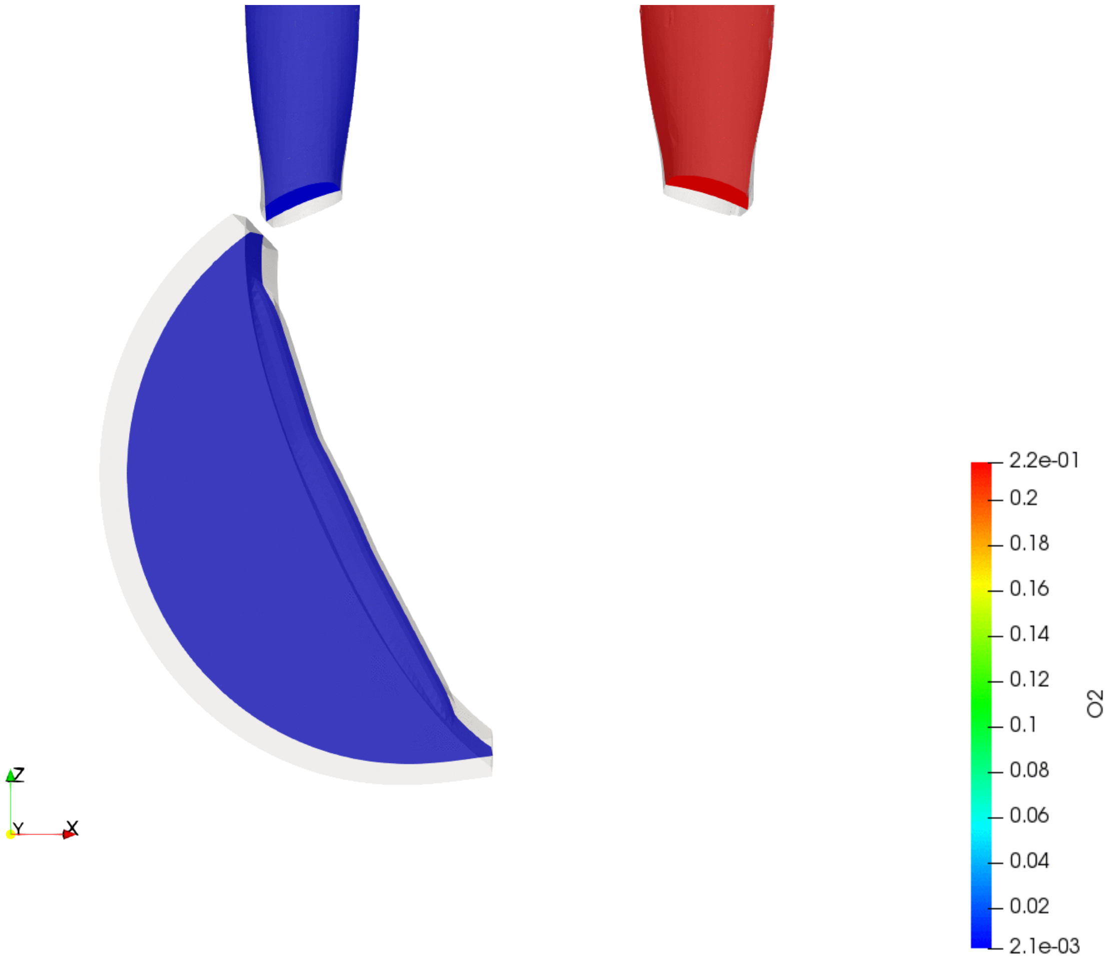
Computational grid cell size:
- Intake and exhaust ports: 2 mm
- Combustion chamber: 1.2 mm

CFD simulation – Results: gas exchange

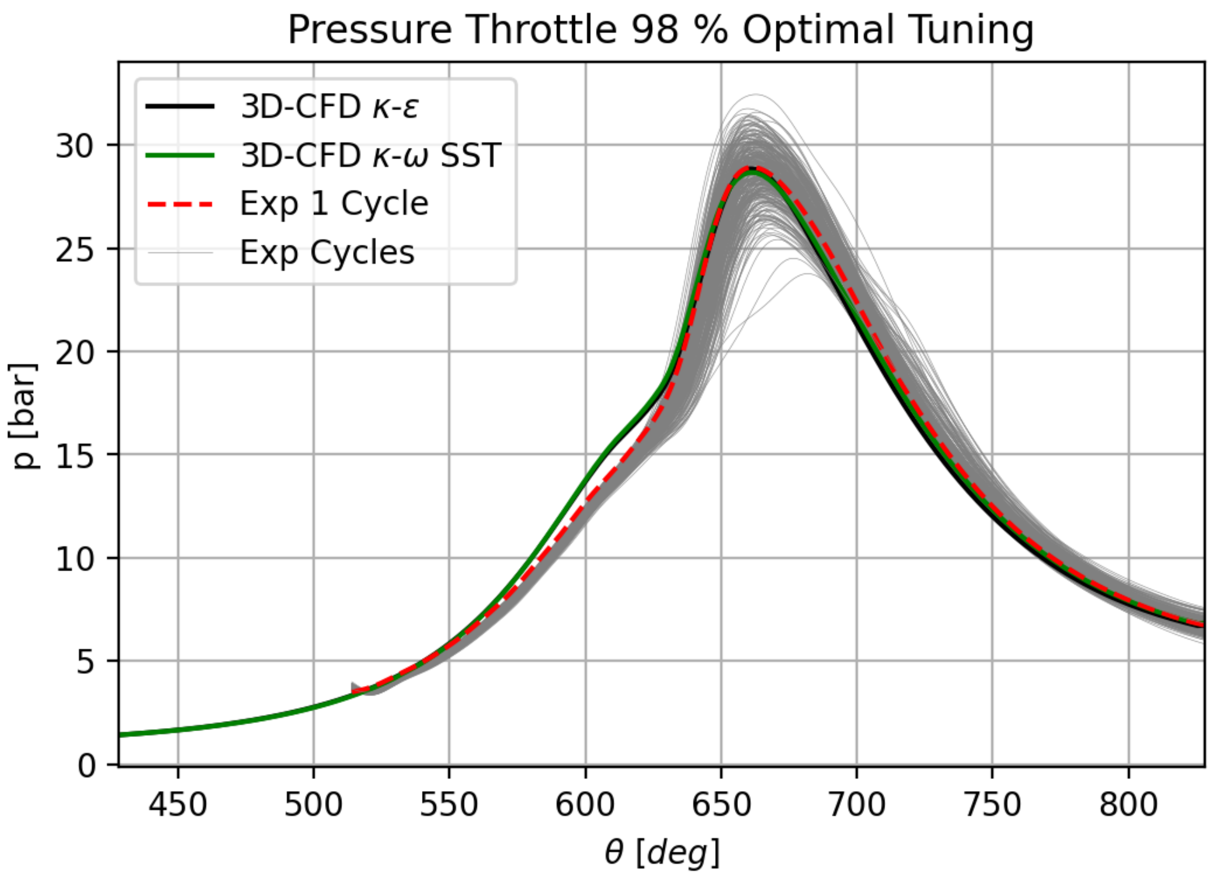
Flow **velocity** streamlines

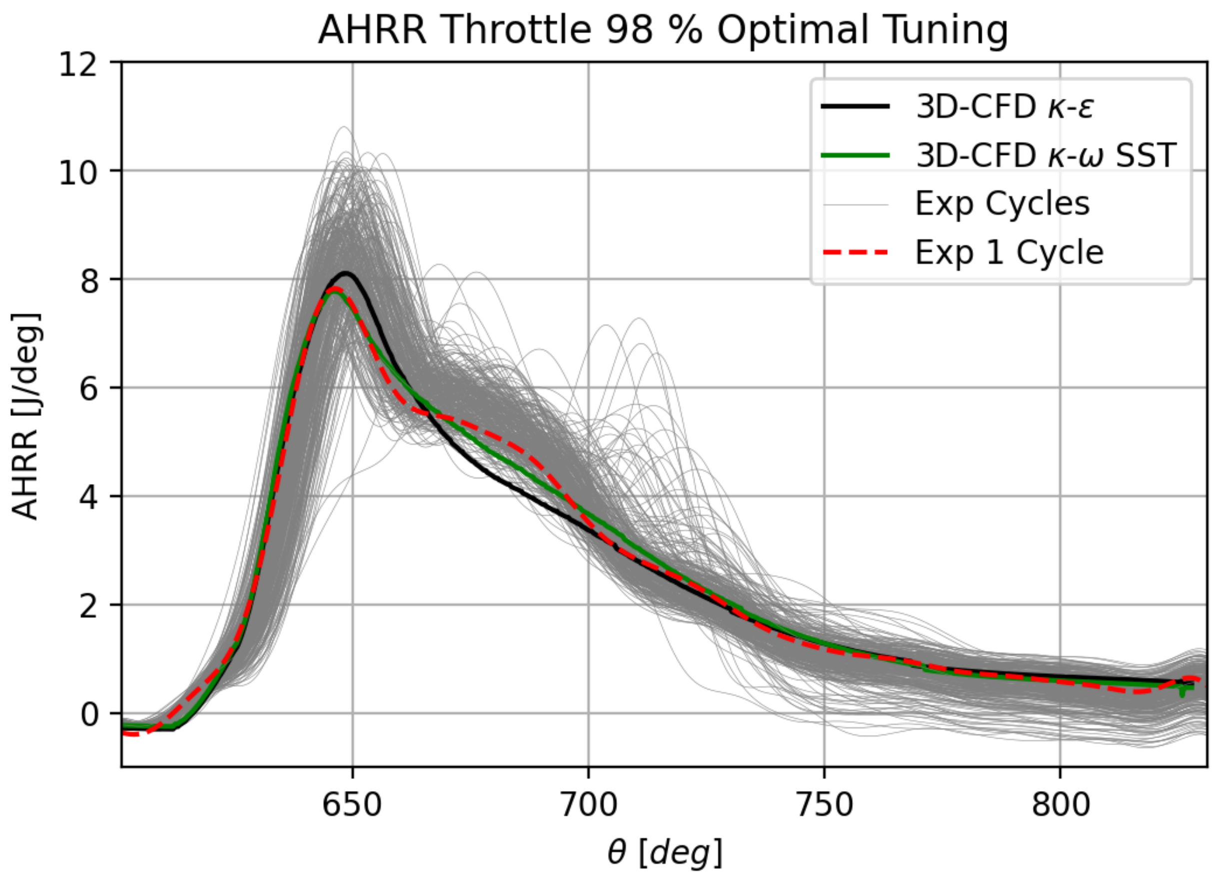


Oxygen mass fraction field



CFD simulation – Results: combustion WOT

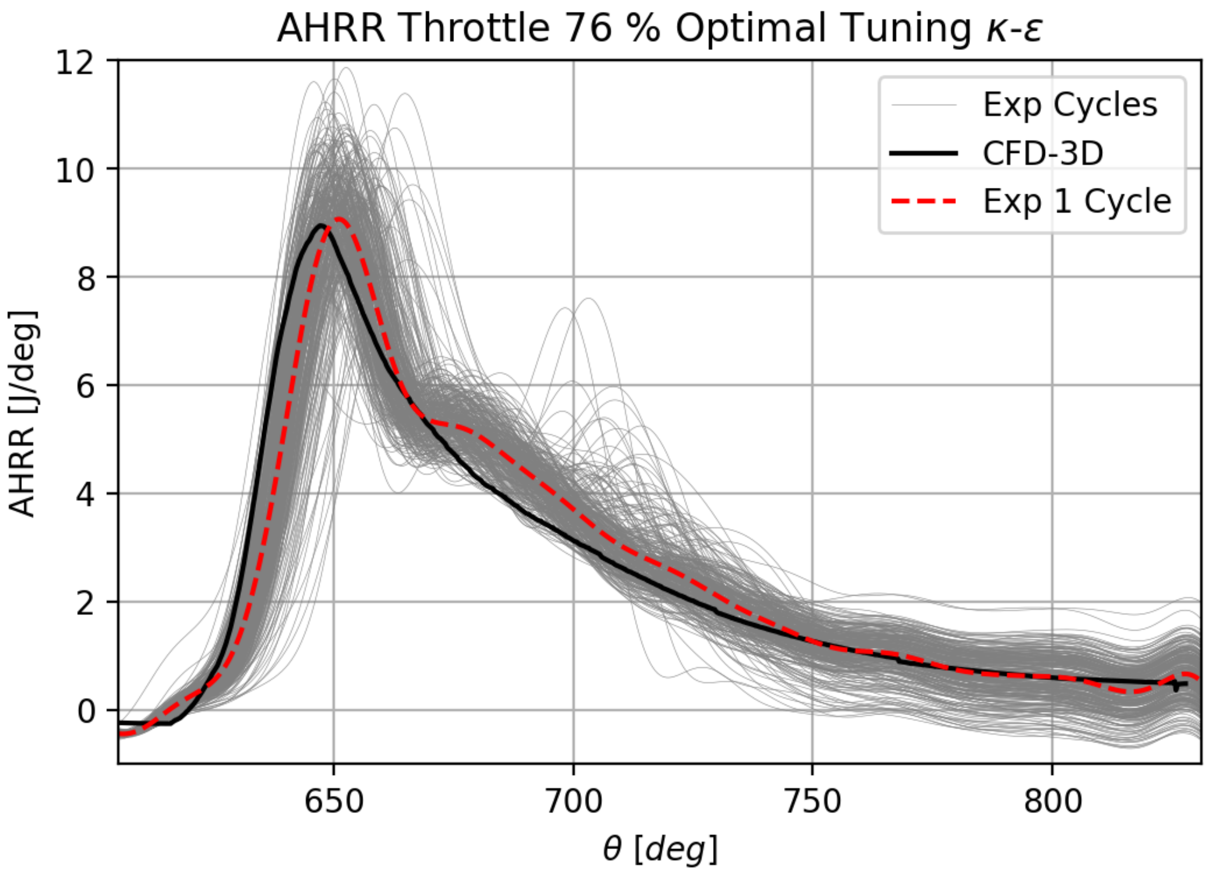


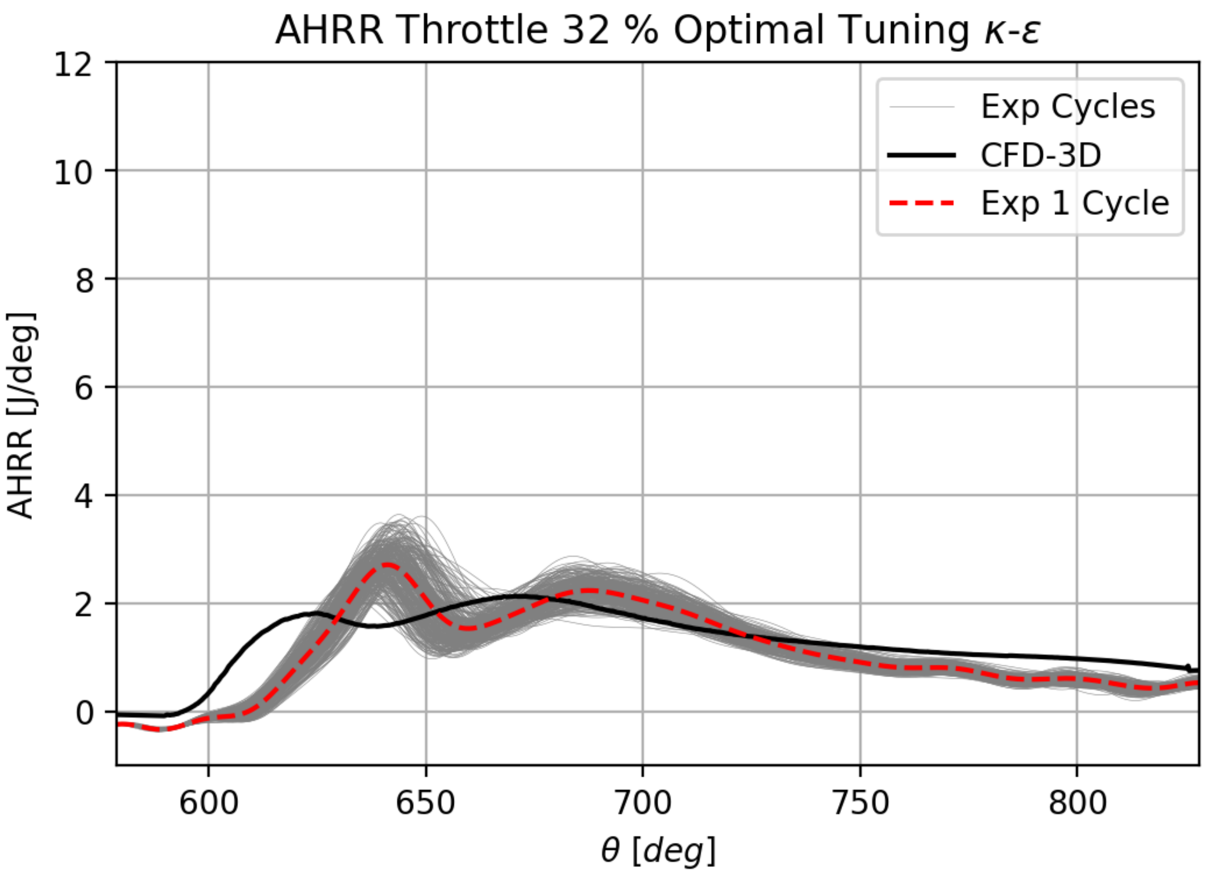


- Good agreement of peak pressure and during expansion phase
- Overestimation of pressure during compression
- Agreement on pressure between the models

- AHRR of both models with experimental scatter
- Underestimation of AHRR during early expansion phase
- $\kappa - \omega\ SST$ model with a second more pronounced hump
- Double Wiebe like behaviour captured but with a less pronounced change in slope

CFD simulation – Results: combustion partial load



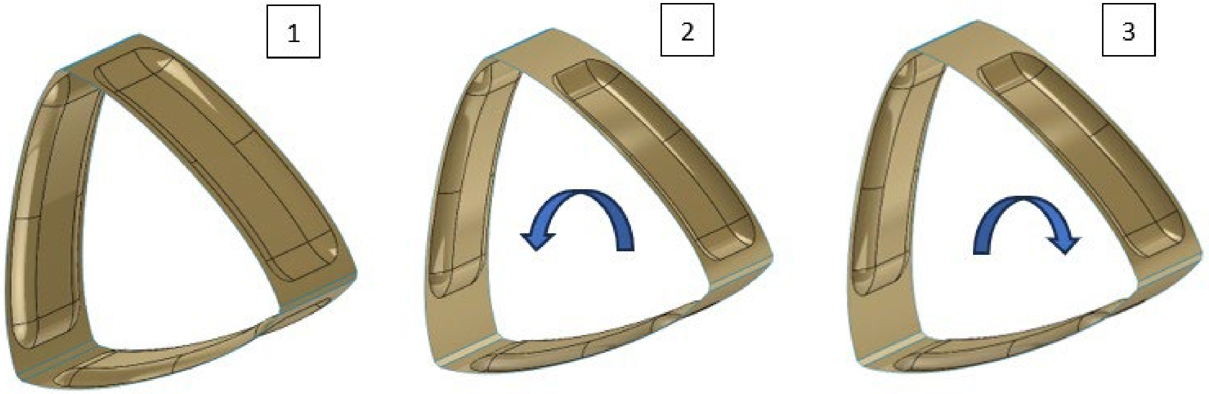


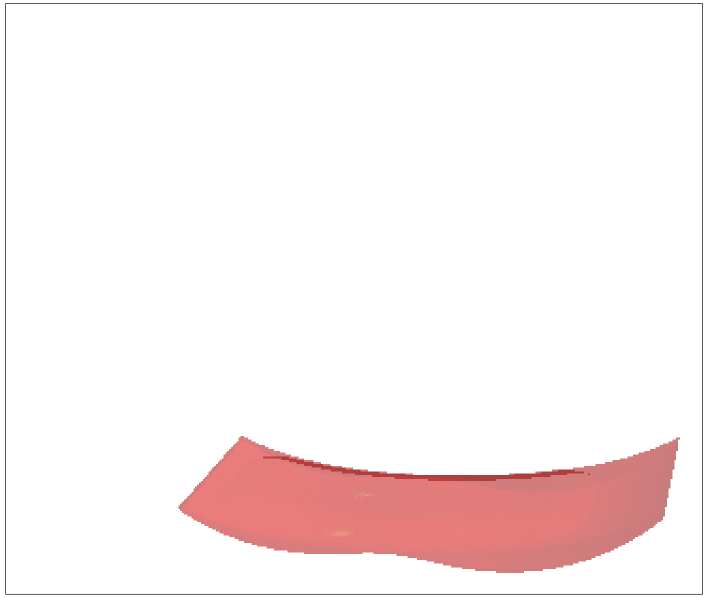
- For limited load reductions (76% and 52%) the tuning of the model produces acceptable results
- Anticipation of AHRR curve and overestimation of pressures

- For lower loads the error is too big and the predicted signal is out of experimental scatter
- General trend is better described w.r.t. WOT, finer tuning of the combustion model is required

CFD simulation – Testing of new recess geometries

MAR MOTORS



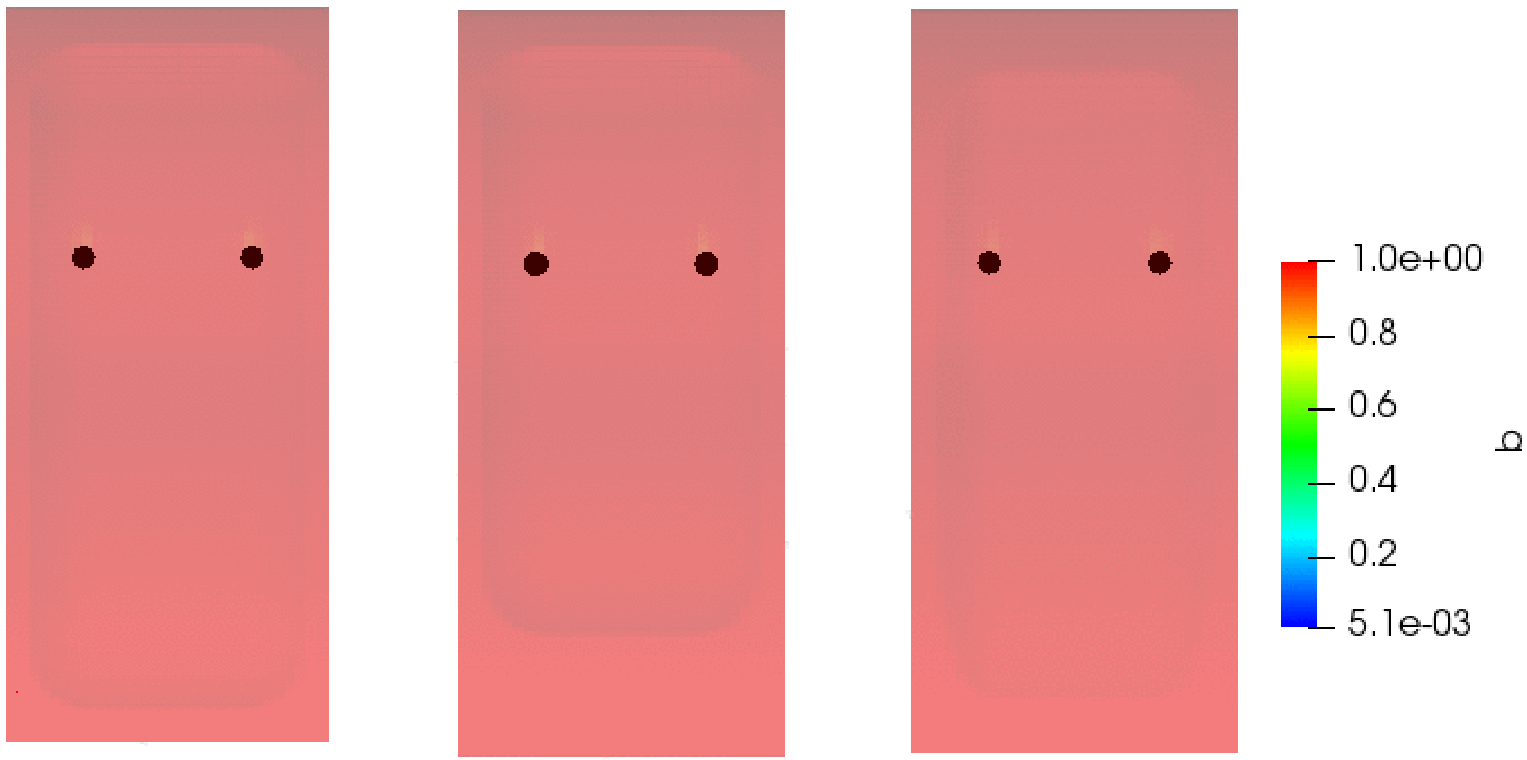


1. Low CR symmetric recess (CR = 7.3) → To avoid knock onset, possibly anticipate spark timing.
2. Asymmetric TE recess → The worst performance expected, to quantify gain of LE recess over TE.
3. Asymmetric LE recess → Enhanced squish effect, faster and more complete combustion.

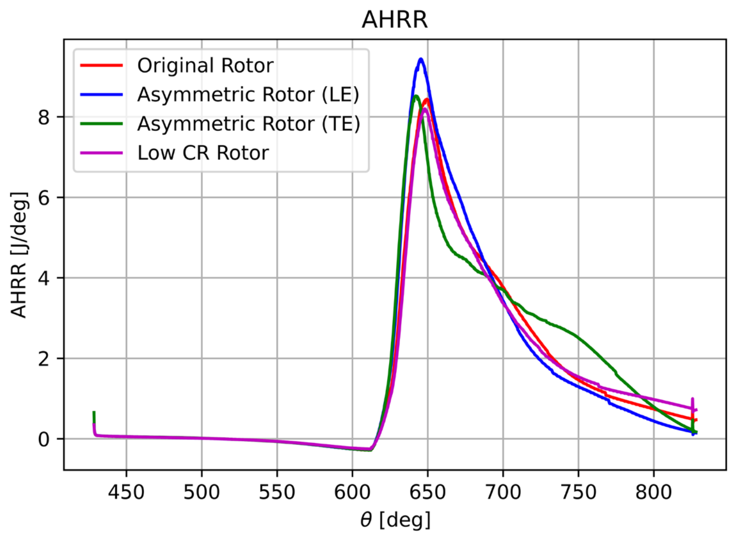
Rotor Geometry	Indicated Torque [Nm]	Indicated Power [hp] ([kW])	Fuel Consumption [kg/h]	Indicated SFC [g/(kWh)]
Original Rotor	28.94	30.9 (22.7)	8.51	374.44
Deeper Recess	27.16 (- 6.15 %)	29.0 (21.3)	8.4 (- 1.29 %)	393.64 (+ 5.13 %)
Leading Side Recess	30.94 (+ 6.91%)	33.0 (24.3)	8.38 (- 1.53 %)	344.66 (- 7.95 %)
Trailing Side Recess	29.41 (+ 1.62 %)	31.4 (23.1)	8.62 (+ 1.29 %)	373.16 (- 0.34 %)

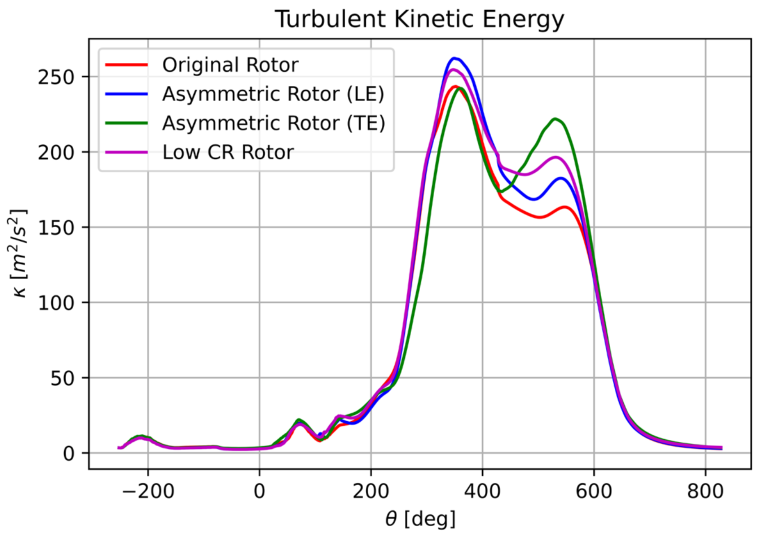
Best Configuration (no mechanical losses included, torque from work definition)

CFD simulation – Testing of new recess geometries



CR 7.3 Symmetric Bowl | Asymmetric LE Bowl | Original Bowl





Conclusions

The satisfying **numerical-experimental results agreement** allows to draw some conclusions from the **CFD analyses** of both the studied engine configurations.

- TJI combustion
  - Flow field evolution in main and pre-chamber
  - EGR distribution in pre-chamber
  - Combustion development in pre-chamber and main chamber
  - Influence of the flow field on the flame front propagation

- Rotary engine
  - Pressure curve validation at different engine loads
  - Combustion development analysis
  - Optimization of the rotor recess geometry at full-load

CFD analyses can clarify the fluid-dynamics inside the engine and can help in the design process of unconventional solutions applied to ICEs.