The Flex-Gen PRIN 2022 project

FLEX-GEN

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Luigi Rubino

Raffaele Saviano

Giancarlo Dellora, Giuseppe Farina

Modeling

Integrated 1D-3D modeling of FPLG including control systems.

Experiments

Characterization of linear generators under FPLG operation.

Fuel

Efficiency maximization with low carbon energy carriers

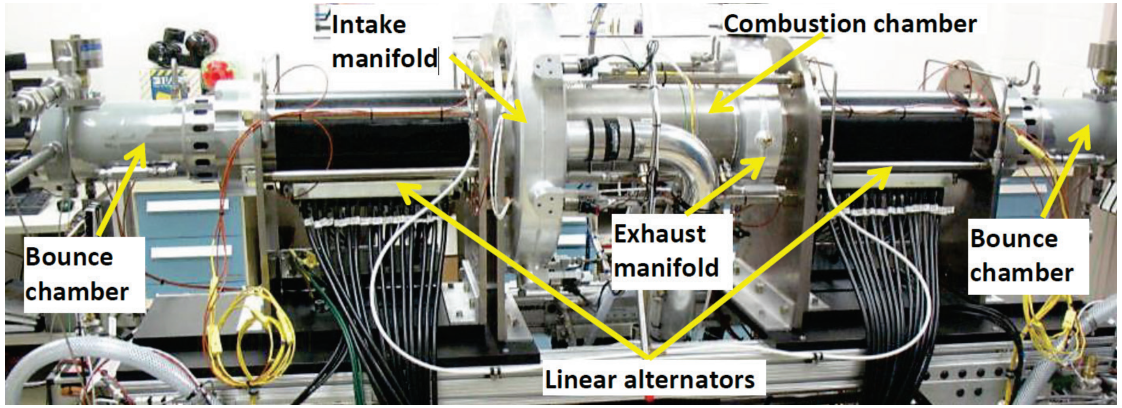
FLEX-GEN aims to provide cutting-edge innovations in the FPLG technology, considered as mid- and long-term sustainable solution for power generations and power units for mobile applications

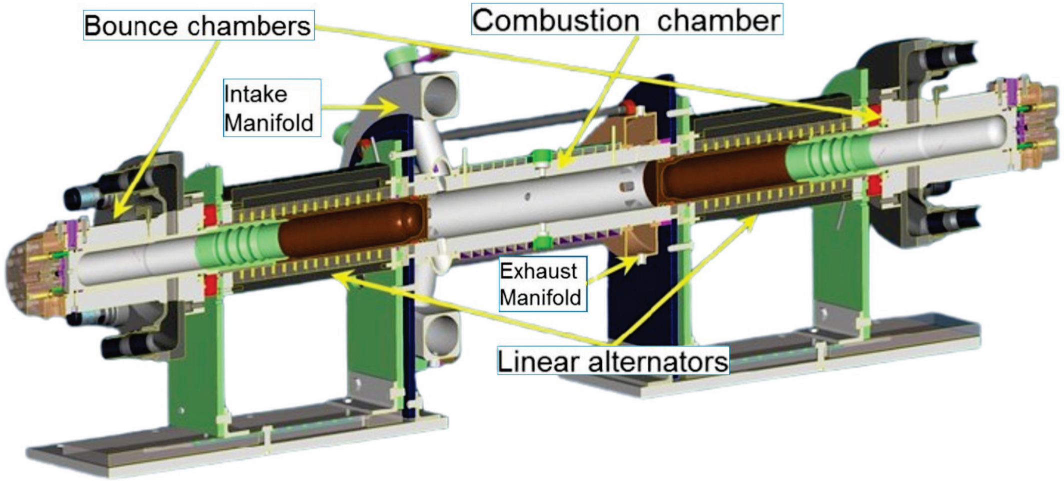
Main aim of **FLEX-GEN** is to develop new models, simulation tools and prototypes maximizing the sustainability of the FPLGs both for gen-set and mobility

The research flow has been divided into three main research areas as follows:

- Development of new mathematical models of all FPLG partes;
- Design, prototyping and testing of novel axial generators;
- Development of 1D and CFD multi-physic simulation tools to be used for pre-design and validation

Sandia National Laboratories





Mainspring

Easy, modular installation
High availability & low maintenance
Up to 25 MW per acre scalability

Each package contains two linear generator cores, operated in tandem.

Architectures & Power Unit sizing

Finanziato dall'Unione europea
NextGenerationEU

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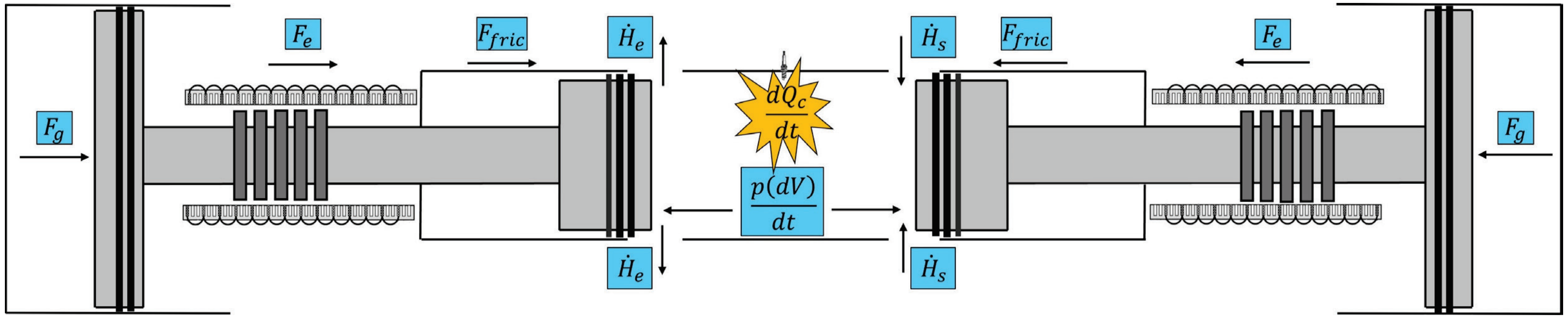
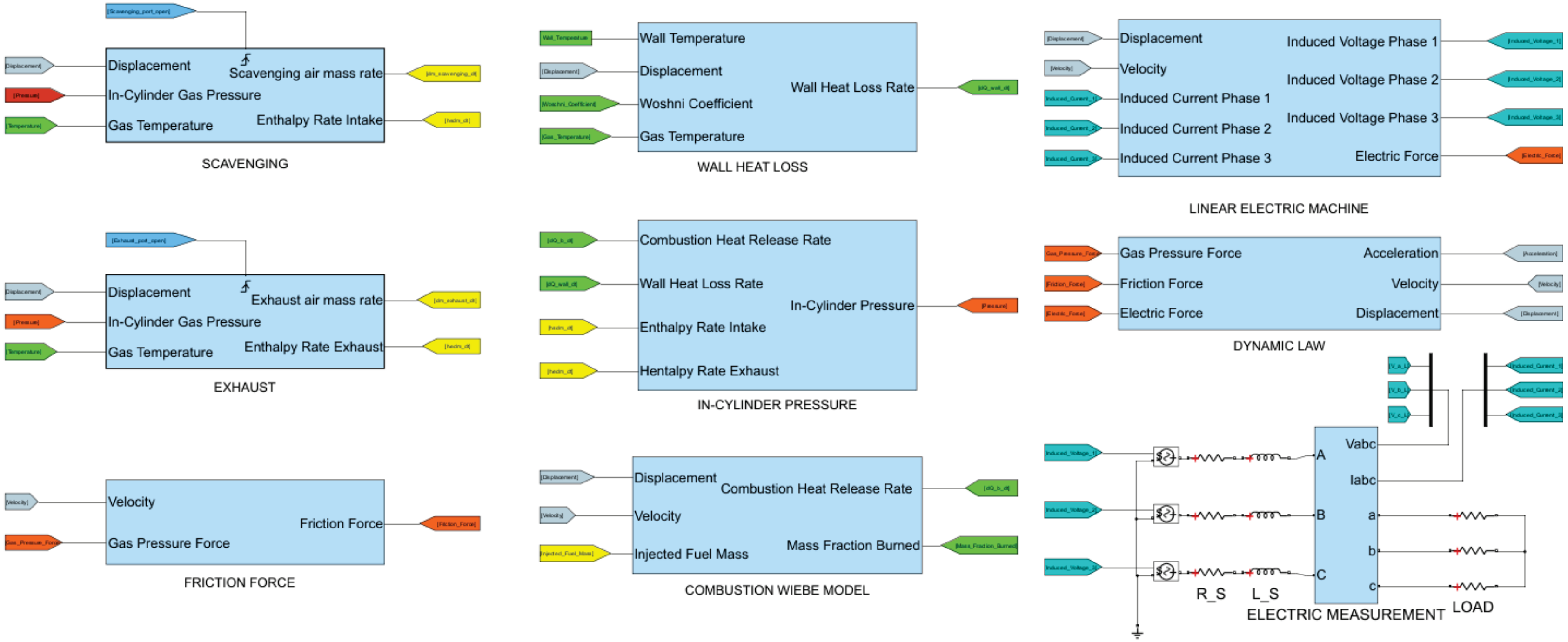
STEMS



PARAMETRS	VALUE
Fuel	Gasoline
Bore	56.5 mm
Stroke	49.5 mm
Nominal CR	12.5
Air-Fuel ratio	14.57
Combustion Duration	3e-3 s
Combustion Efficiency	0.9

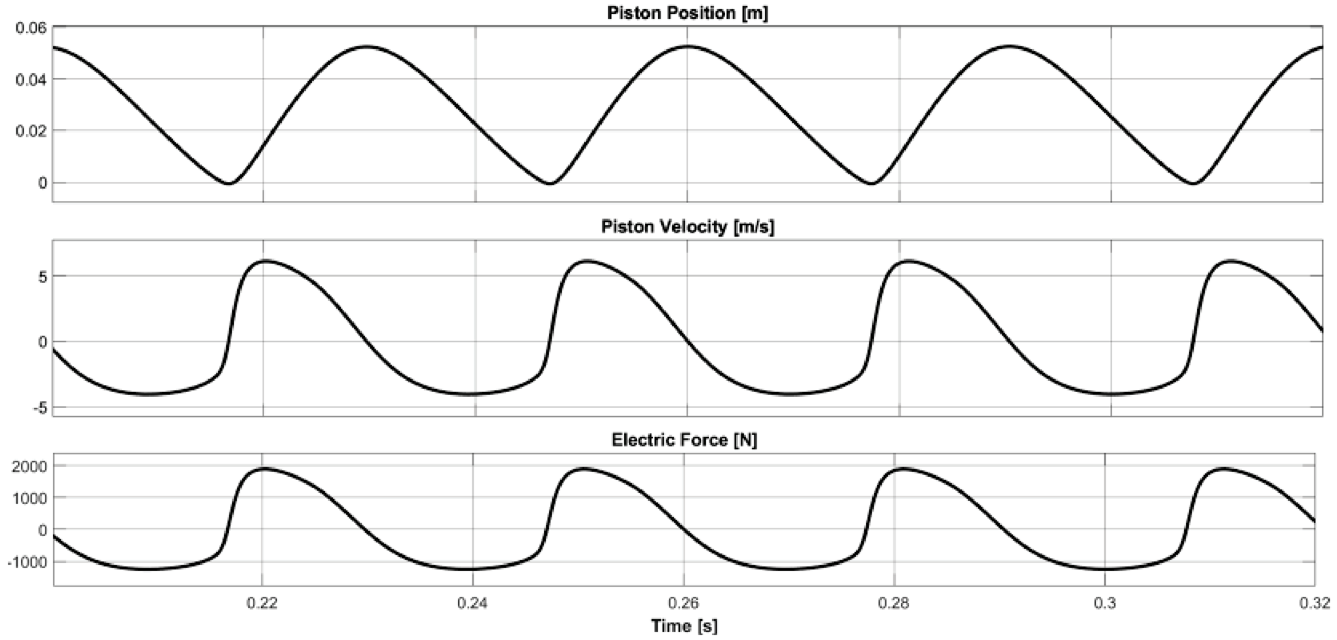


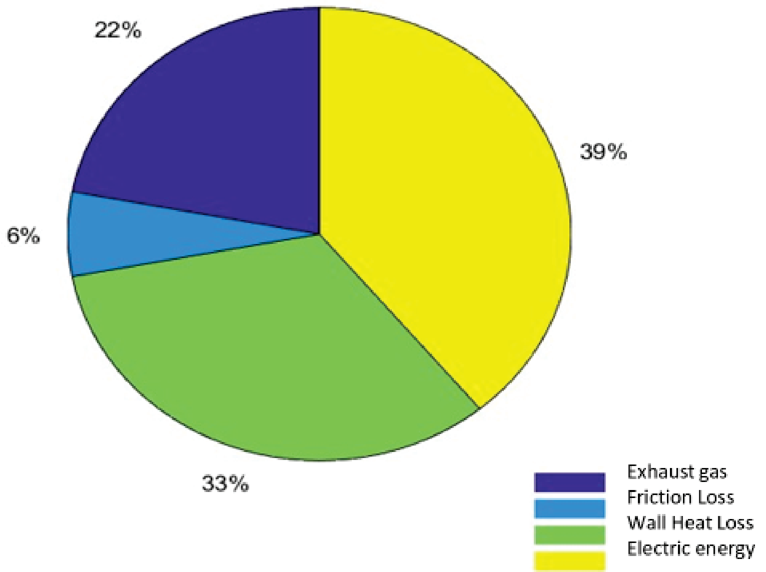
0D FPLG Matlab&Simulink Model And Main Parameters

By developing a 0D model in a simulink environment, we tried to evaluate the overall efficiency of the technology for an 'Opposed Piston' application

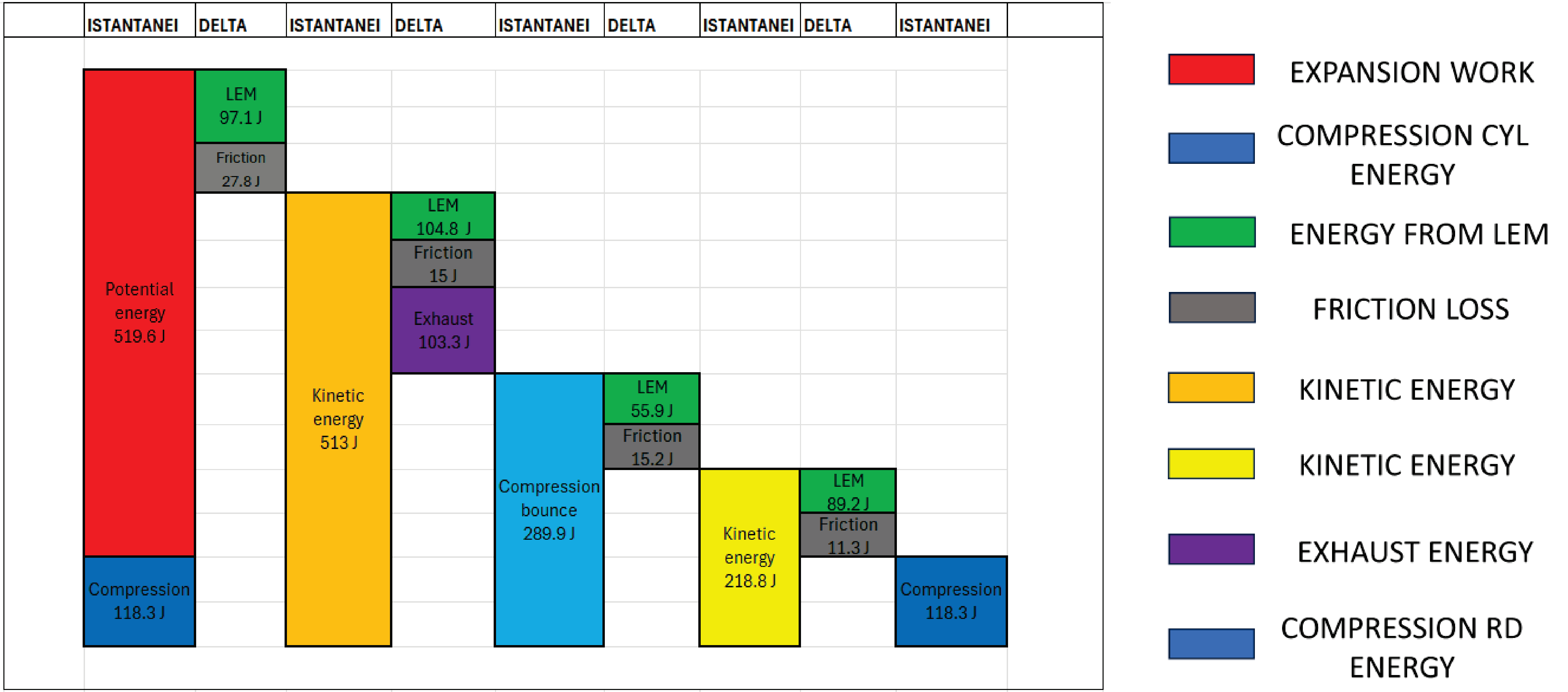
In order to simulate correct operating condition, the following sub-models have been modelled: combustion, scavenging process, friction loss, heat wall loss, linear electric machine

The net electric global efficiency reached is about 40 % and this value can be improved upon with the support of 1D 3D simulation tools, thanks to which the thermofluid-dynamic processes involved in the cycle will be refined





0D FPLG Matlab&Simulink Model Results



0D FPLG Matlab&simulink Model Results

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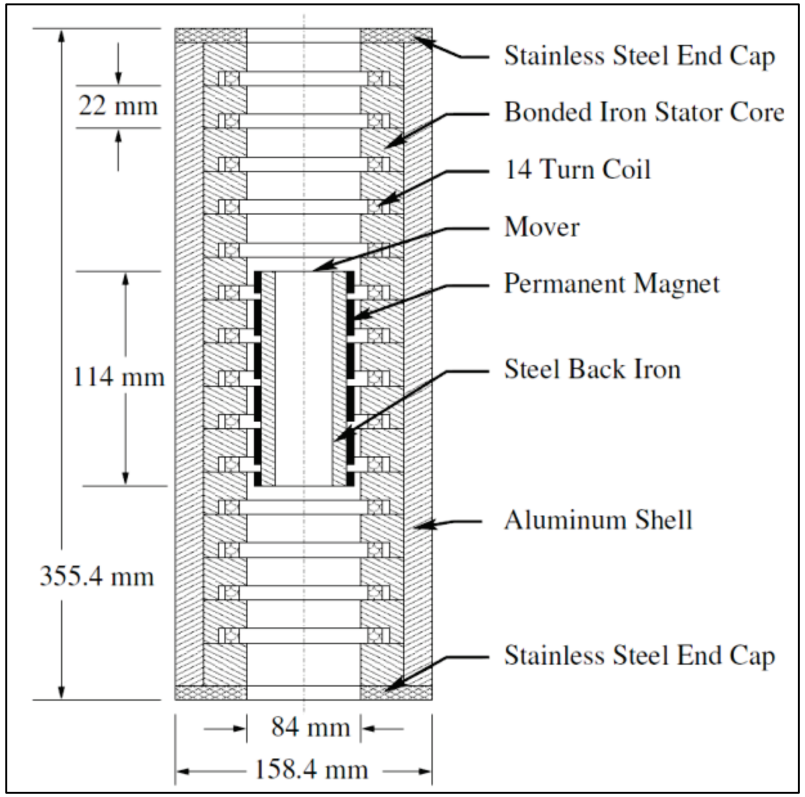
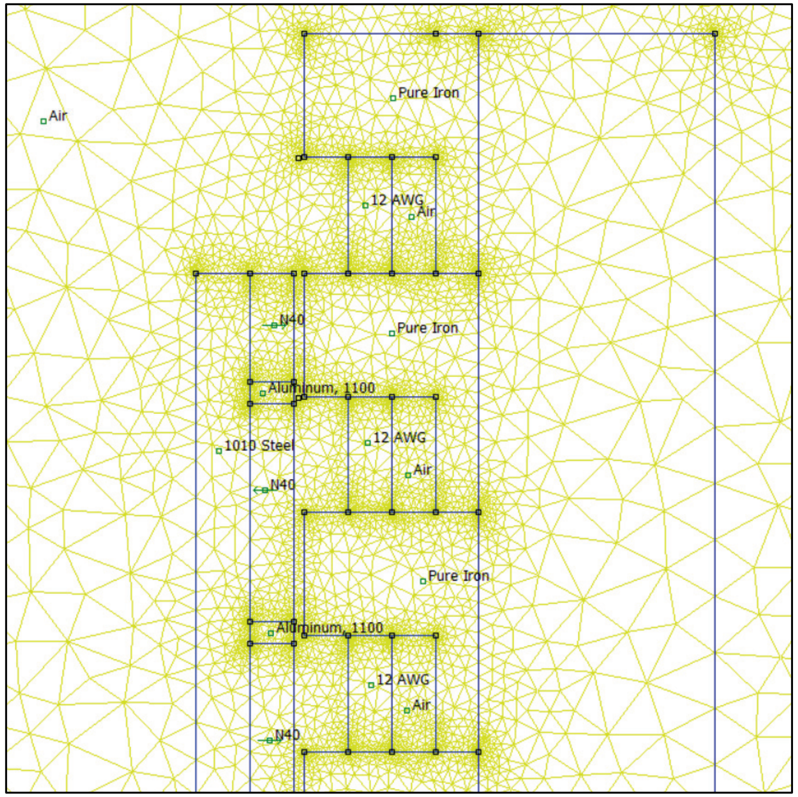
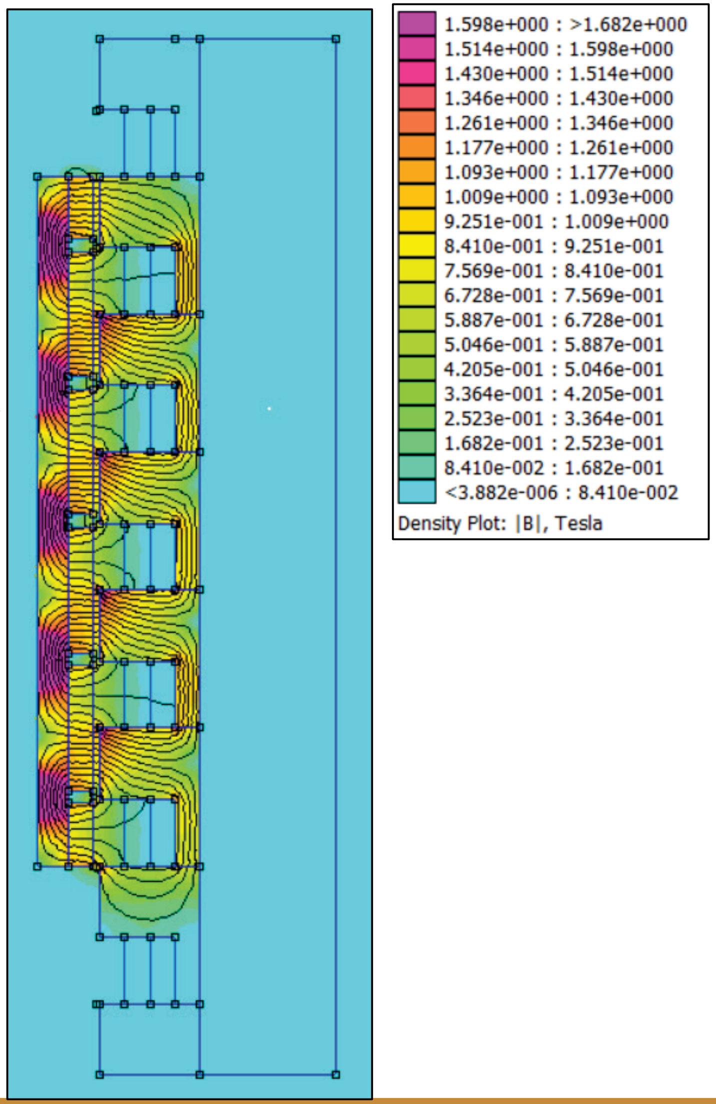






Università degli Studi della Campania *Luigi Vanvitelli*

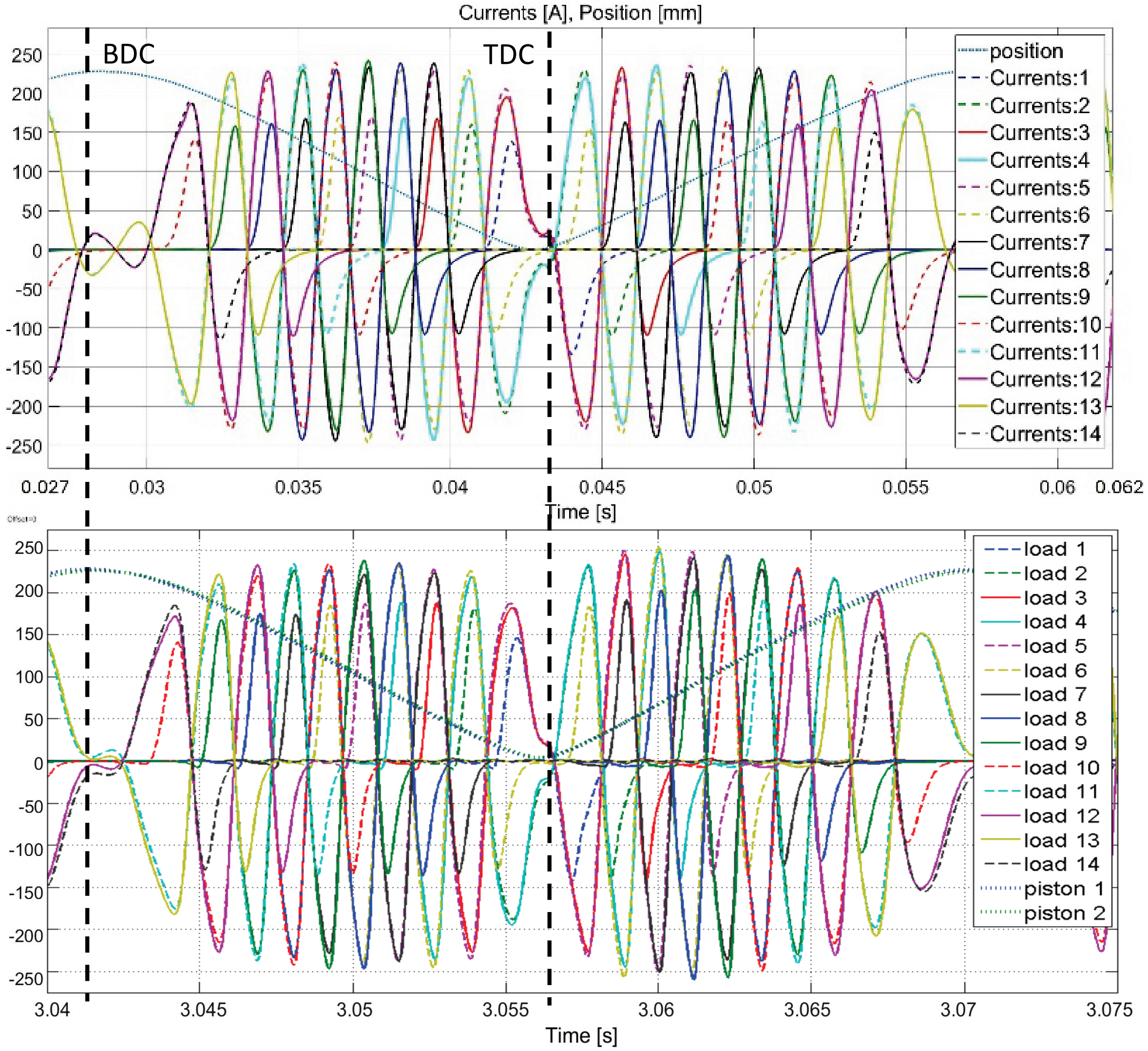
UNIVERSITÀ DEGLI STUDI DEL SANNIO
Benevento

[1] SAE Technical Paper 2016-01-0677, 2016.

SANDIA Permanent Magnet Linear Generator Prototype (PMLG)

FEMM/Simulink simulation

Experimental SANDIA Results



Model/Experimantal Results Comparison

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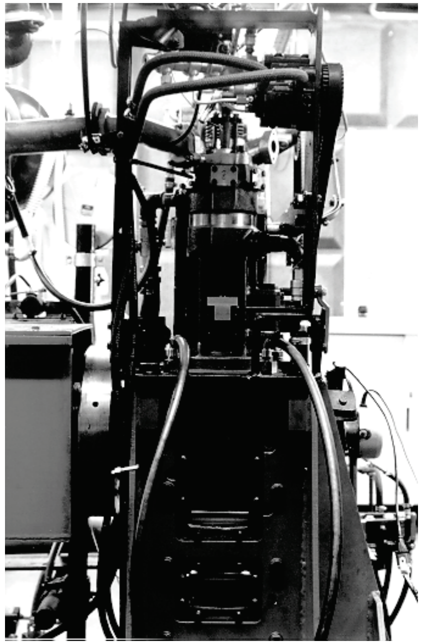
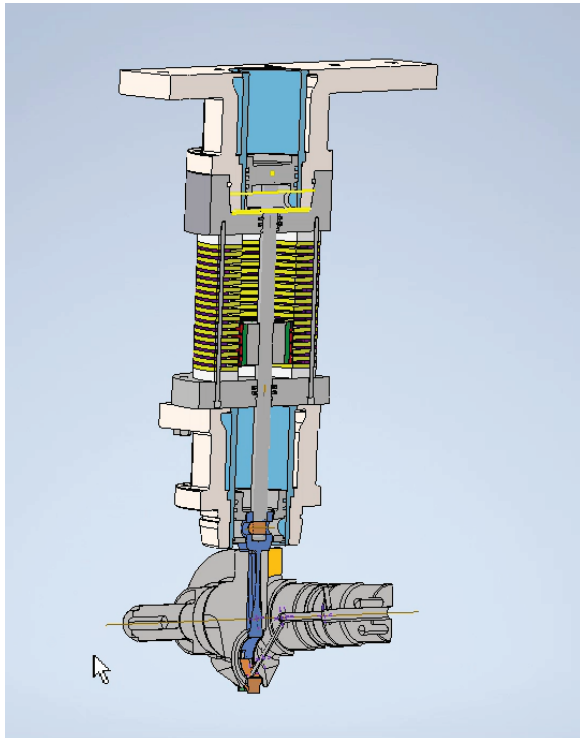
Current SCE



Updated SCE with axial generator



To design and validate the ax-GEN, a SCE will be exploited.

This process will be crucial for the characterization of the waveforms (induced voltages and currents) generated by the ax-GEN and its validation.

BEING AHEAD STO

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STEMS

This study has been partially carried out within the **MOST – Sustainable Mobility Center** and received funding from the **European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR)** – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1033 17/06/2022, CN00000023).

This study has been also partially carried out within the project "**FLEXi-fuel high-efficiency linear piston engine for future power GENerators (FLEX-GEN)**" funded by **MUR** within the "Fondo per il Programma Nazionale di Ricerca e Progetti di Rilevante Interesse Nazionale (PRIN)"**PRIN 2022", project number PRIN 2022 2022988F33_PE8**.

This study has been also partially carried out within the project "**HEFFYMAXGEN - High EFFiciency** hYdrogen Motor Axial GENerator

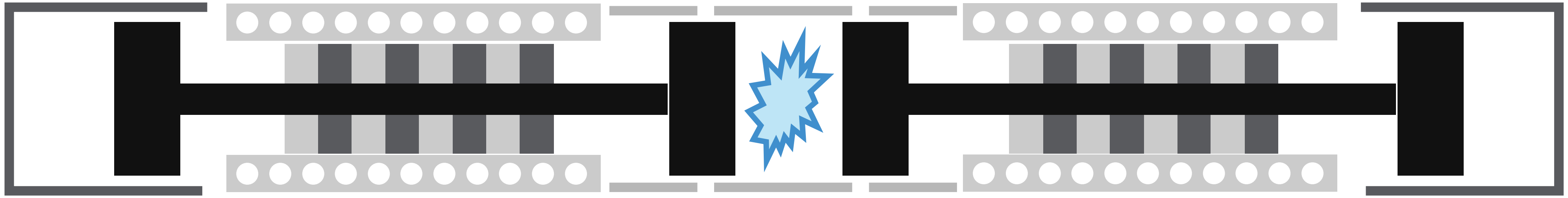
Finally, this study has been also partially carried out within the PhD research program of **Raffaele Saviano** carrying out within the **Industrial PhD program of University of Naples "Parthenope"** funded by the **MUR** and **STC Srl** through the Ministerial decree DM 117/2023. The PhD program received funding by **PNRR, Missione 4, Componente 2, Investimento 3.3**.

Aknowledgements

The Flex-Gen project

FPLG characterization and potential assessment via 1D modeling

Mirko Baratta – Politecnico di Torino



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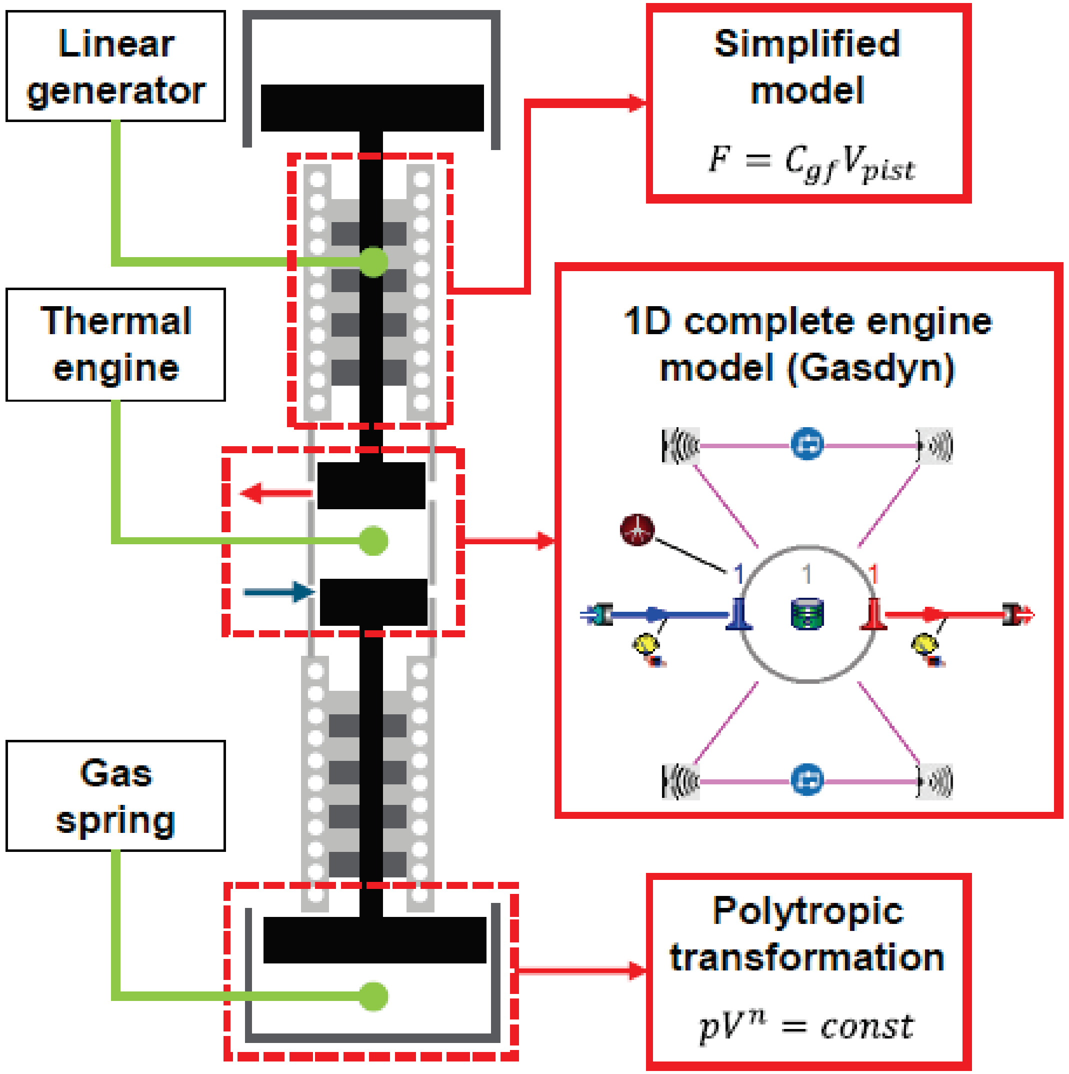
Acknowledgement

POLITO team

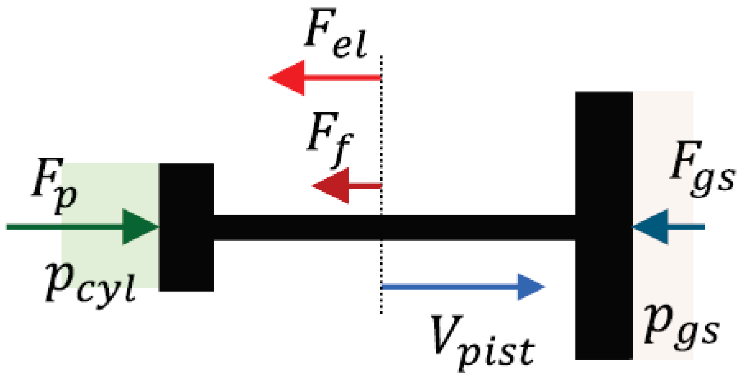
- Mirko Baratta
- Daniela Misul
- Alex Scopelliti
- Fabrizio Santonocito
- Antonella Accardo

The work



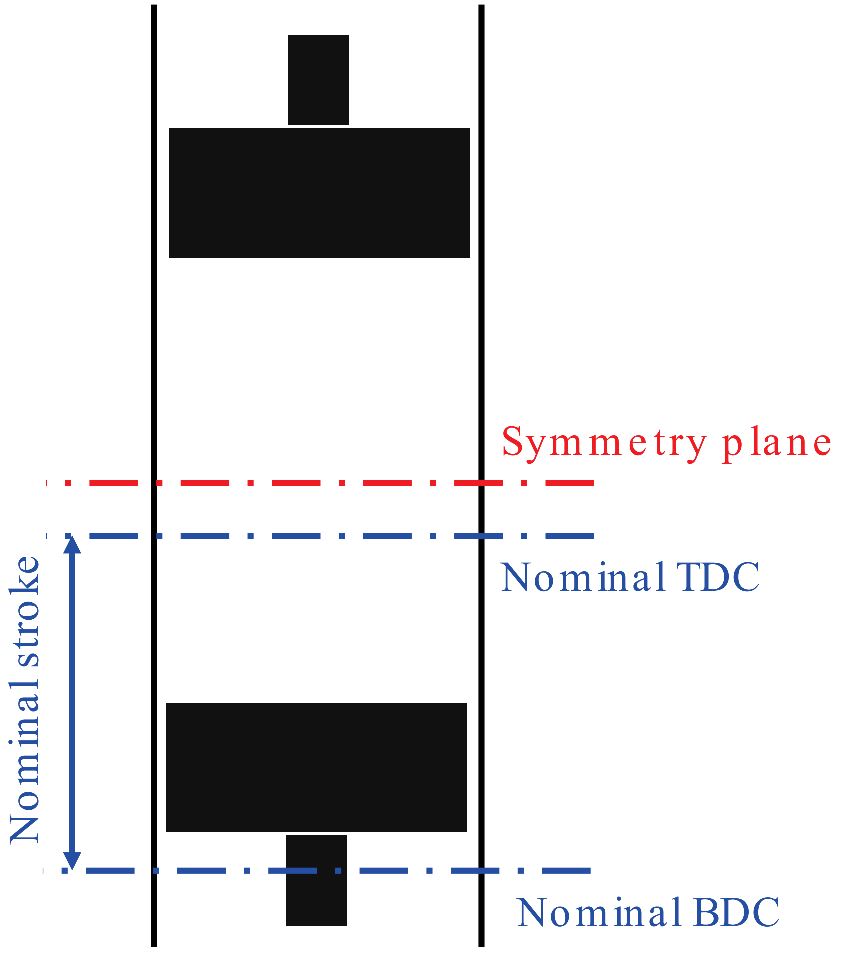
Integration of

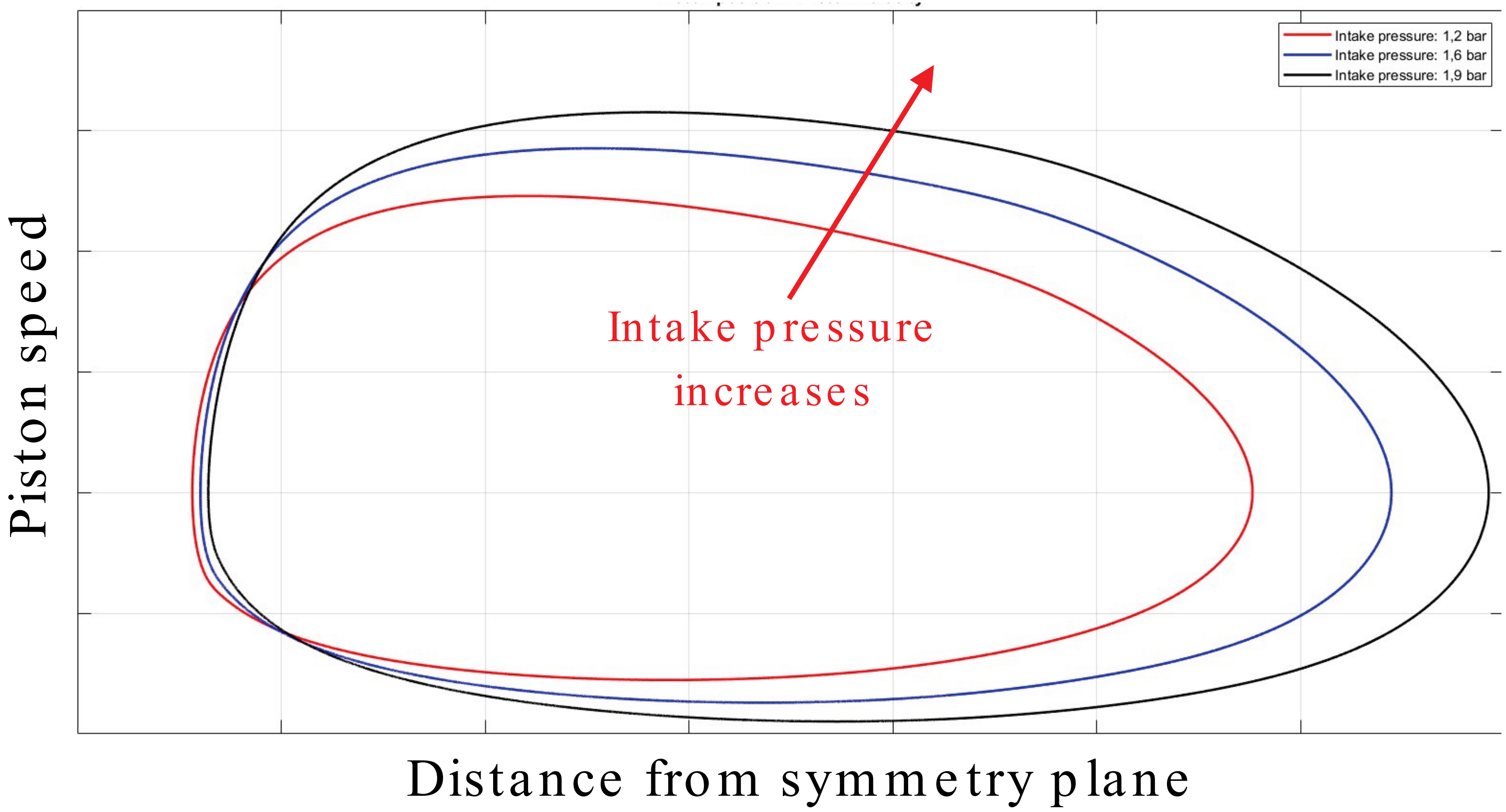
- 1-D modeling of intake/exhaust pipes and scavenging
- 0-D modeling of in-cylinder thermodynamics
- Piston dynamics



‘Free system’ behaviour

Effective TDC/BDC positions, stroke, CR, depend on operating variables!





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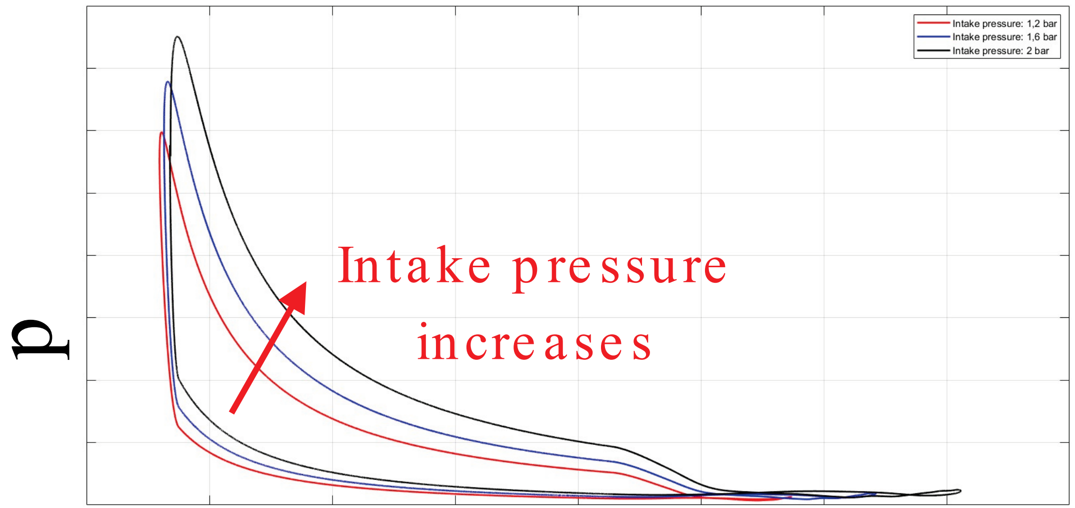
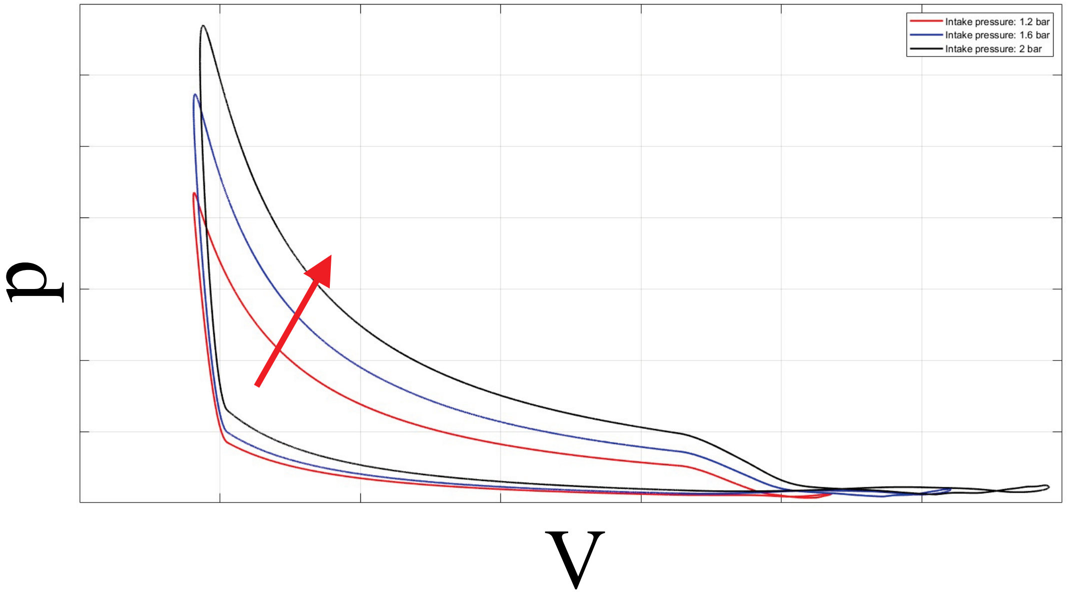
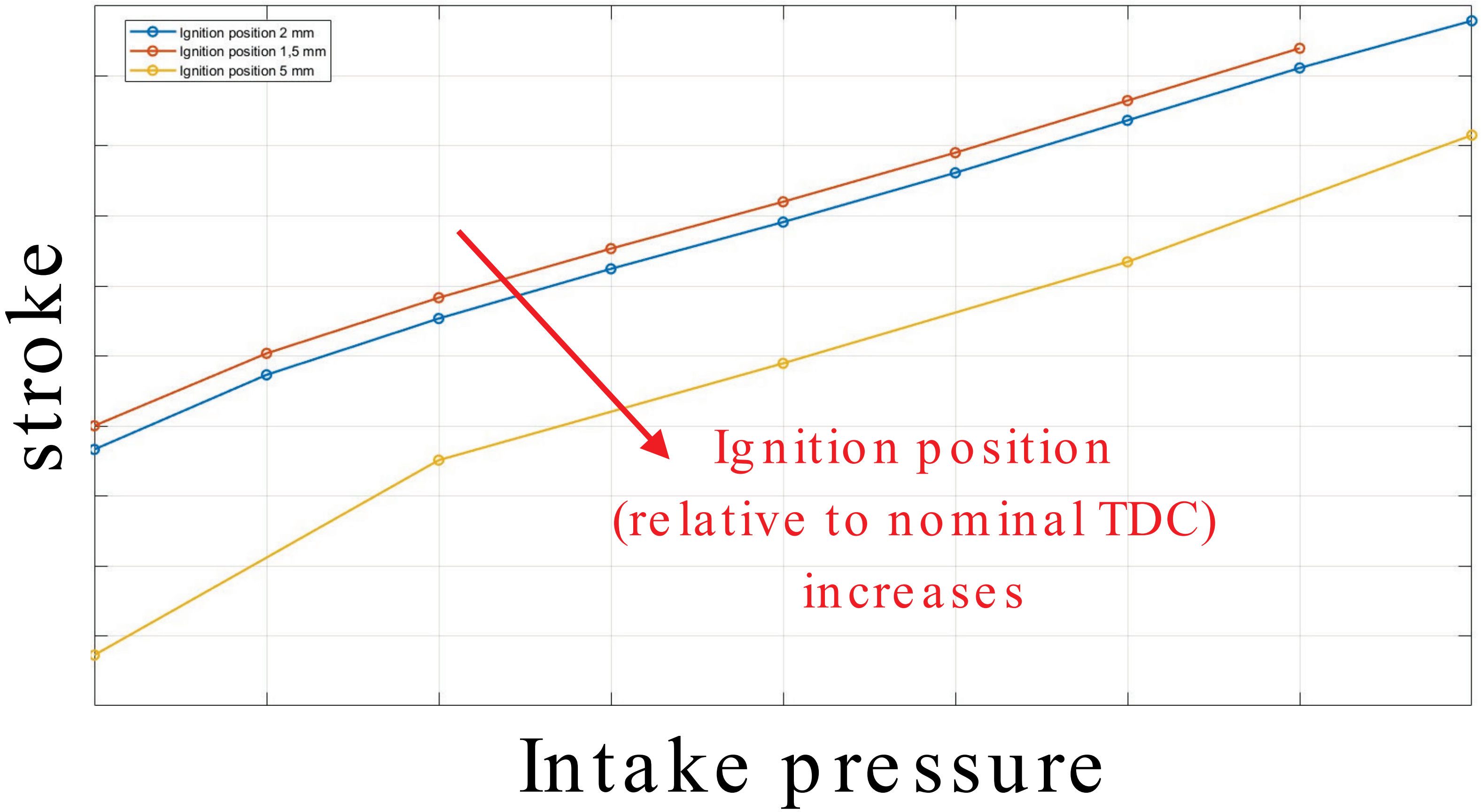
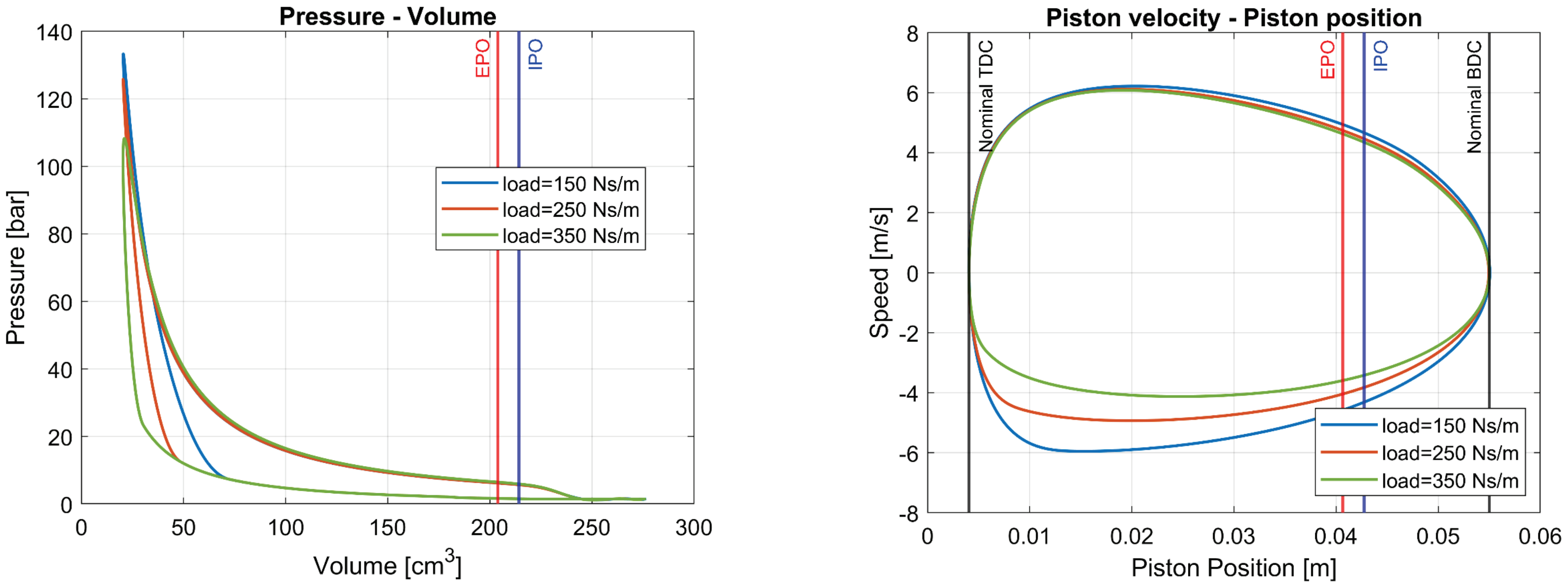






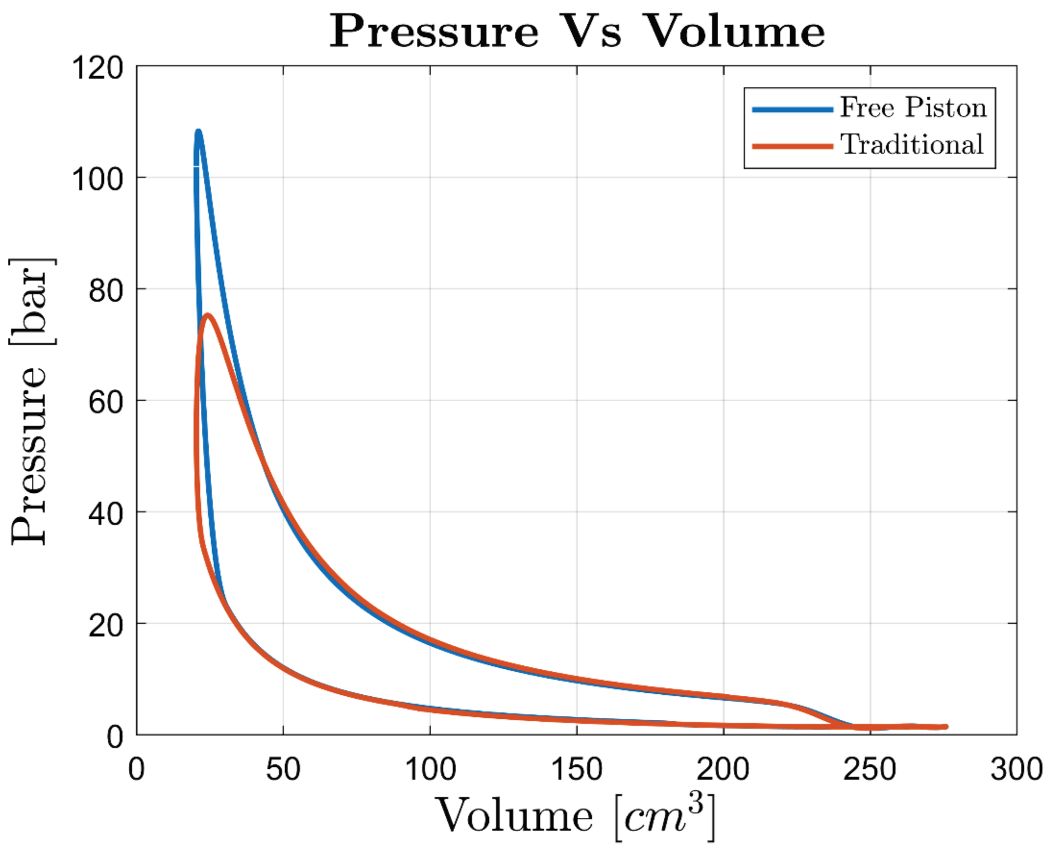
FPLG + controller

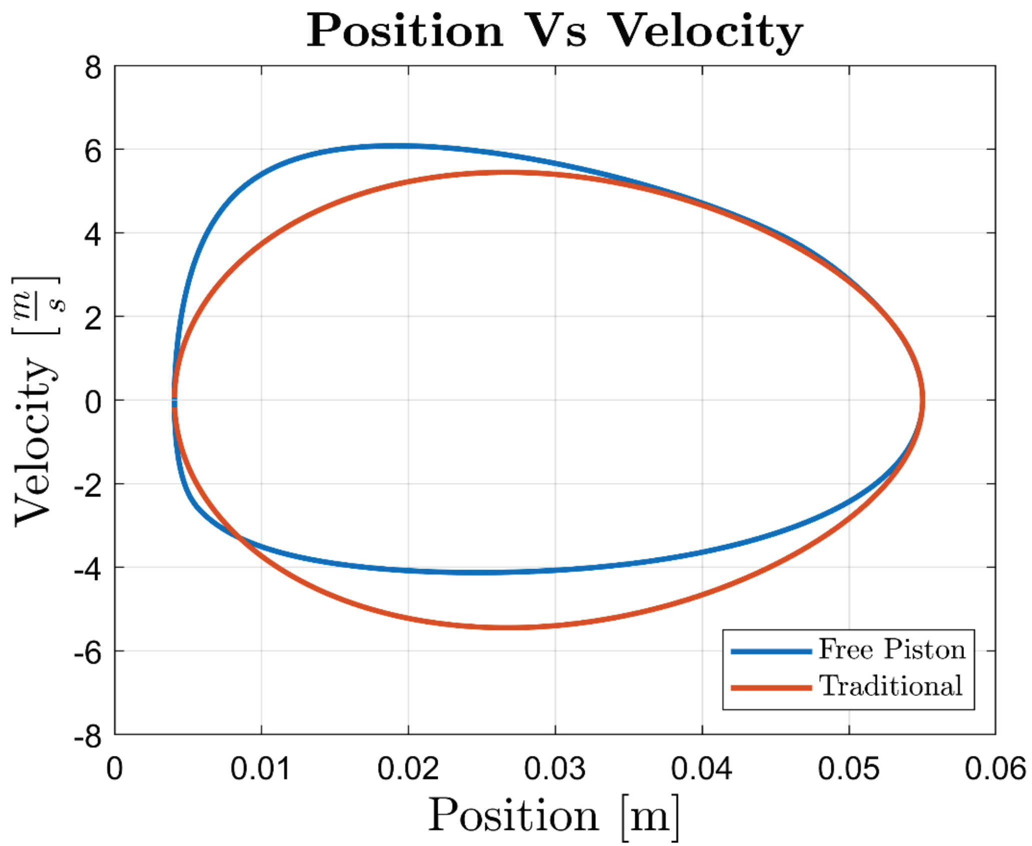
TDC and BDC positions controlled by acting on ignition position and gas spring pressure



- Increase in the generating load coefficient improves efficiency

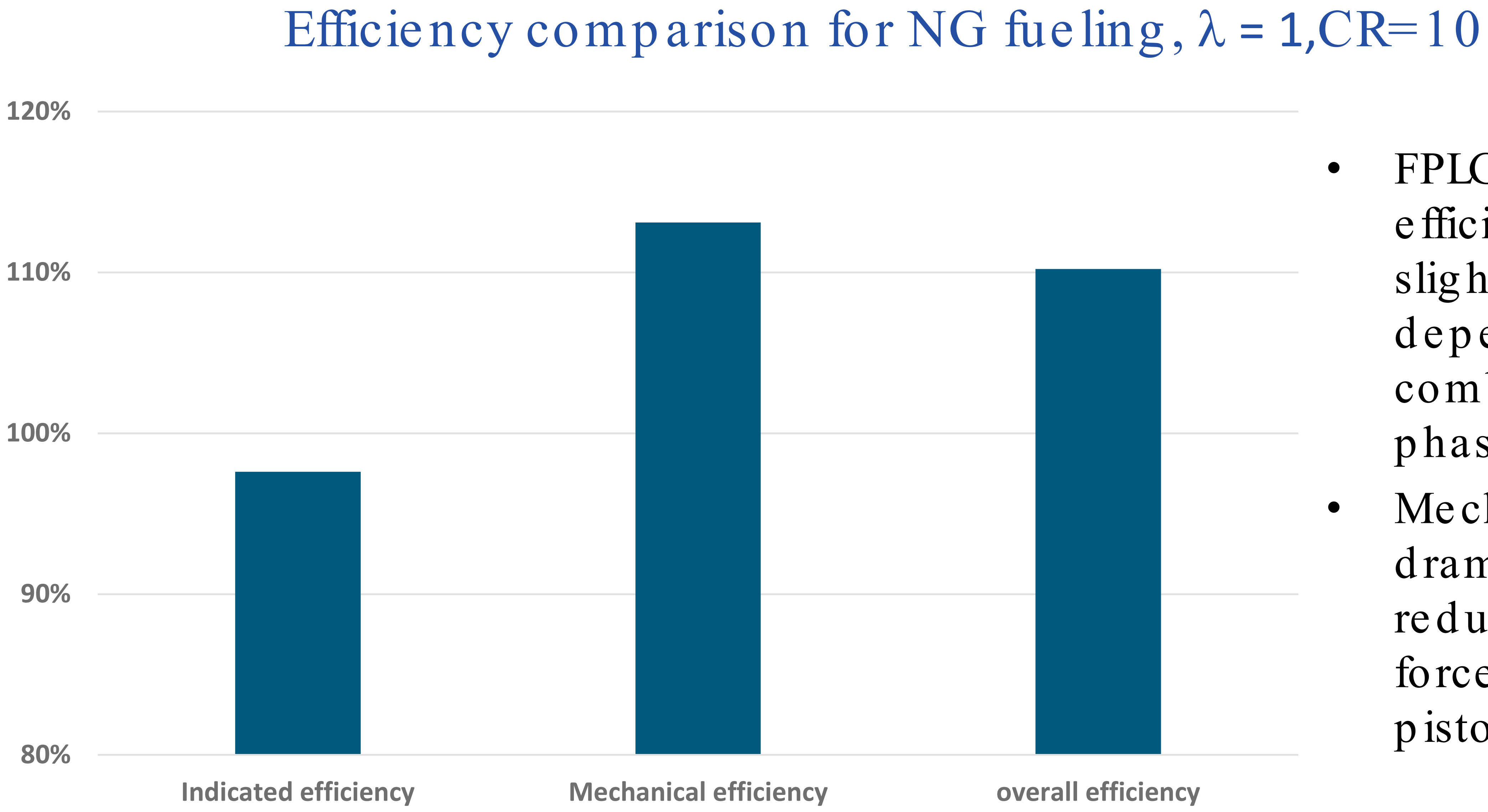
FPLG vs traditional SI engine





- Combustion timing:
  - Optimized for traditional engine (MBT)
  - Controls the engine CR for the free piston
- Faster expansion stroke in the FPLG, wrt compression

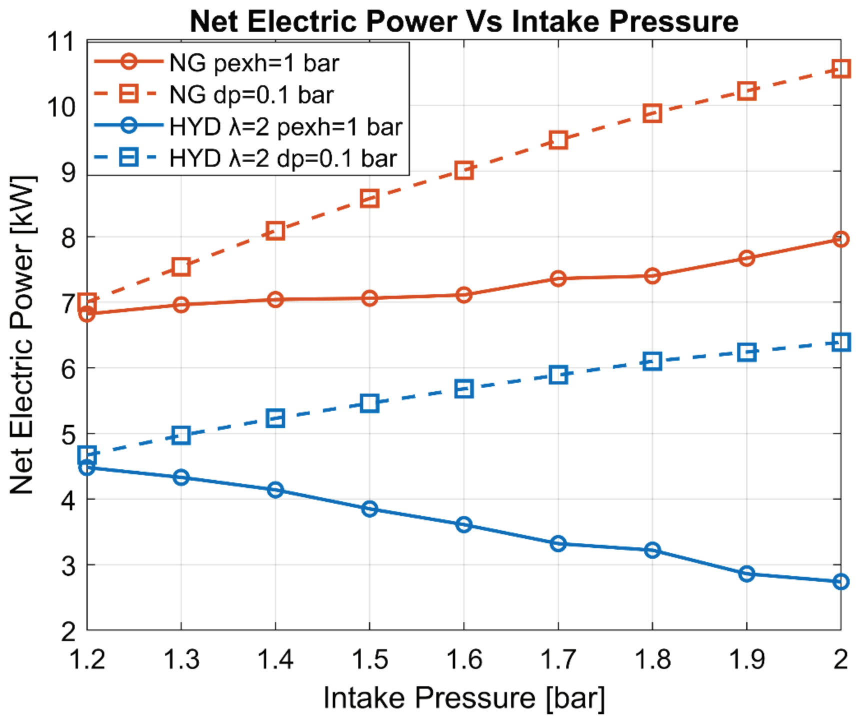
FPLG vs traditional SI engine

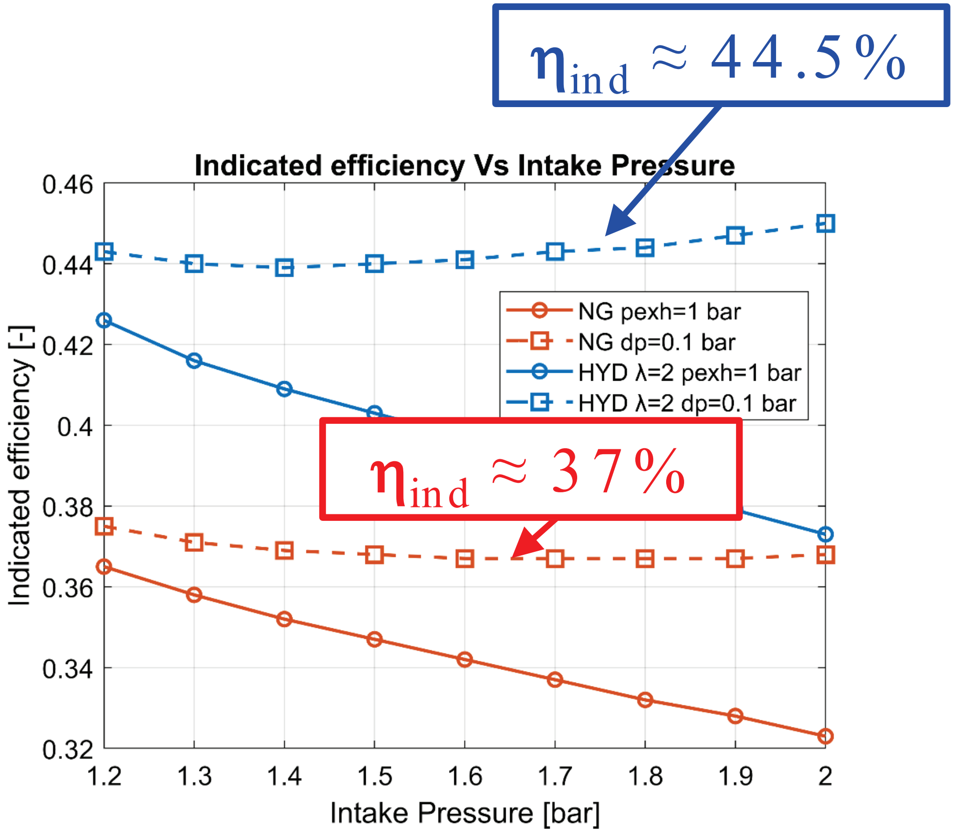


- FPLG indicated efficiency might be slightly lower, depending on combustion phasing
- Mechamical losses dramatically reduced (lack of forces normal to piston motion)

FPLG + controller

TDC and BDC positions controlled by acting on ignition position and gas spring pressure



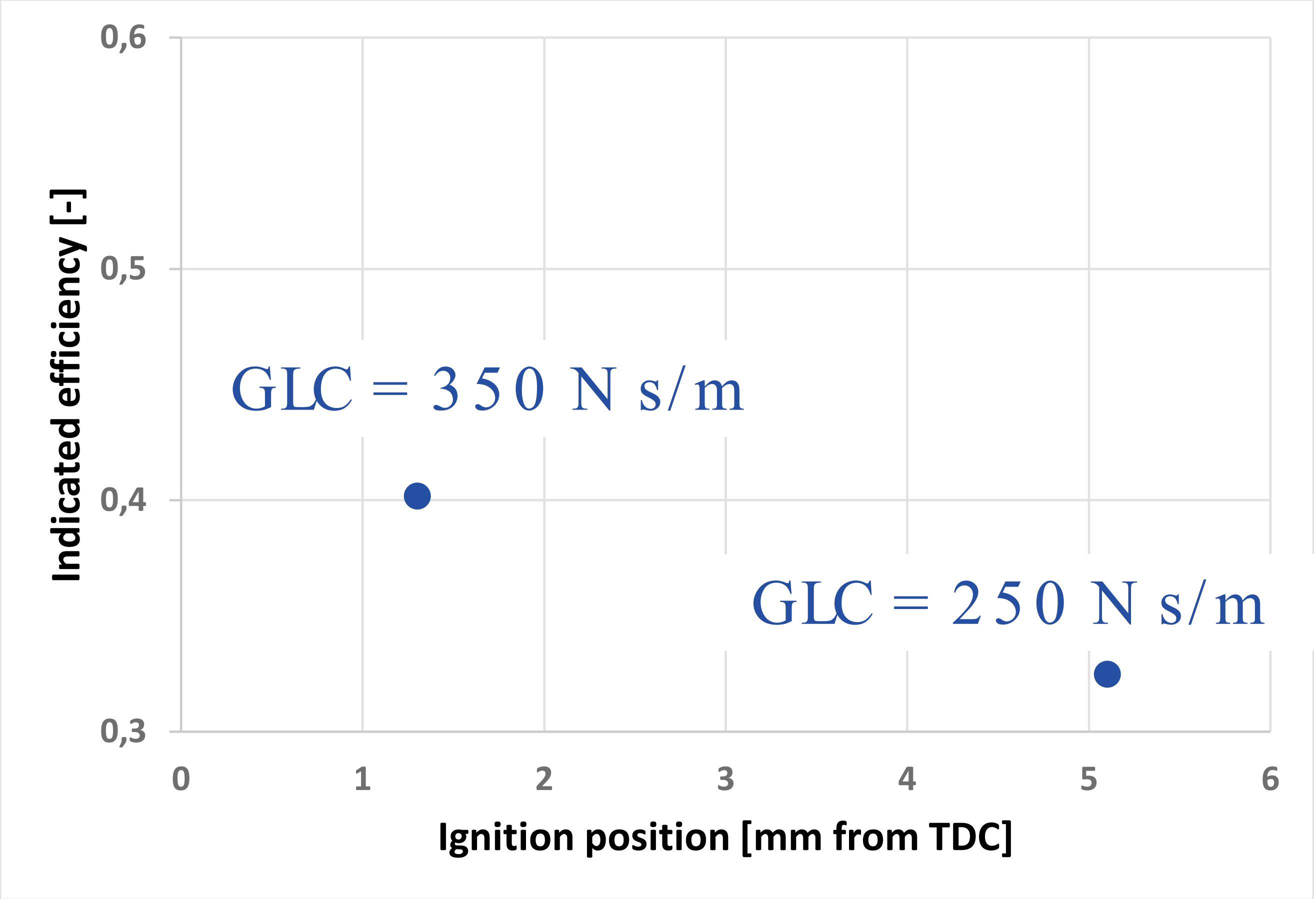


- Results for CR = 10
- GLC = 350 N s/m (NG, λ = 1), 250 N s/m (H2, λ = 2)

FPLG + controller

TDC and BDC positions controlled by acting on ignition position and gas spring pressure

Results for CR = 13 – NG - λ = 1

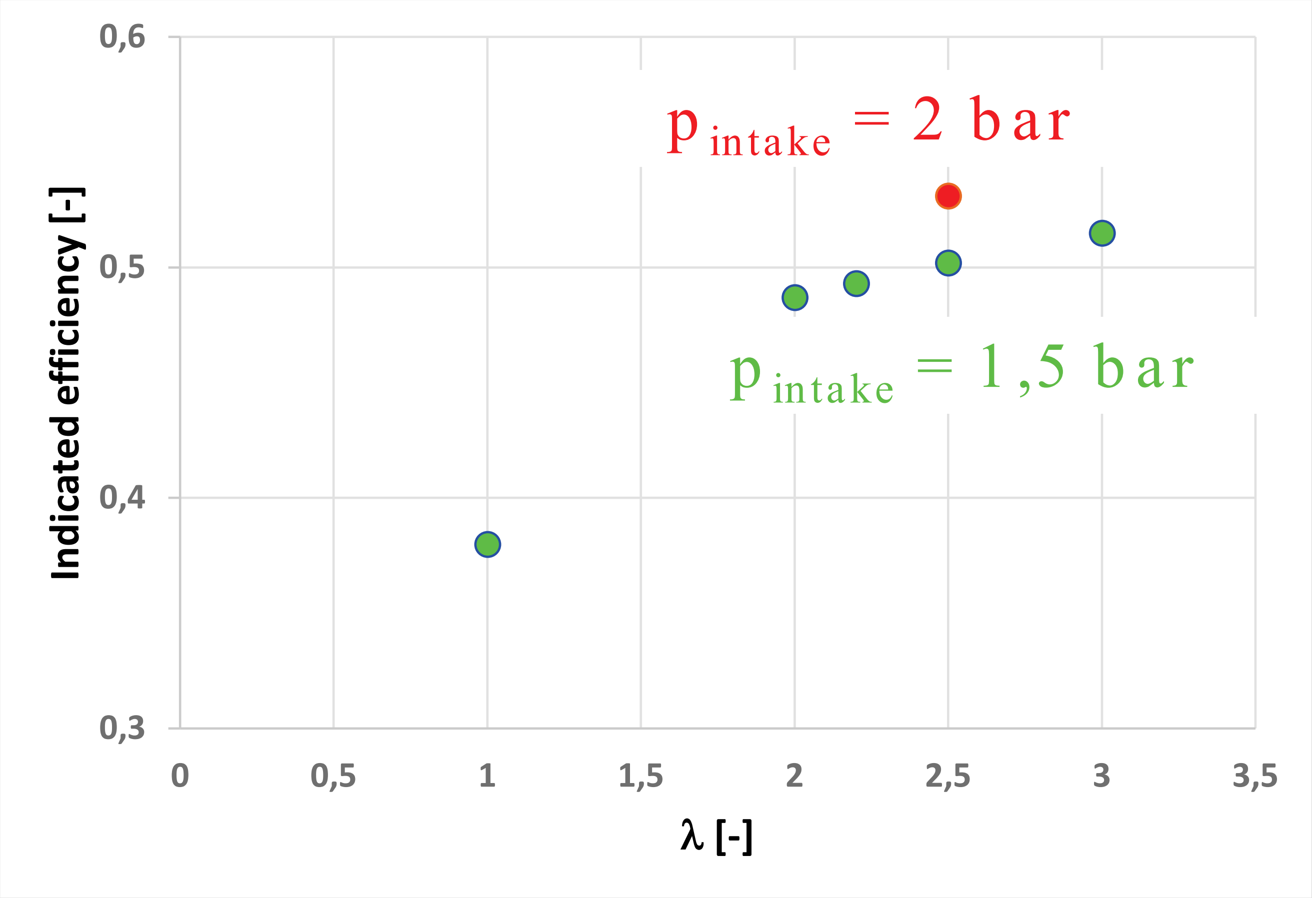


- Efficiency could be further increased by maximizing the load, so as to reduce the ignition position (optimal phasing)
- Lean mixtures also increase the efficiency due to reduced heat losses
- Higher PFP limits -> ground for CR increase for lean mixtures

FPLG + controller

TDC and BDC positions controlled by acting on ignition position and gas spring pressure

Results for CR = 13, H_2 fueling



- The efficiency is reported here for the maximum load at each lambda
- 53% of efficiency has been found for lambda = 2.5 and p_{intake} = 2 bar.

Conclusion and future perspectives

- The activity in the Flex-Gen project highlighted the peculiar behaviour of the FPLG concept
- Optimization process, workflow and independent variables had to be redefined
- The integrated dynamic/thermodynamic/gasdynamic approach represented a key factor within the new optimization process
- Further research work is necessary to consolidate and validate the approach -> prototype and experimental tests
- Lean combustion, HCCI or high-CR SI combustion represent the most promising technology ways for a very high efficiency

Thank you!

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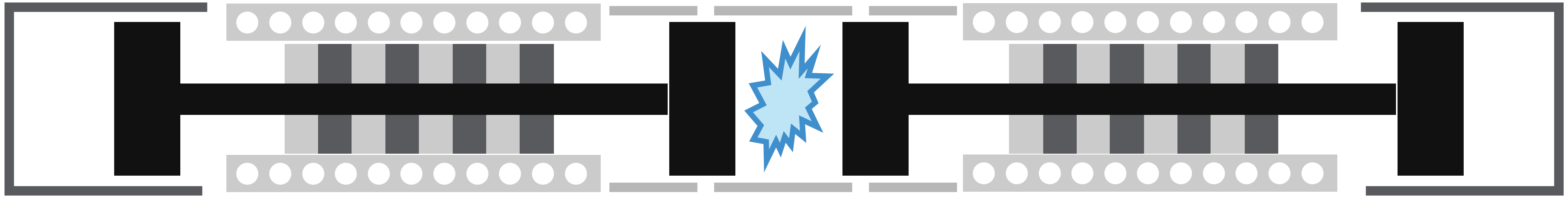
LinkedIn

The Flex-Gen project

FPLG >50% efficiency with HCCI combustion and alternative fuels

Tommaso Lucchini – Politecnico di Milano



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Acknowledgments

- Giovanni Gaetano Gianetti
- Nicola Morandi
- Matteo Ferrarini

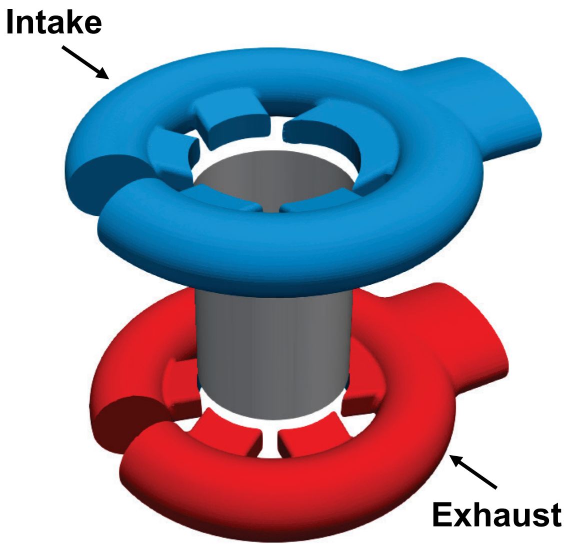
Topics

- Assessment of a multi-fuel, high-efficiency FPLG for power generation
- Opposed piston configuration
- Fuels: (bio)methane and H_2
- Low temperature combustion (HCCI)

Polimi Flex-Gen activities

CFD study of gas exchange and combustion in FPLG geometries

SI-FPLG: mobility



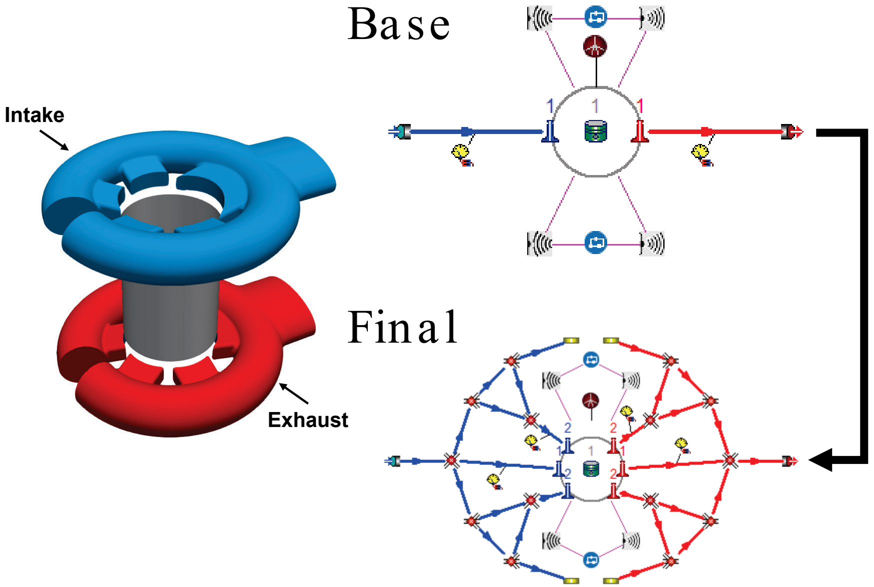
Target: 10-20 kW
SI stoichiometric combustion with tumble flow
Low-Pressure direct-injection
Bore: 56.5 mm
Stroke: 49 mm
Compression ratio: 12

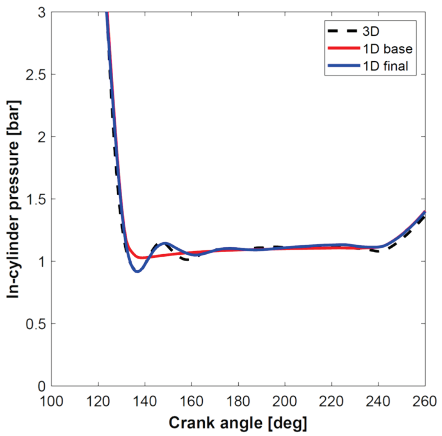
HCCI-FPLG: power generation

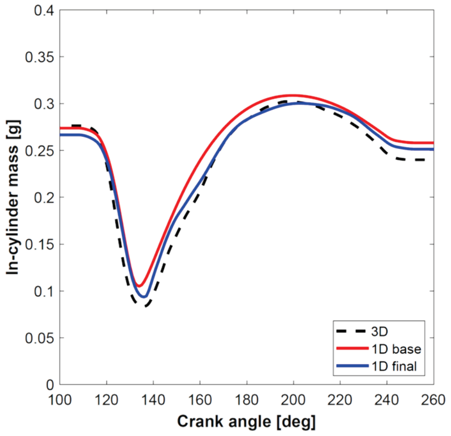
Target: 40-60 kW
HCCI ultra-lean combustion
Port-fuel injection (gas from the grid)
Bore: 80 mm
Stroke: 450 mm
Extreme compression ratio

SI-FPLG

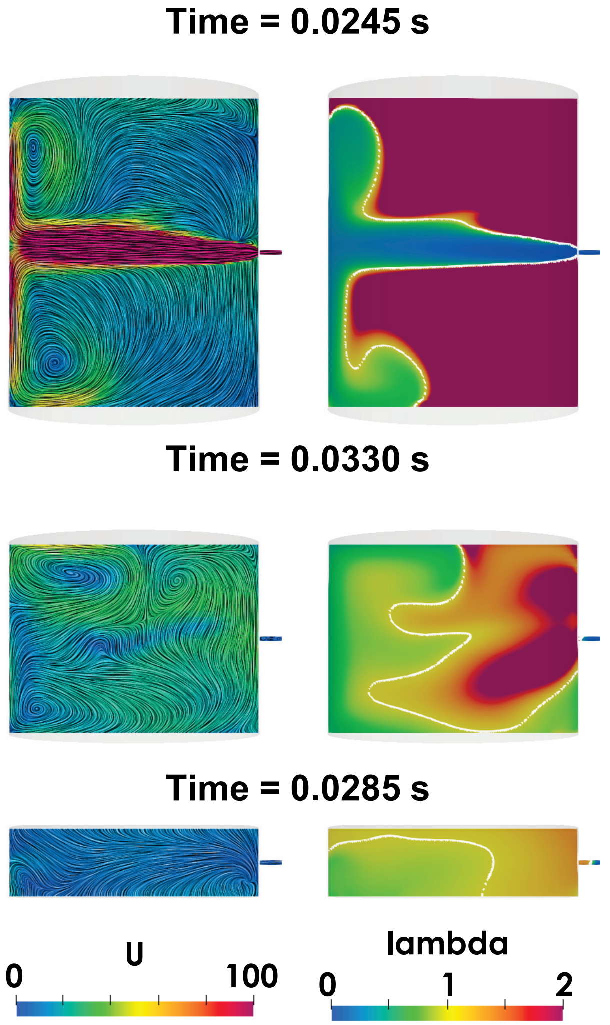
1D realistic schematic definition with CFD simulation results



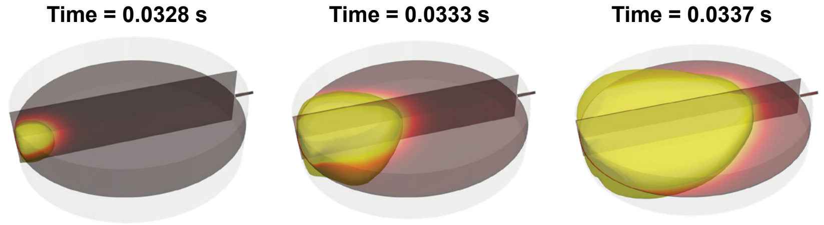




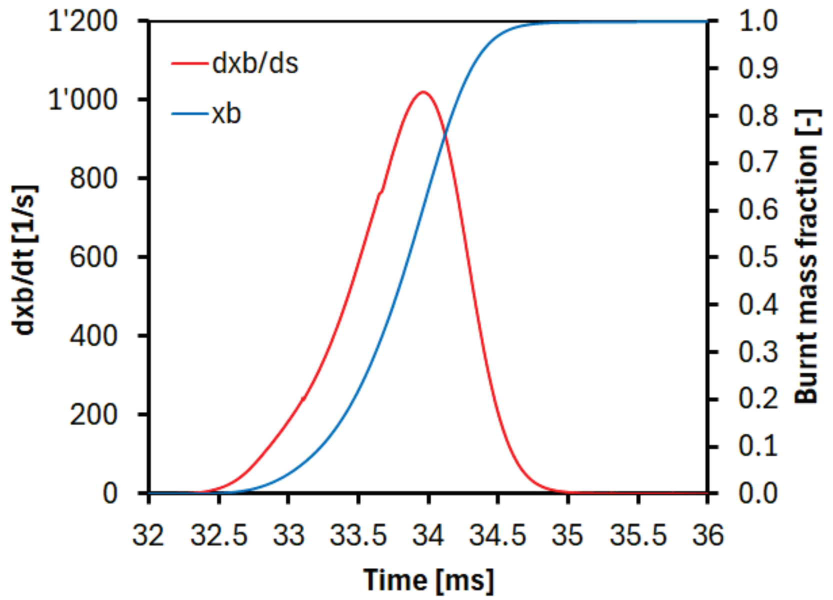
Understanding charge motions and fuel-air mixing



Combustion simulations



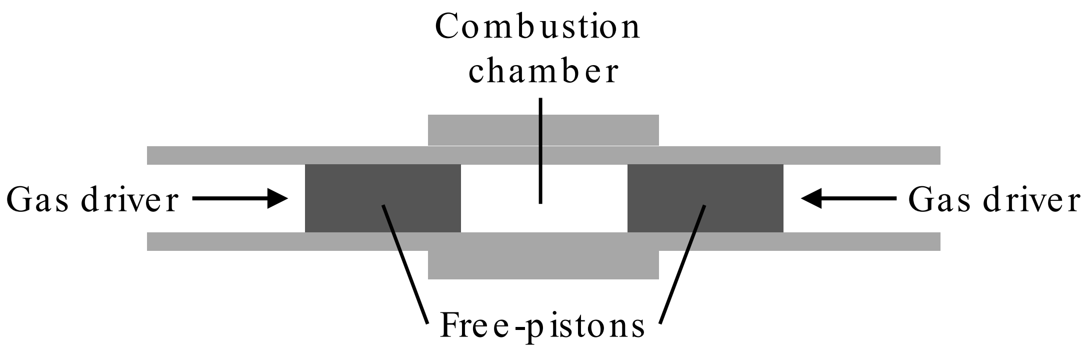
CFD computed burned mass fraction unconventional profile used in 1D simulations



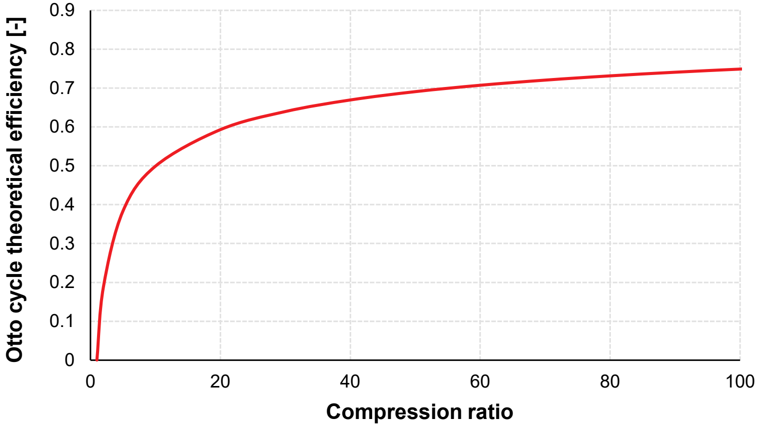
How to maximize the efficiency of an IC engine?

Svreck (2011) Exploration of Combustion Strategies for High-Efficiency, Extreme Compression Engines

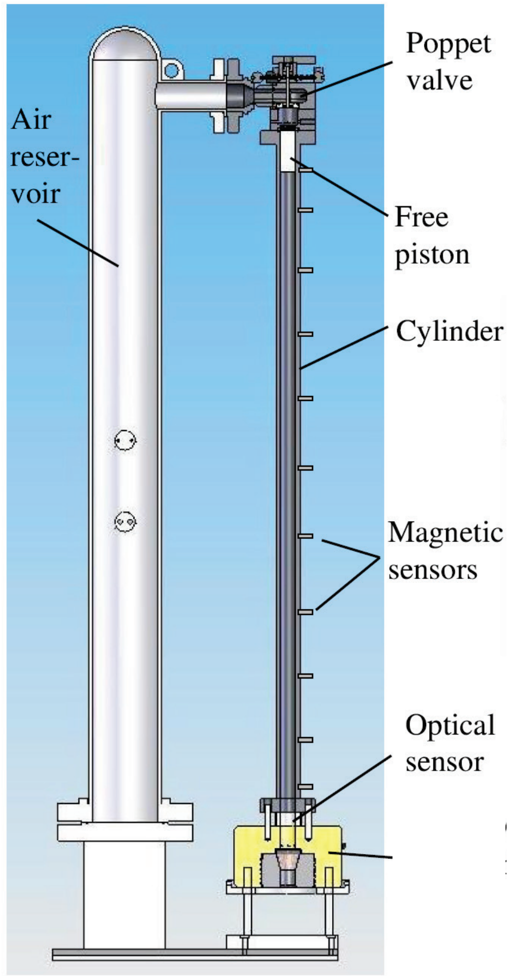
Opposed free-piston configuration



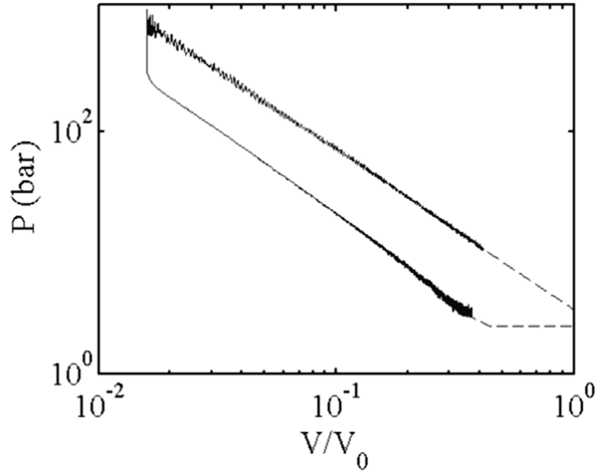
HCCI combustion with extreme compression ratio (>50)



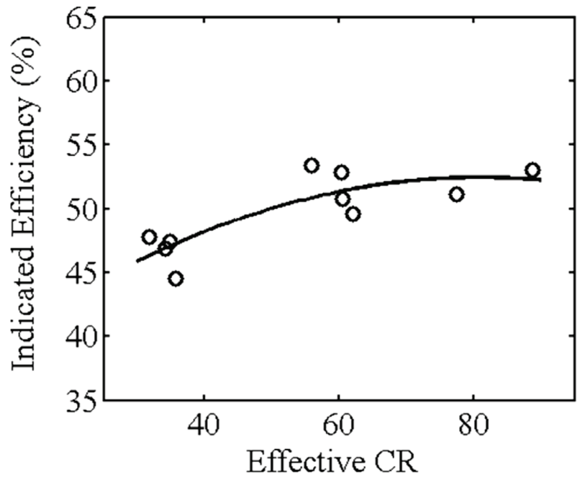
Rapid compression machine (RCM)



Extrapolated cycle from experiment

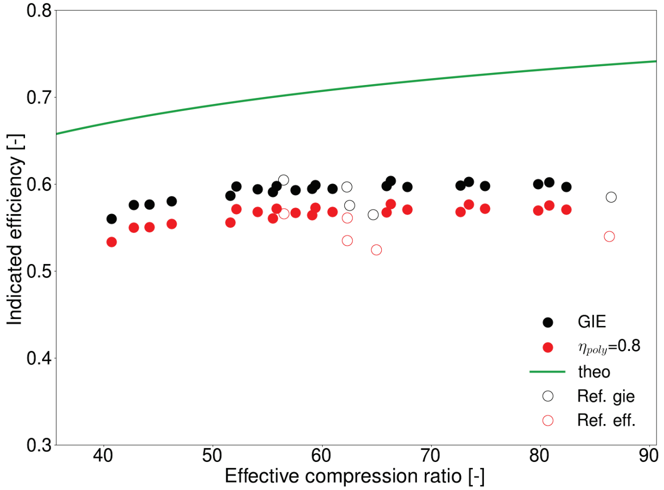


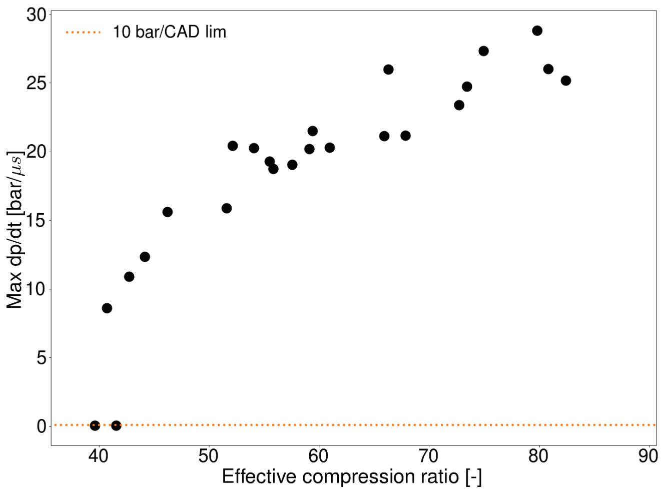
Measured indicated efficiency (CH_4, $\boldsymbol{\phi} = \mathbf{1}$)



CFD simulations: from RCM to CH_4-FPLG

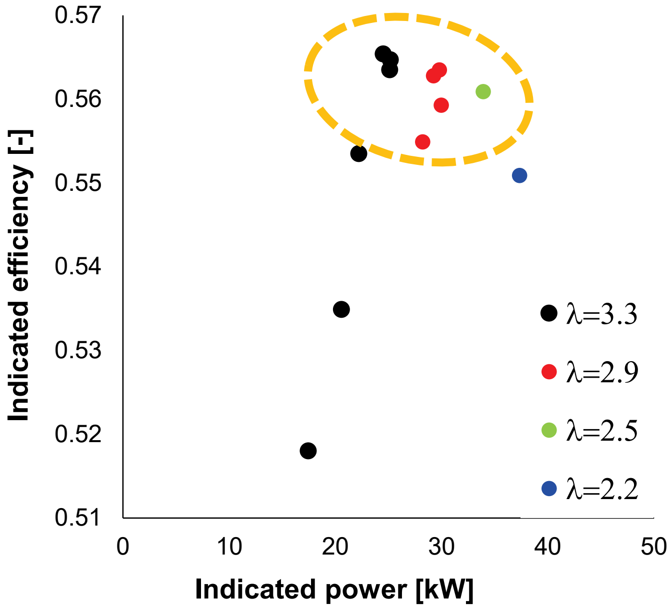
RCM Experiment CFD validation (CH_4, $\lambda = 1$)





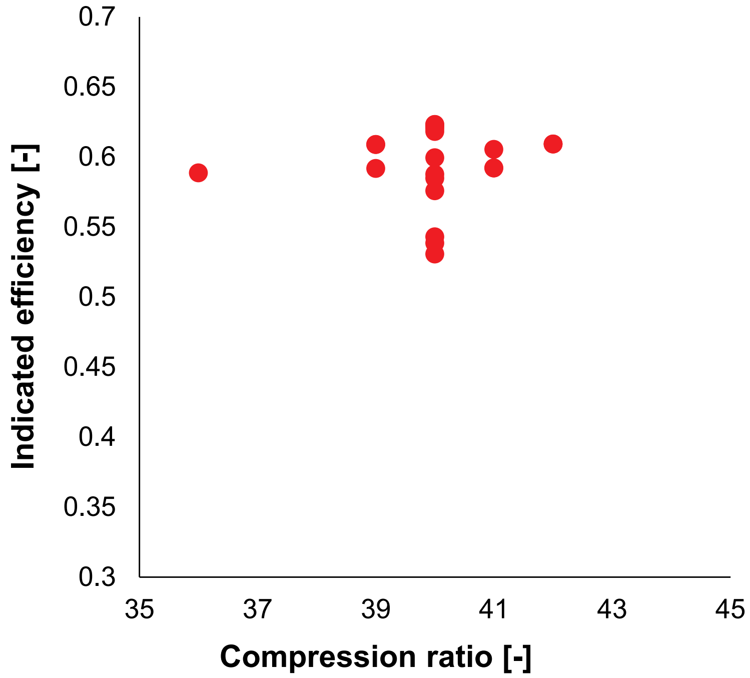
RCM Simulations (CH_4,lean)

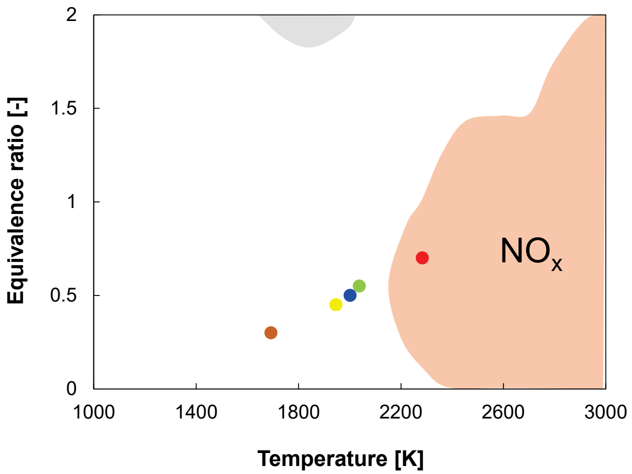
- Original RCM geometry
- Max dp/dt limited to ~10 MPa/ms to avoid knock
- Bore = 50 mm
- Stroke = 1700 mm

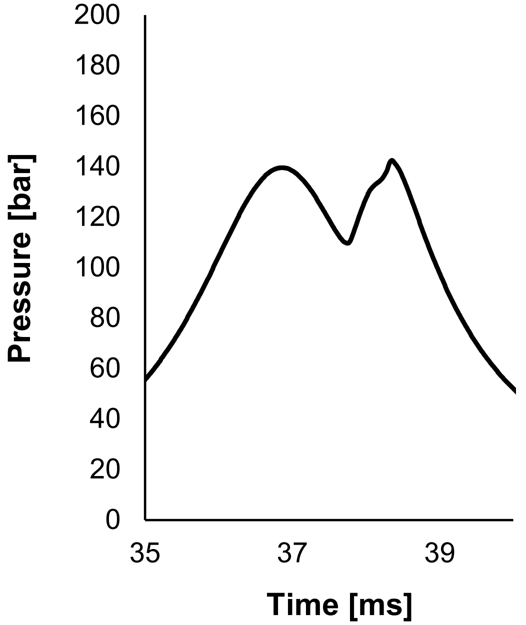


RCM engine-like geometry (CH_4,lean)

- Bore = 80 mm
- Stroke = 400-600 mm
- Variable pressure in the gas spring
- Piston mass: 10 kg
- $\lambda = 1.5 - 3.3$



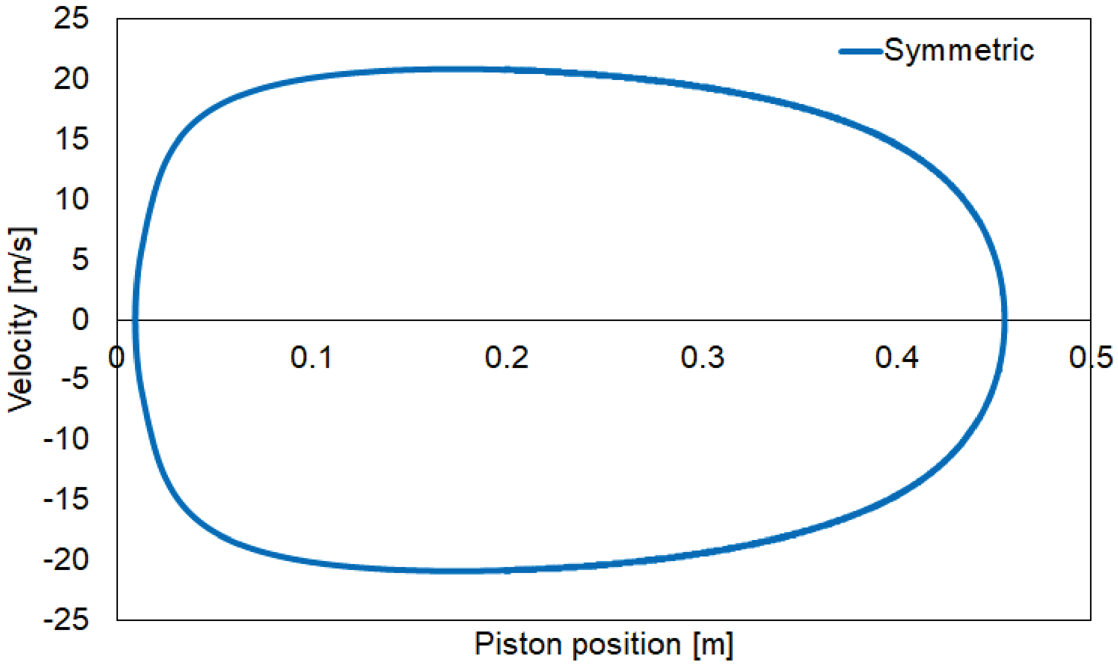


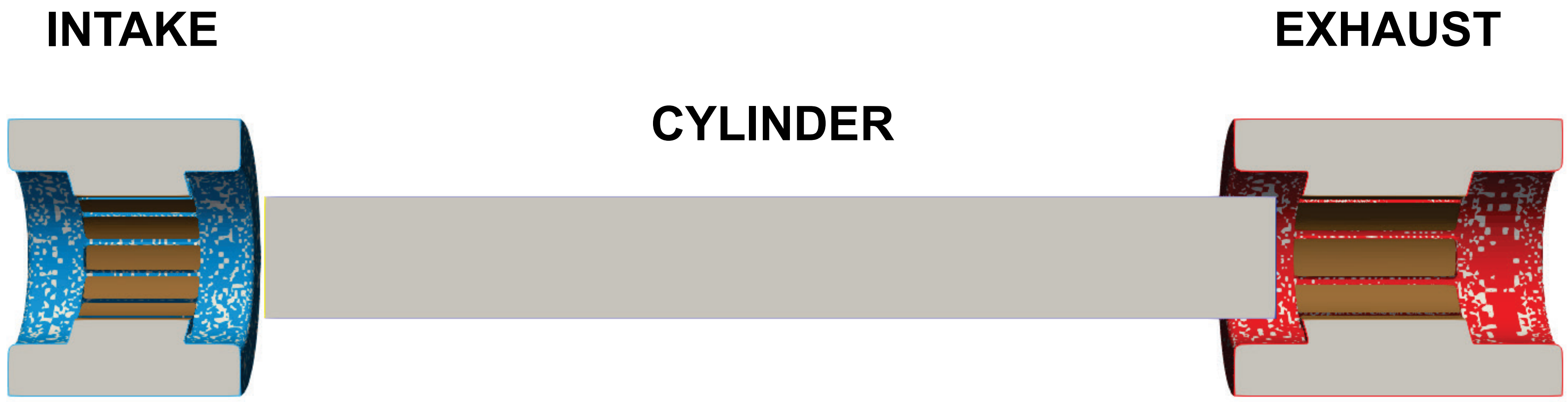


CH_4-FPLG CFD simulations: first geometry

First assessment of the FPLG:

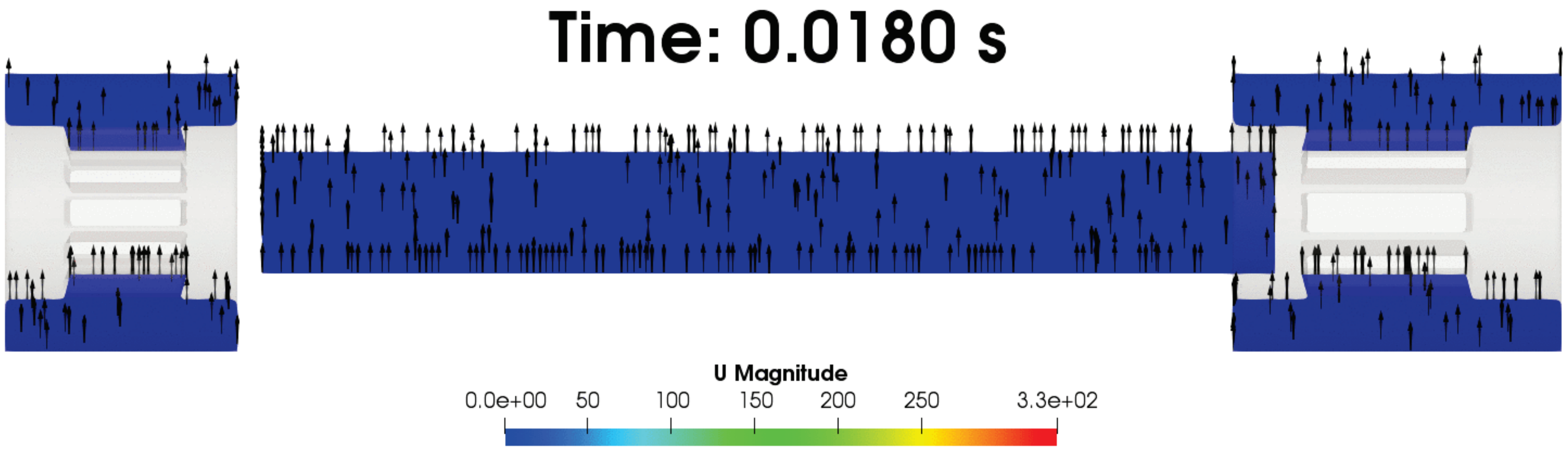
- Uniflow configuration
- 8 ports exhaust
- 12 ports intake
- Symmetric piston motion law profile obtained from RCM engine-like experiment



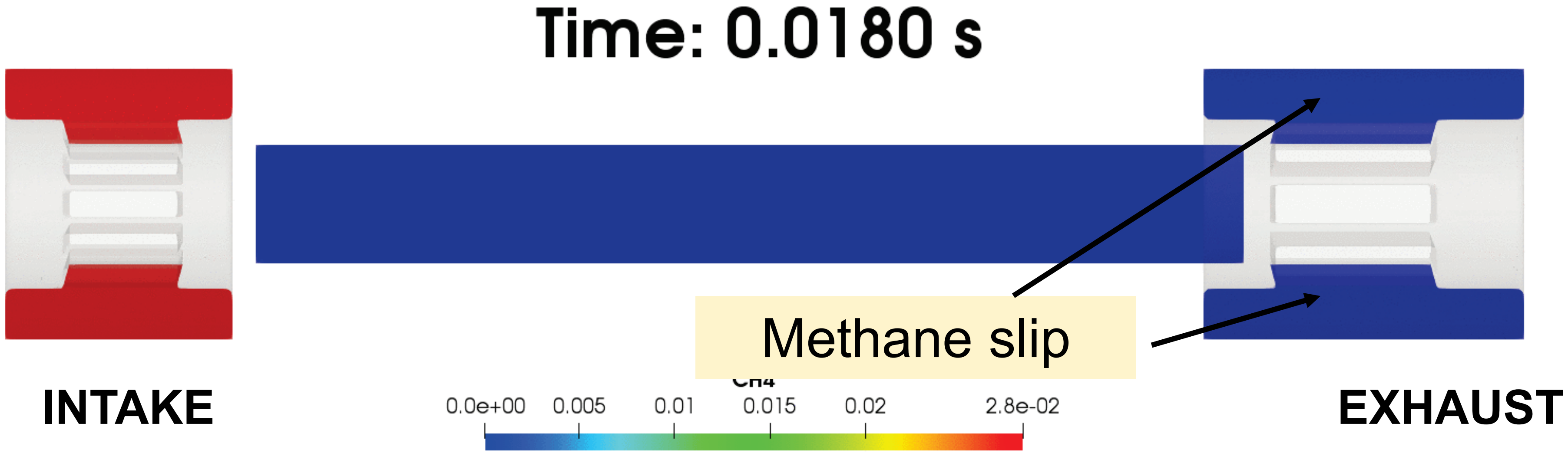


Engine data	
Bore	80 mm
Stroke	446 mm
Compression ratio	50

CH_4-FPLG CFD simulation results : gas exchange



Operating condition	
Frequency	16.5 Hz
Intake pressure	1.05 bar
Injection	Port fuel
Lambda	≈ 2



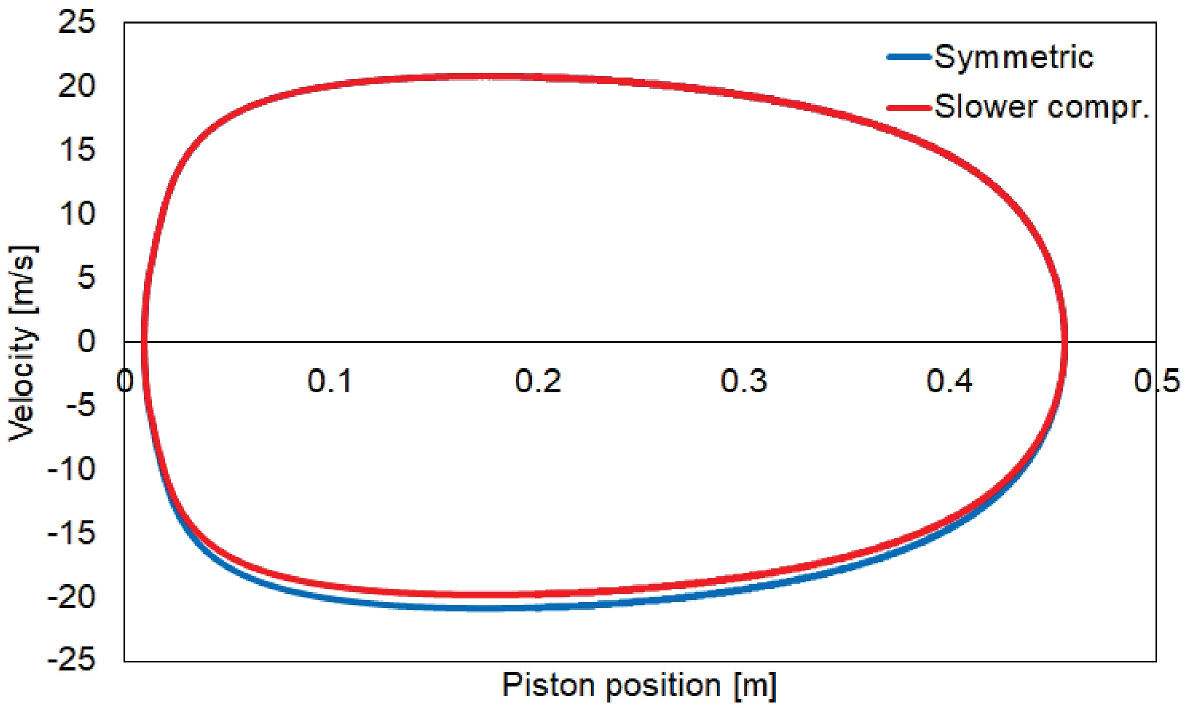
Methane slip:
>5000 ppm

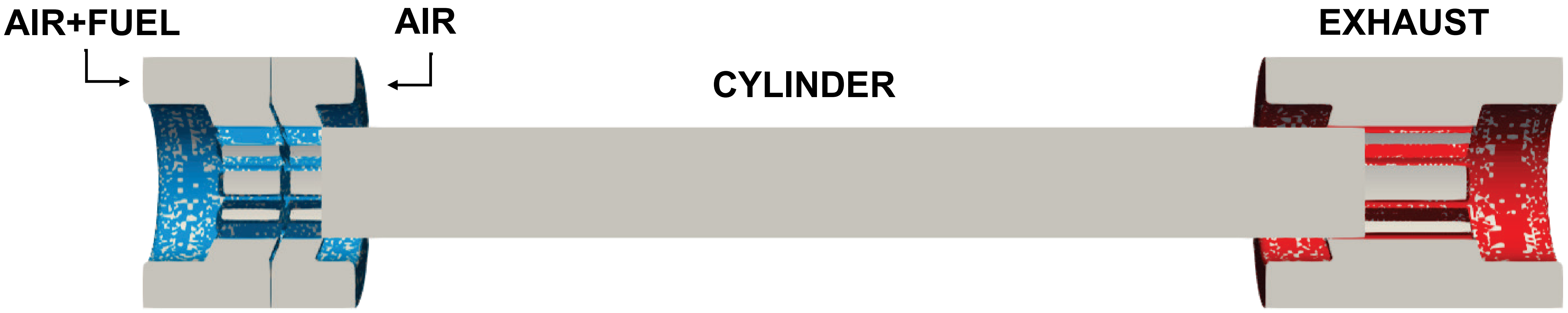
CH_4-FPLG CFD simulations: final geometry

Intake manifold divided into two regions to limit methane slip:

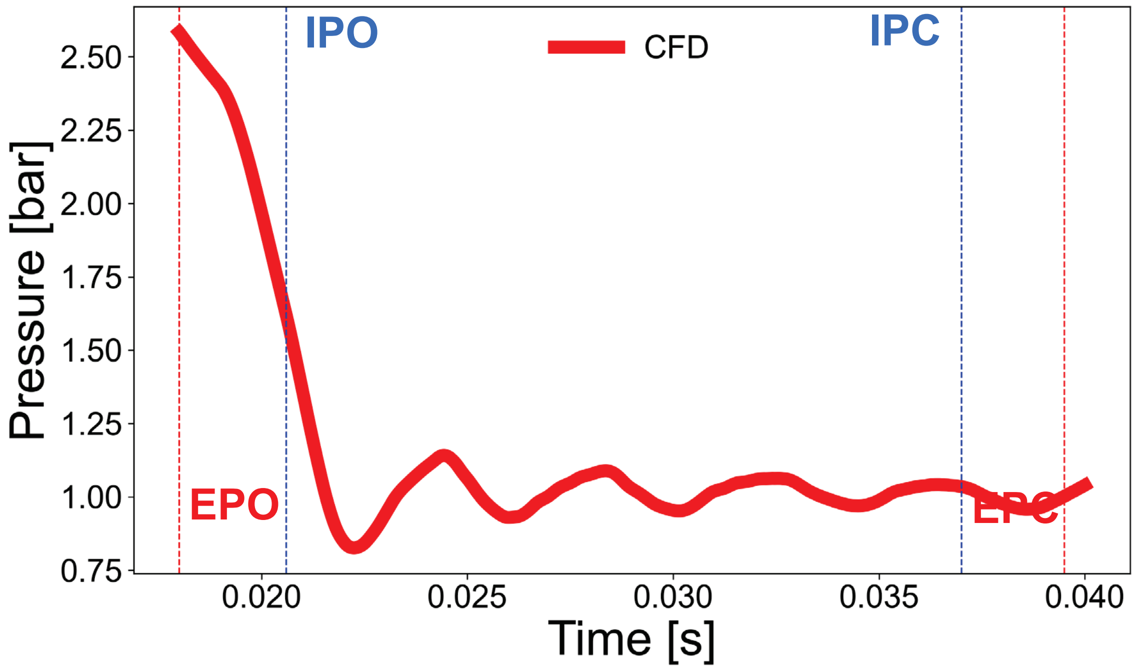
- First one that is open filled with air only
- Second one with air and fuel

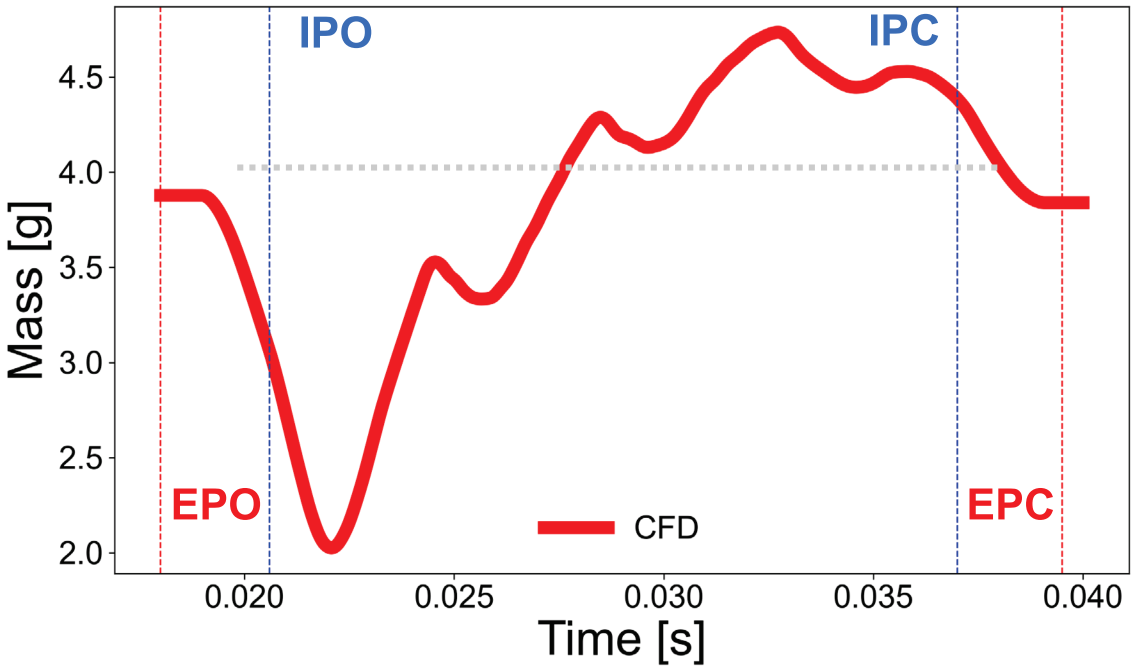
Compression stroke was slowed down by a 5% compared to expansion

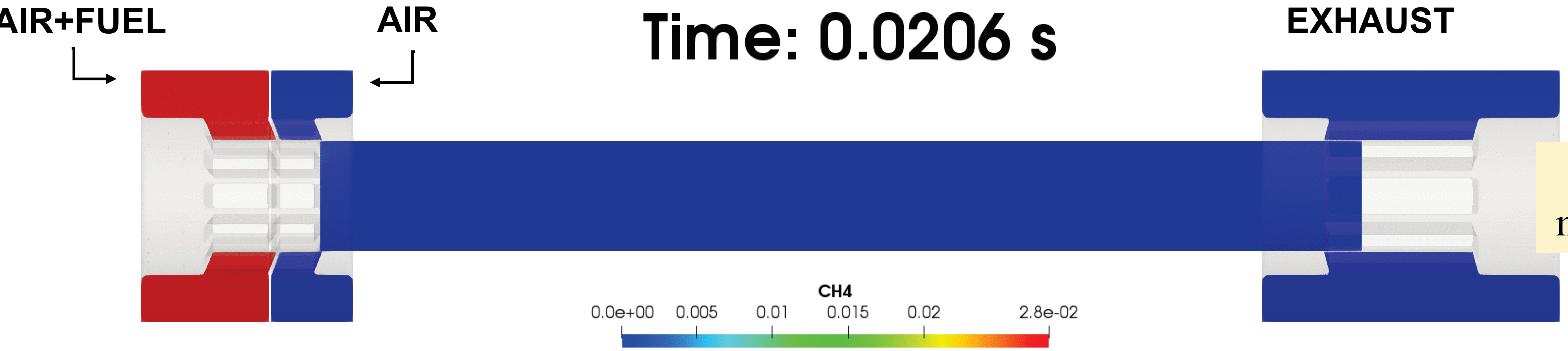




CH_4-FPLG CFD simulations: gas exchange

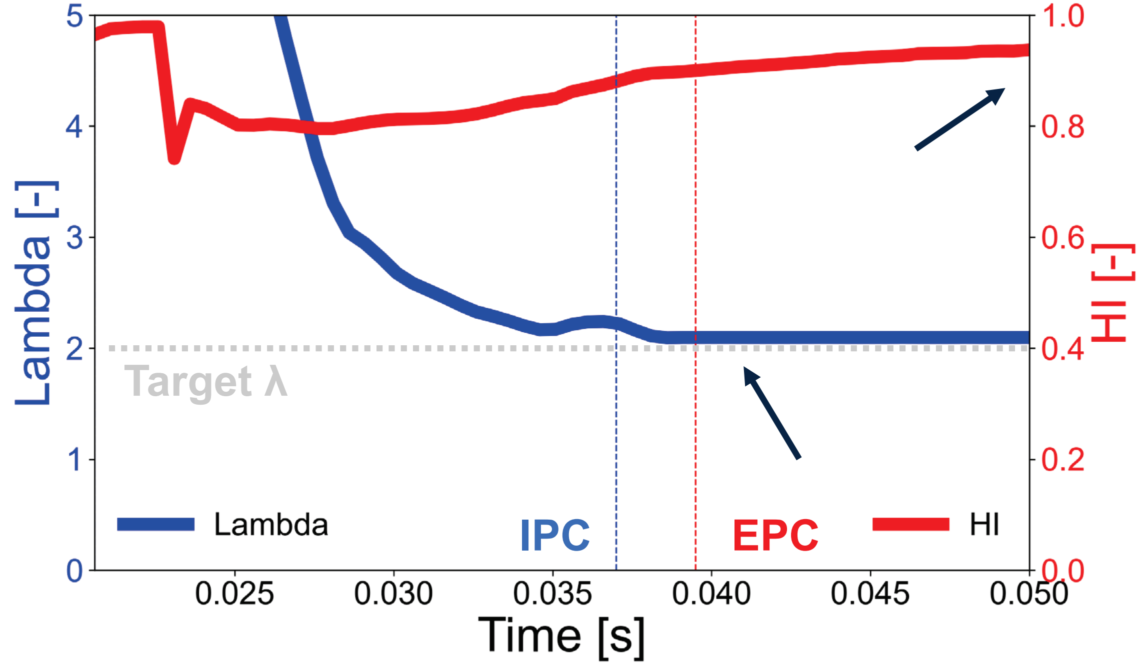






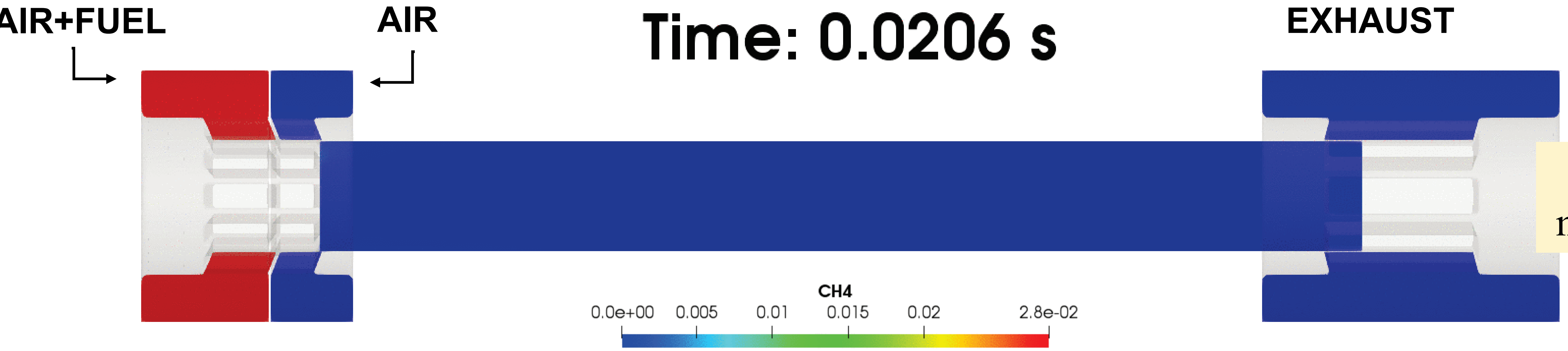
Reduced methane slip

CH_4-FPLG CFD simulations: gas exchange



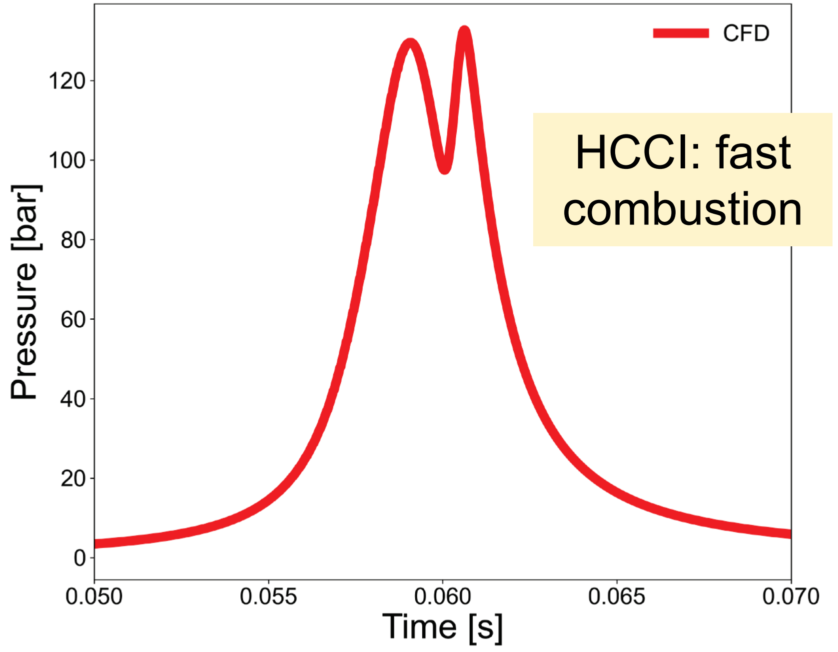
Main outputs after gas exchange:

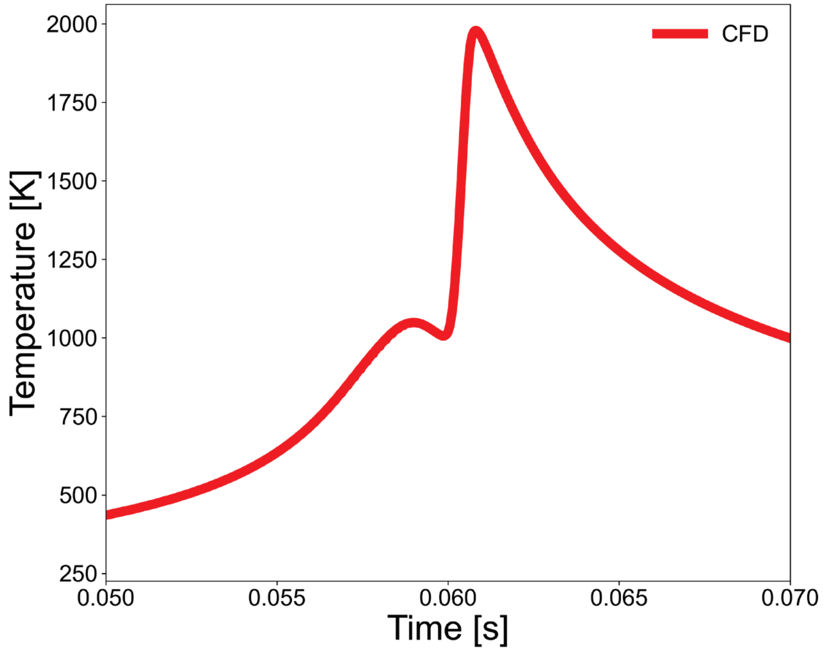
- Target $\lambda = 2$ reached
- Good homogeneity index before TDC
- Methane slip reduced (-70%) but some improvements are required

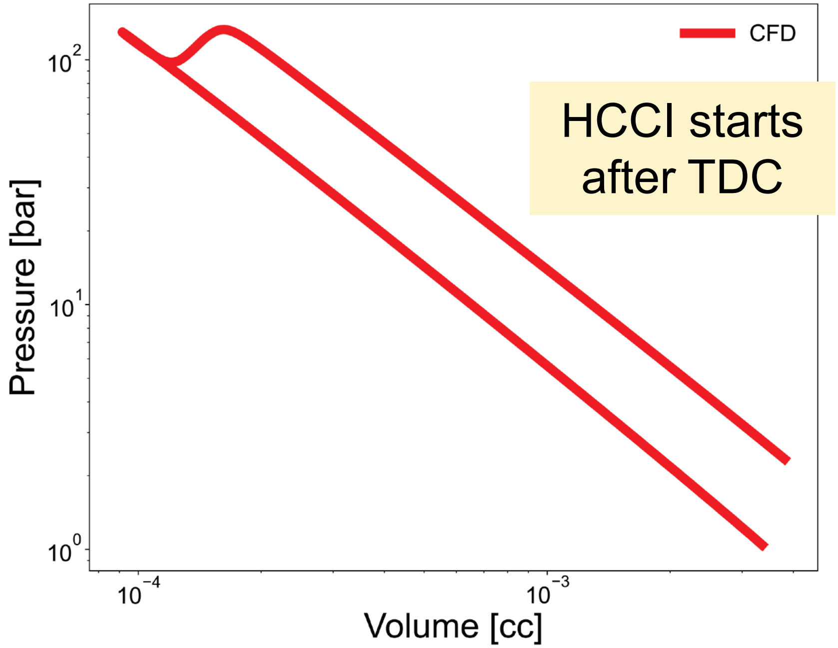


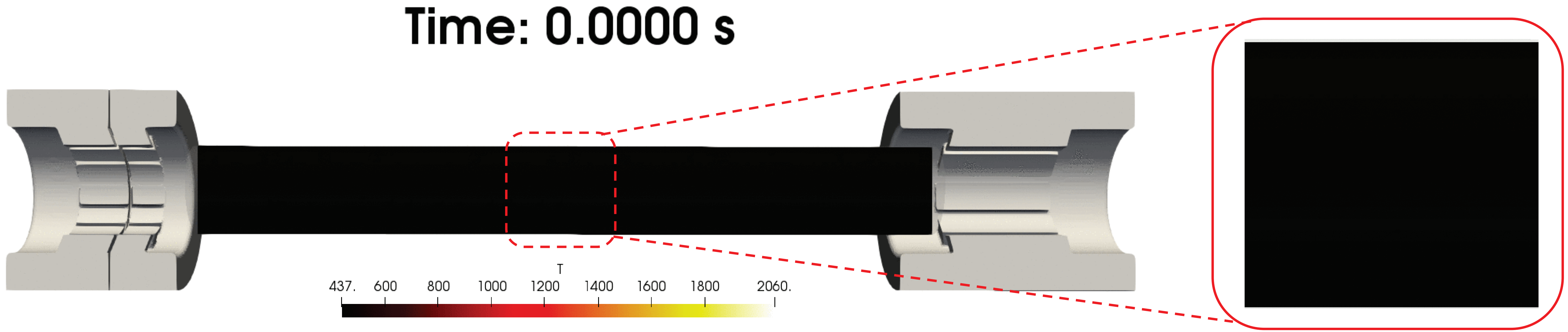
Reduced methane slip

CH_4-FPLG CFD simulations: combustion

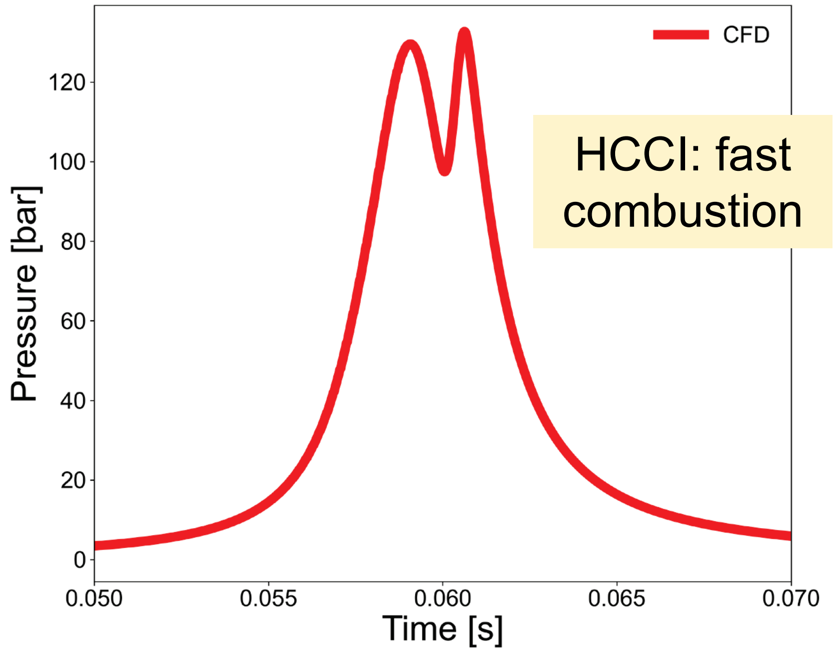


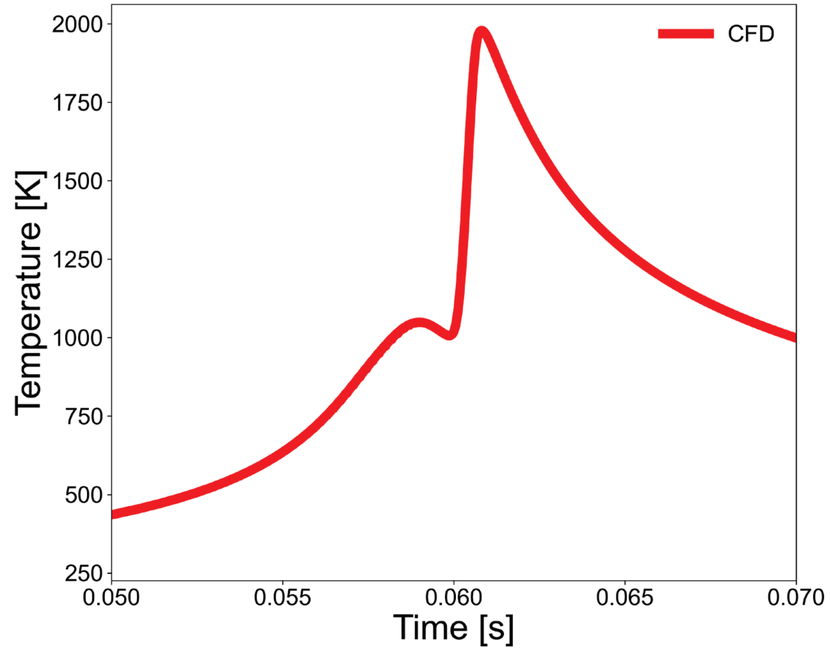






CH_4-FPLG CFD simulations: combustion

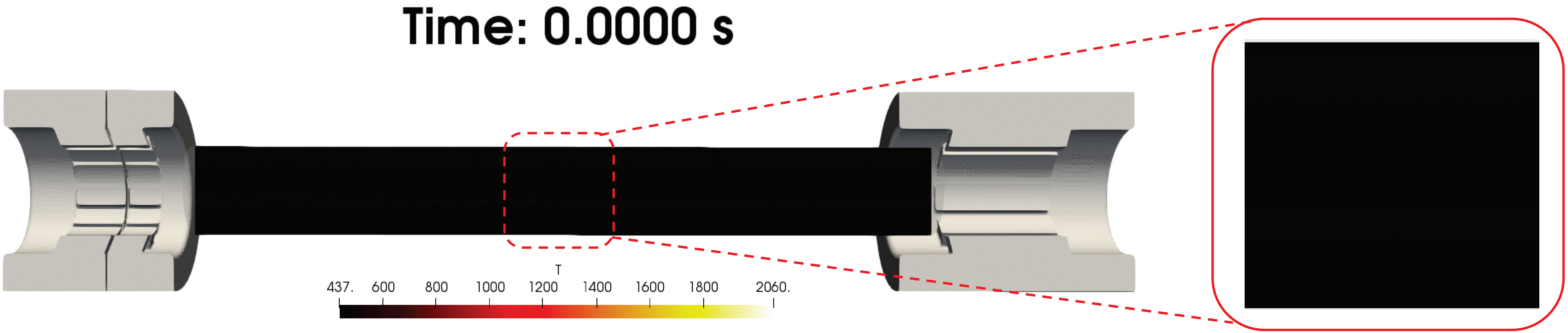




CFD output	
IMEP	6.7 bar
Indicated power	49 kW
Indicated efficiency	58%

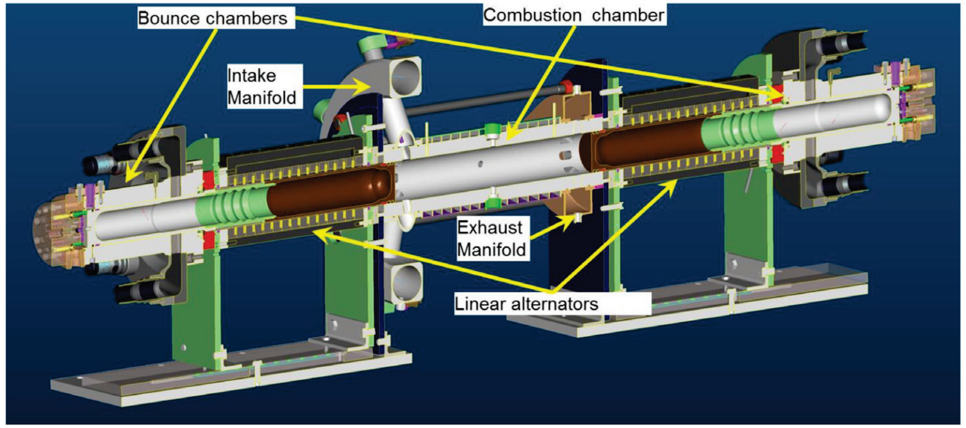
Possible issues:

- Blowby not considered
- HCCI ignition control
- After-treatment (no TWC)



H_2-FPLG simulations

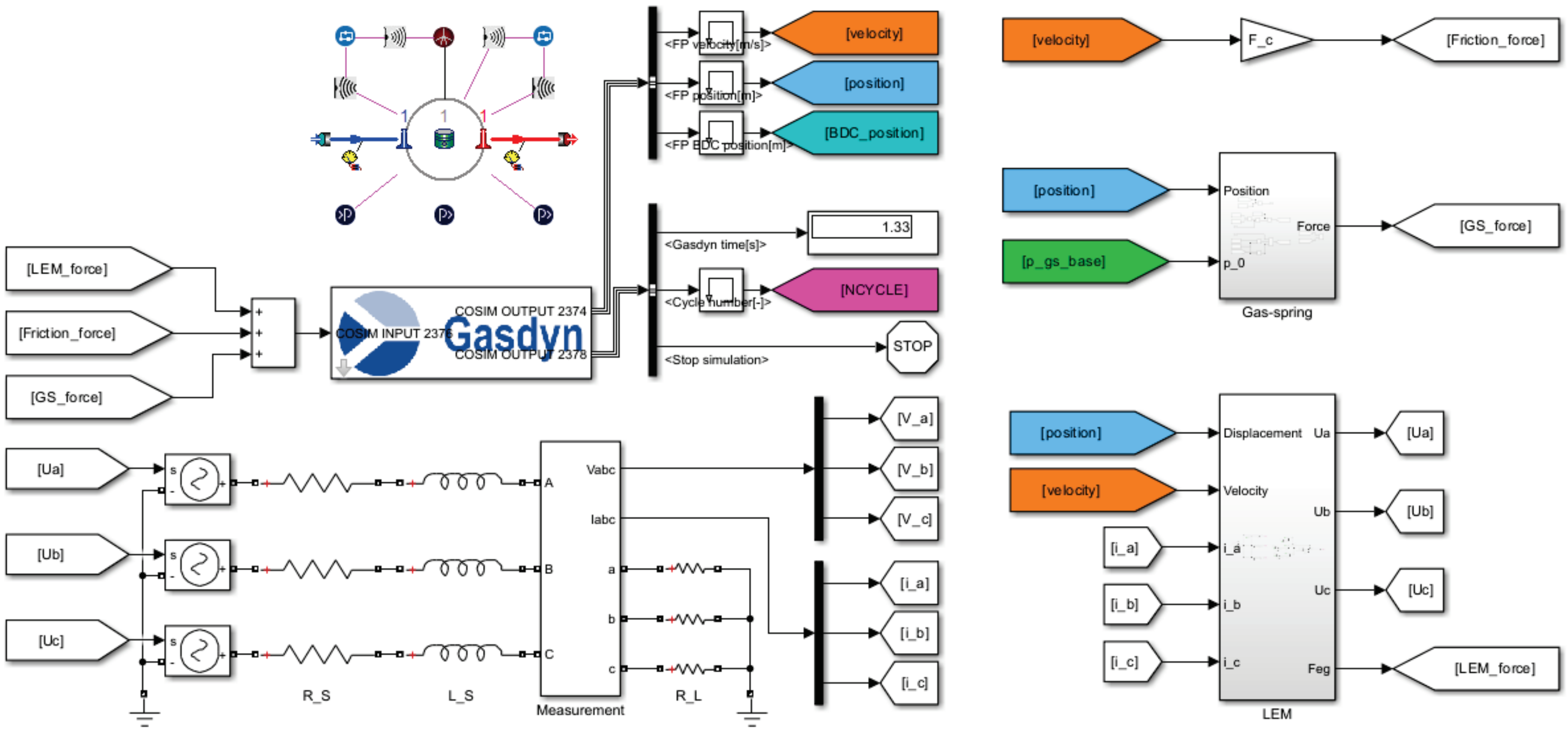
Sandia prototype (2016)



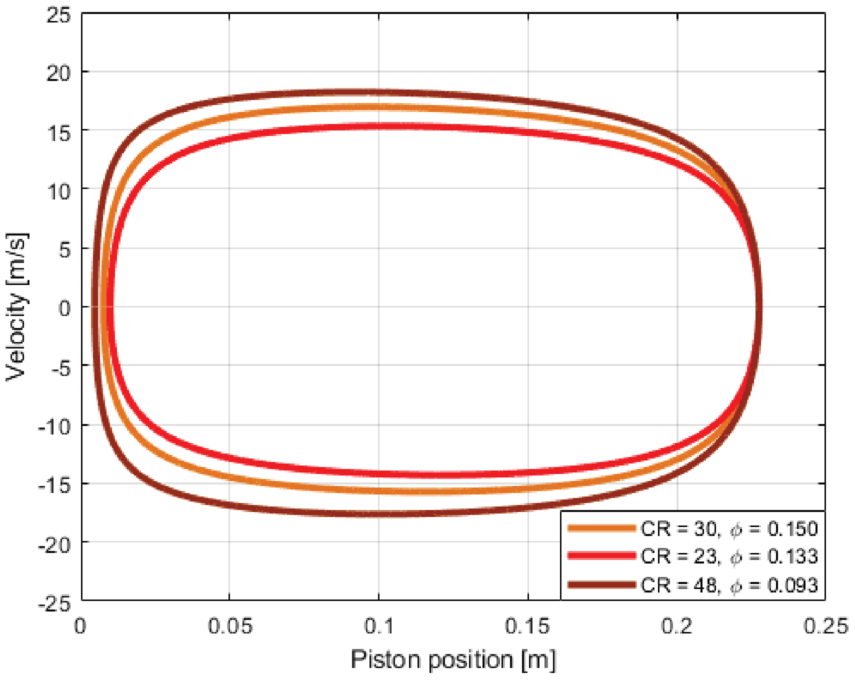
Bore	81.15 mm
Stroke	220 mm
Mover mass	4.9 kg
Compression ratio	~ 30
Frequency	~ 30 Hz
Power	~ 15 kW
Intake pressure	1.2 bar
Intake temperature	300 K
Equivalence ratio	0.15

Gasdyn+Simulink integrated model

- Gasdyn for combustion chamber and ducts
- Simulink for gas-spring and electric machine

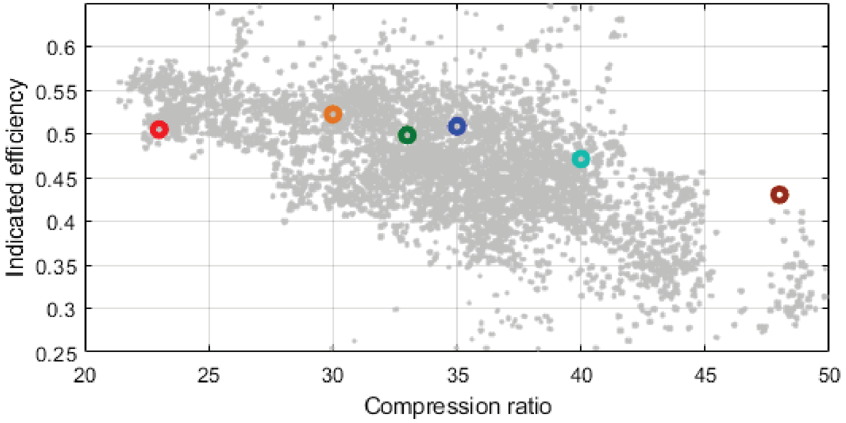


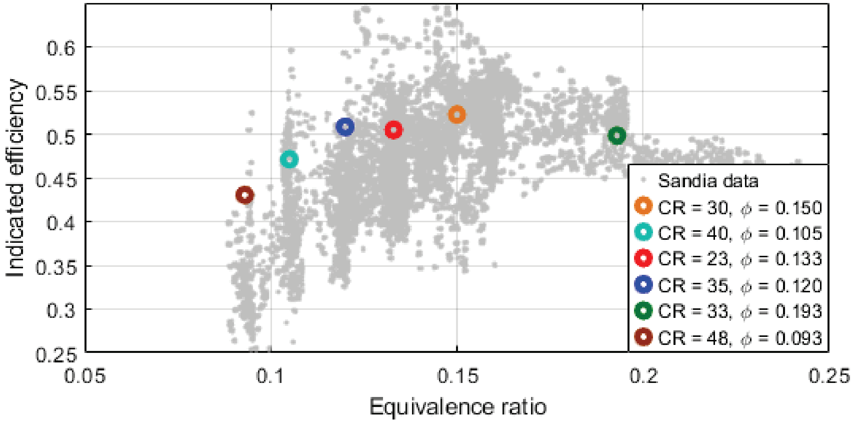
H_2-FPLG simulations

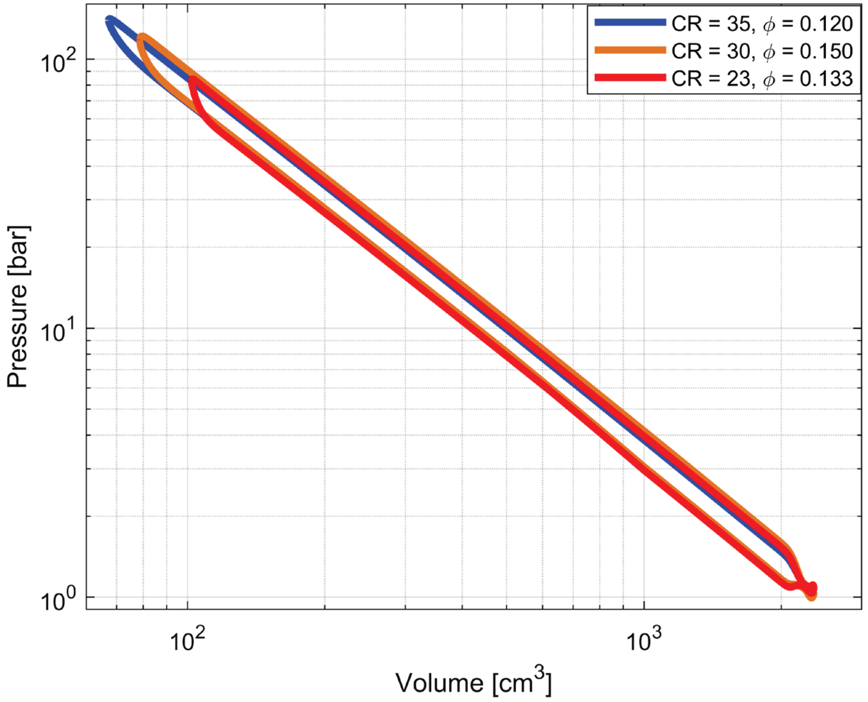


- Stroke increases with CR
- Symmetry of position-velocity diagram increasing with stroke

- Slightly lower efficiency values (H_2 ignites earlier than CH_4)
- Efficiency decrease after CR = 35







- H_2 ignites always before TDC (compression ratio limitation)
- All cases with $dp/dt < 10\ MPa/ms$

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Conclusions

- 1D and CFD simulations supporting opposed-FPLG development for mobility and power generation applications;
- Definition of a SI combustion system for mobility applications
- Potential of HCCI combustion for power generation:
  - Definition of a preminiary combustion chamber configuration
  - Very lean combustion ($\lambda > 2$)
  - Indicated efficiency > 55%
  - Near-zero emissions