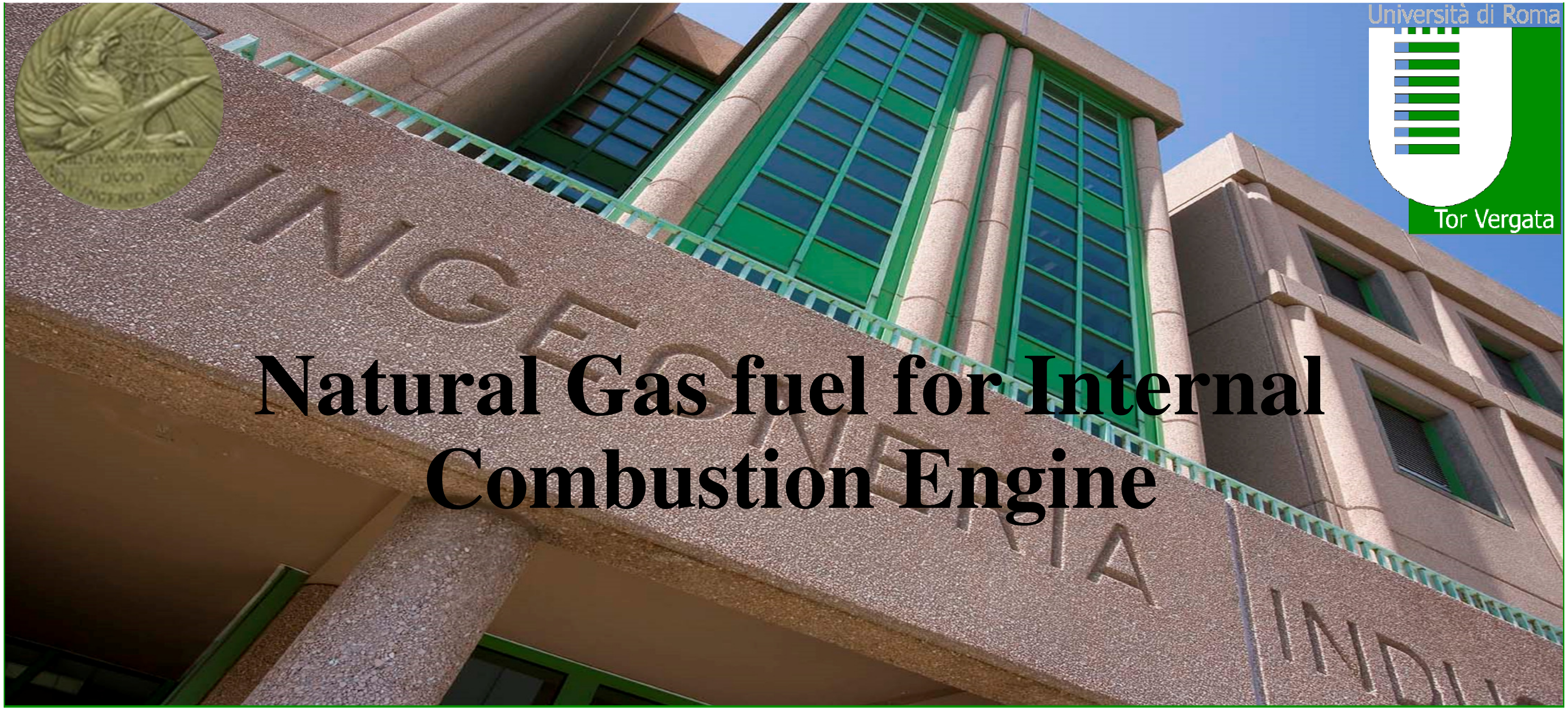

Natural Gas fuel for Internal Combustion Engine

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Department of Industrial Engineering

Outline

Introduction

- Motivations and Goals

1. Partially Stratified Charge combustion

- Experimental data
- Numerical approach
- Numerical investigation

2. Dual Fuel combustion

- Experimental data
- Numerical approach
- Numerical investigation

Conclusions and Future Development

Motivation & Goals

Natural gas as a fuel:

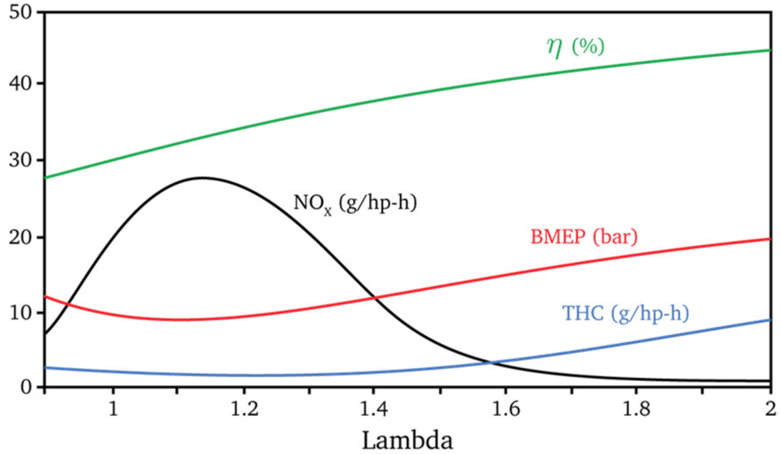
- Widespread availability
- Low cost
- Cleaner emission characteristics

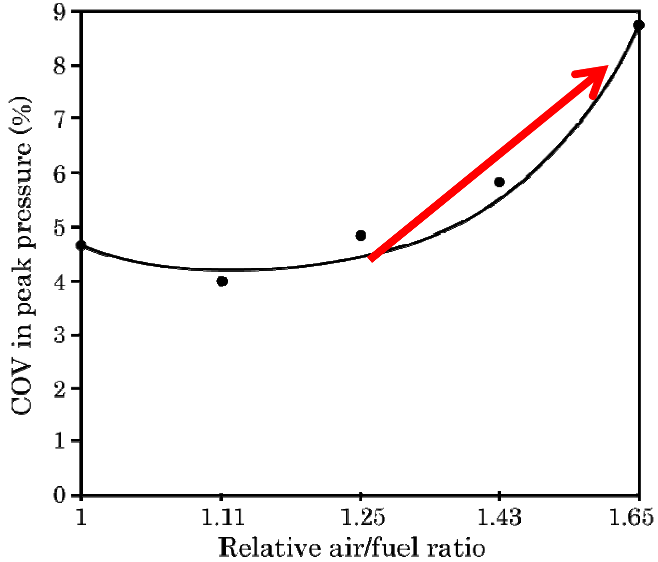
Advantages of Lean-Burn natural gas engines:

- Lower flame temperatures
  - NO_X reduction
  - Lower heat losses through the engine walls
- Higher ratio of specific heats
- Increased thermal efficiency
  - Partial load without throttling
  - Greater volumetric efficiency
  - Higher compression ratio

Disadvantages of Lean-Burn natural gas engines:

- Lower combustion stability – low flame speed
- Greater cycle-by-cycle variability

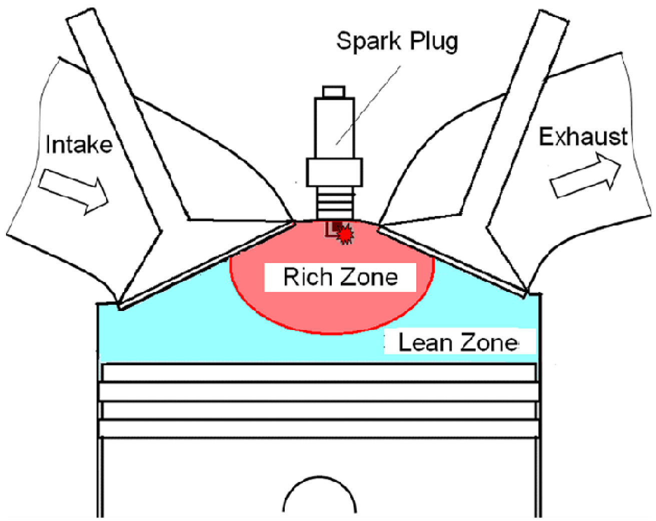


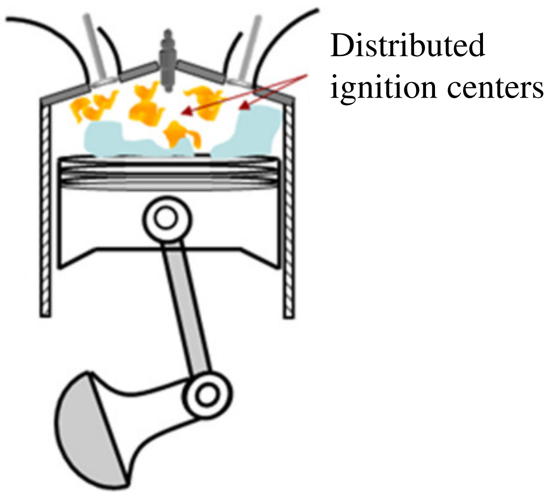


Motivation & Goals

Need for faster and more efficient combustion process

STRATIFICATION OF THE CHARGE	COMPRESSION IGNITION
• Ignition and first propagation into a richer mixtures to allow for a more stable and faster kernel growth	• Generation of multiple ignition spots to promote homogeneous combustion





Motivation & Goals

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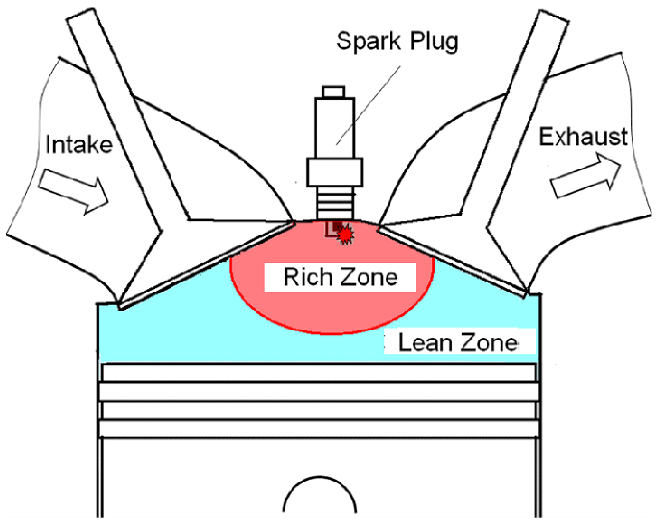


For the development of such strategy is essential:

- Studying the mixing process and the interaction between the flow characteristics and the combustion process
- The availability of reliable tools for the investigation of occurring phenomena during mixture formation, combustion process, and pollutant production

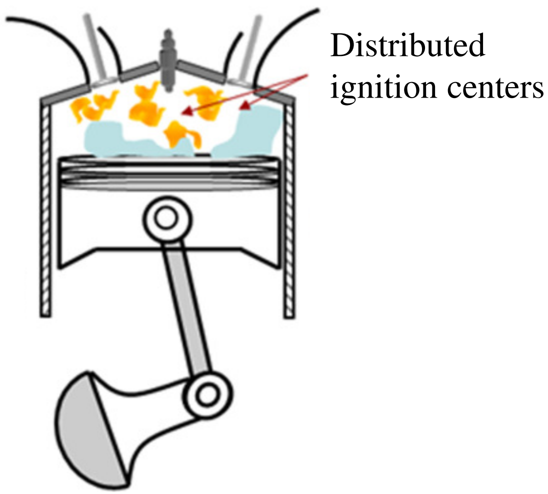
- **Direct Injection of Natural Gas**
- **Combustion of Stratified mixtures**

Motivation & Goals

Need for faster and more efficient combustion process

COMPRESSION IGNITION

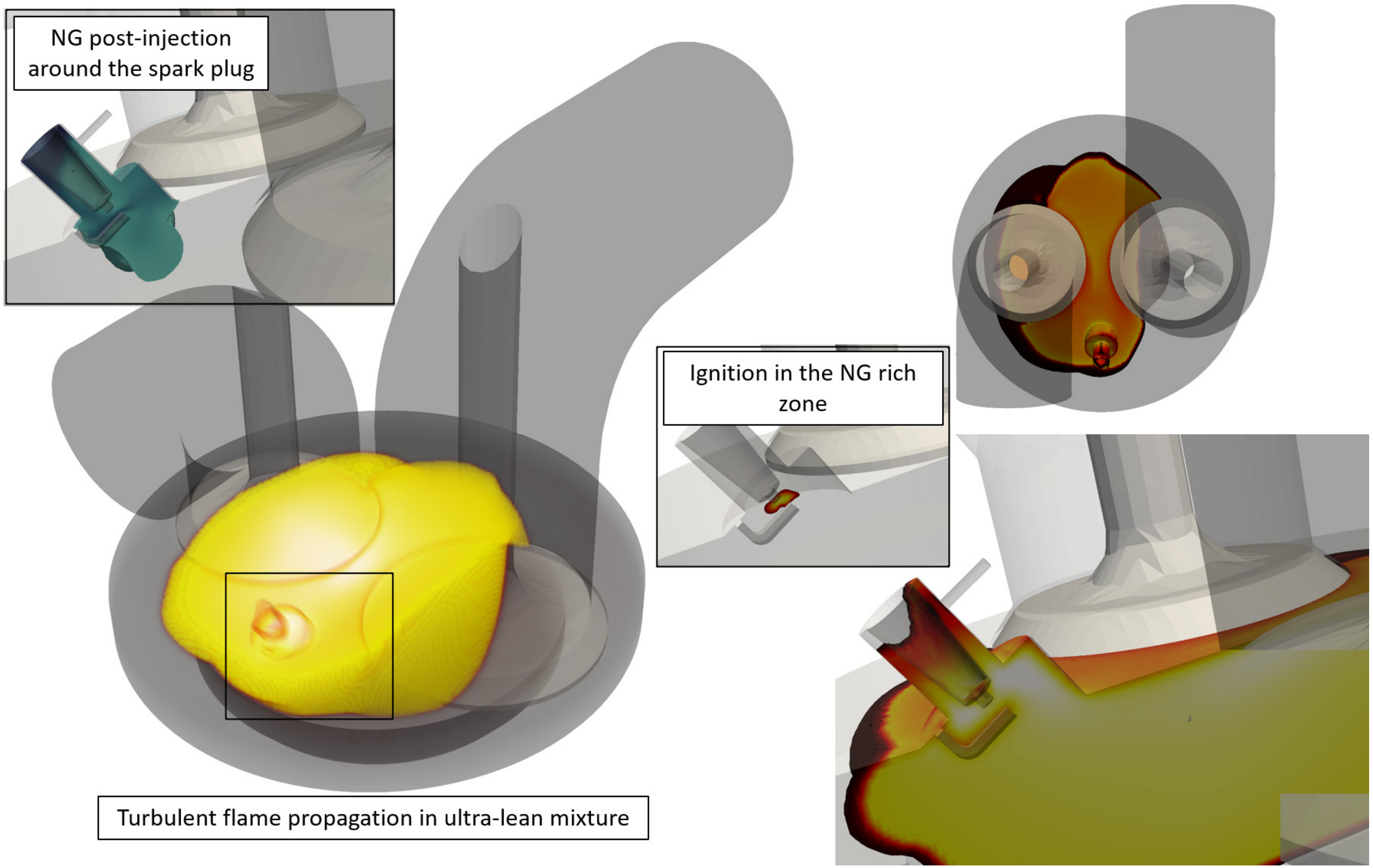
- Generation of multiple spots of ignition to trigger an homogeneous and quite instantaneous combustion



Due to anti-detonation properties, natural gas can be ignited in CI engines through the injection of a pilot fuel.

It is thus key to investigate the interaction between the combustion process of each fuel, and to develop a numerical tool for the optimization of the engine design and operating parameters

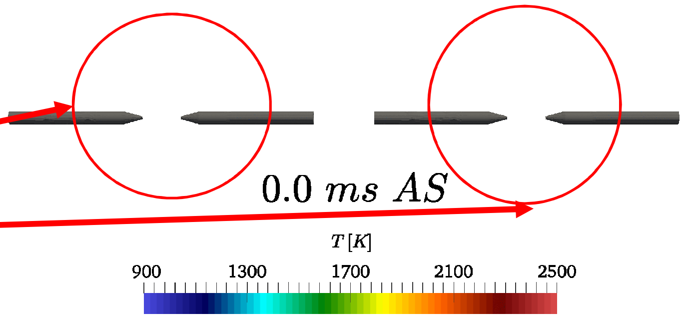
1. PSC combustion strategy



PSC combustion strategy

- Richer mixture in spark location allows for:
  - High flame speed during the beginning of the combustion event
  - More stable flame propagation
  - More stable ignition process
  - Extension of the flammability limit

	λ = 1.2	λ = 1.4	λ = 1.6	λ = 1.8	λ = 2.0
HOMOG					
PSC					

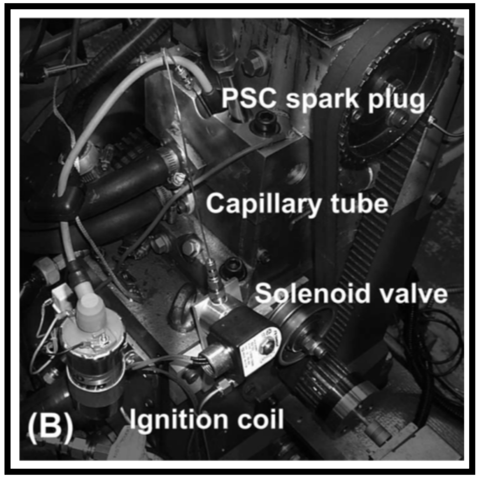


[4] L. Bartolucci, S. Cordiner, V. Mulone, V. Rocco, Natural Gas Partially Stratified Lean Combustion: Analysis of the Enhancing Mechanisms into a Constant Volume Combustion Chamber, Fuel, Volume 211, 2018, Pages 737-753, https://doi.org/10.1016/j.fuel.2017.09.100.

Experimental setup

- Ricardo Hydra research engine:

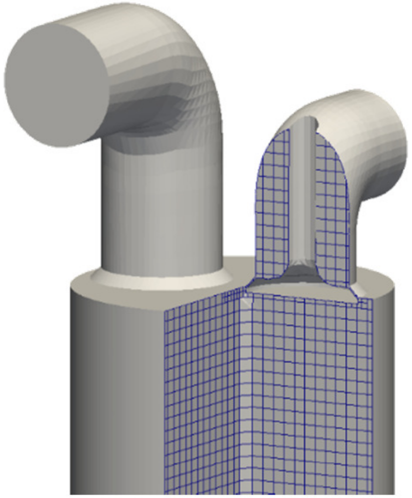
Number of cylinders	1
Number of valves	2
Fuel	**CNG → CH4**
Bore (mm)	81.4
Stroke (mm)	88.9
Connecting rod (mm)	158
Compression ratio	9.25
Displacement (cc)	463
Speed (rpm)	**2000**
Throttling	**WOT**
Inlet valve opening	12 CAD BTDC
Inlet valve closing	56 CAD ABDC
Exhaust valve opening	56 CAD BBDC
Exhaust valve closing	12 CAD ATDC

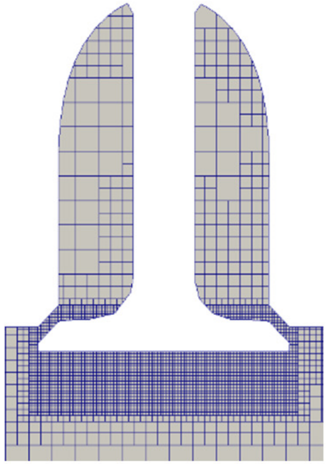


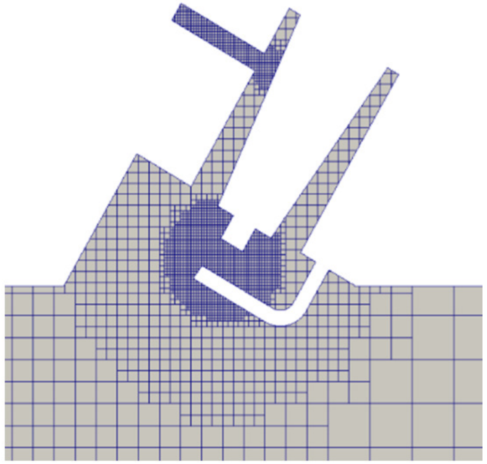
- PSC injection:

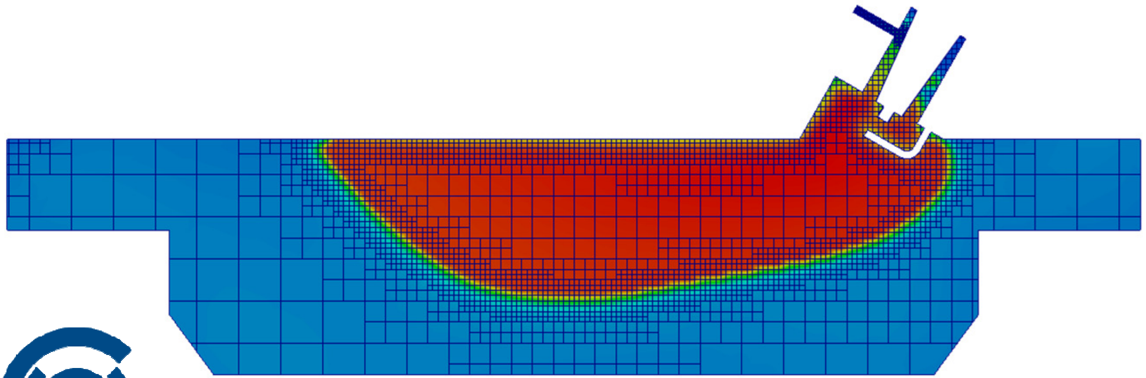
PSC fuel	CNG
Capillary tube diameter (mm)	0.571
Mean mass flow rate (g/h)	40
Start of injection (CAD before ST)	**10**
Injection duration (CAD)	**8**

Numerical setup







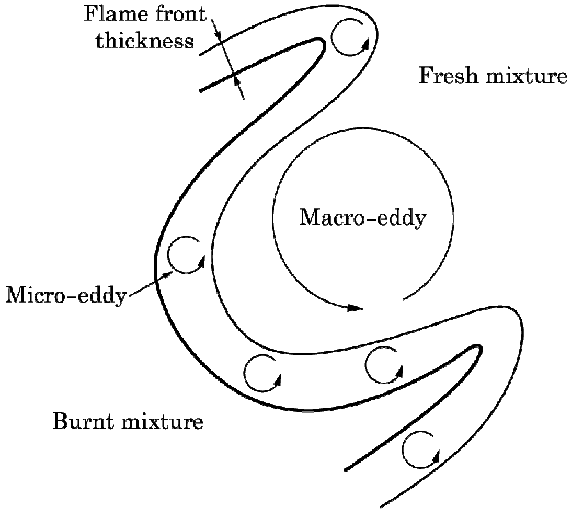


- Base mesh: 3 mm
- Fixed Embedding:
  - Valves – 0.375 mm
  - Capillary tube – 0.094 mm
  - Spark plug – 0.094 to 0.375 mm
- AMR:
  - In-cylinder– 0.75 mm
  - Flame front – 0.375 mm

Turbulence Chemistry Interaction

Fast heat release due to COMBUSTION → Strong variations of both temperature and kinematic viscosity → TURBULENCE is significantly affected

TURBULENCE interacts with the flame structure → The flame surface is wrinkled with thickness increase → COMBUSTION evolution is modified



- A combustion model representing the interaction between turbulence and chemistry on a sub-grid scale is required

→ **Partially Stirred Reactor (PaSR) combustion model**

Test Matrix

	λ=1.53		λ=1.68	
Case	Homogeneous	PSC	Homogeneous	PSC
PSC injection timing (CAD)	-	-55	-	-63
Spark timing (CAD)	-51	-45	-59	-53
Availability of Experimental Data	Yes	Yes	No	Yes

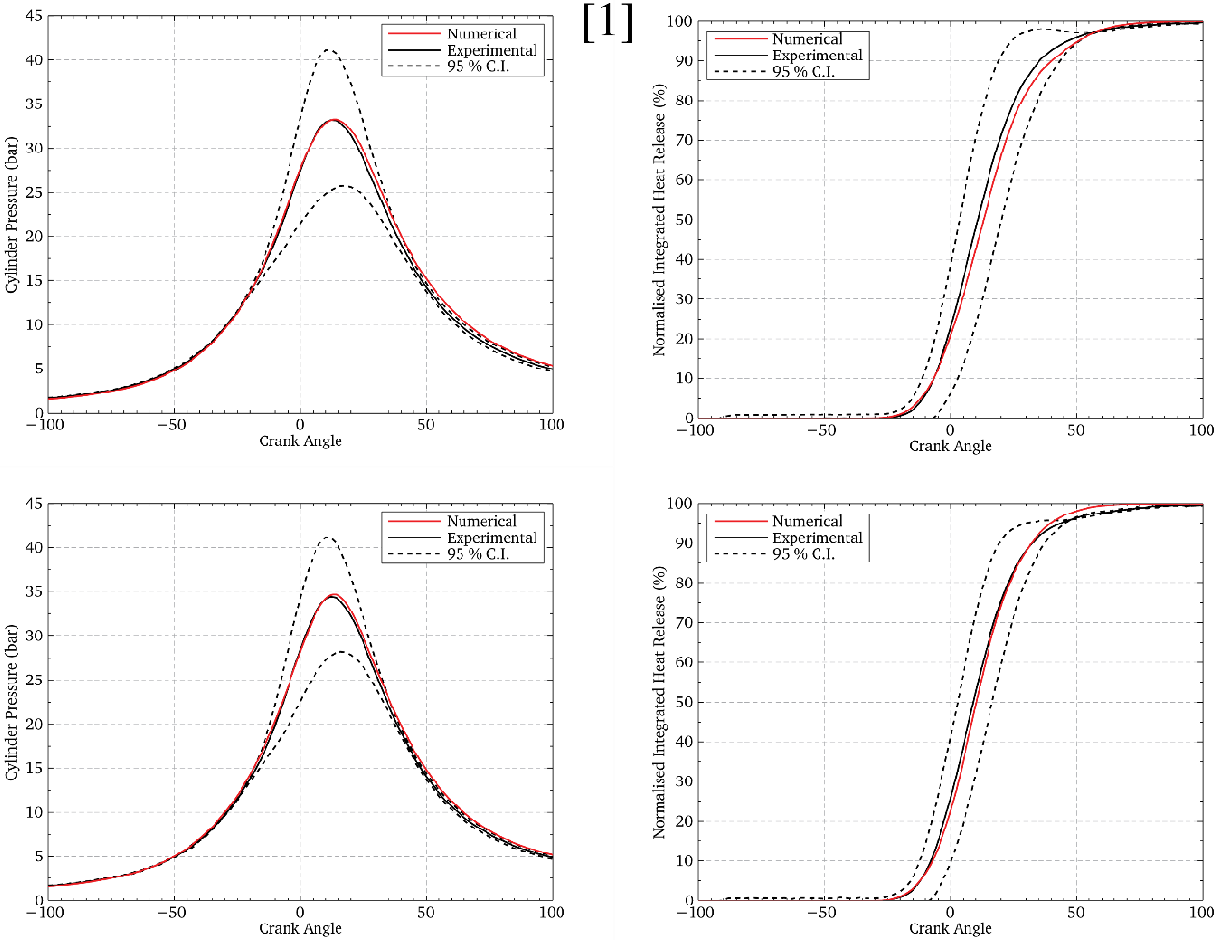
- **Numerical details:**
  - RANS approach
  - Chemical Kinetic Mechanism (30 species, 184 reactions)

Results - λ=1.53

Homogeneous

PSC

[1]

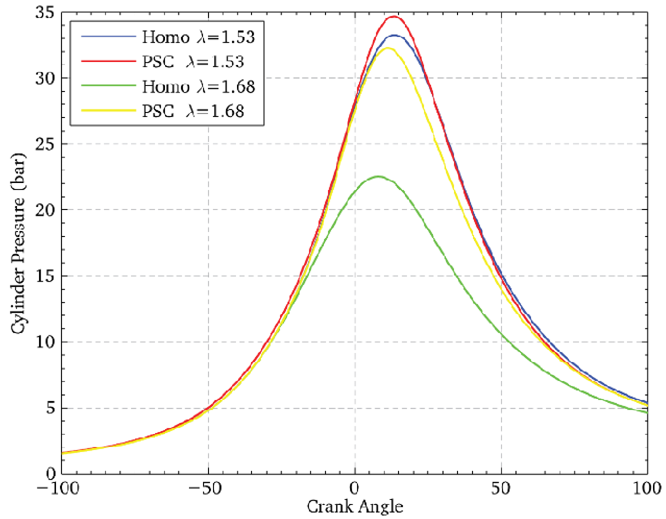


- Good agreement with the experimental data
- Both Homogeneous and PSC cases
- Slight discrepancy during the expansion stroke

[1] Bartolucci, L., Cordiner, S., Mulone, V., and Rocco, V., "Natural Gas Fueled Engines Modeling under Partial Stratified Charge Operating Conditions," SAE Technical Paper 2017-24-0093, 2017, doi:10.4271/2017-24-0093.

Comparison of pressure trace

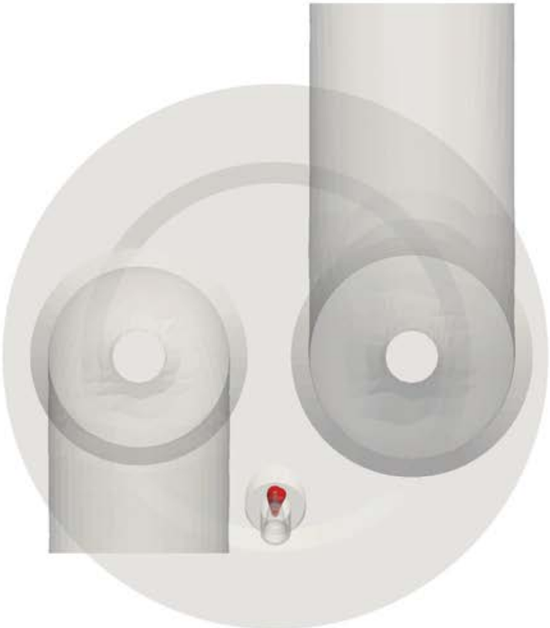
- In-cylinder pressure gain due to the PSC ignition system

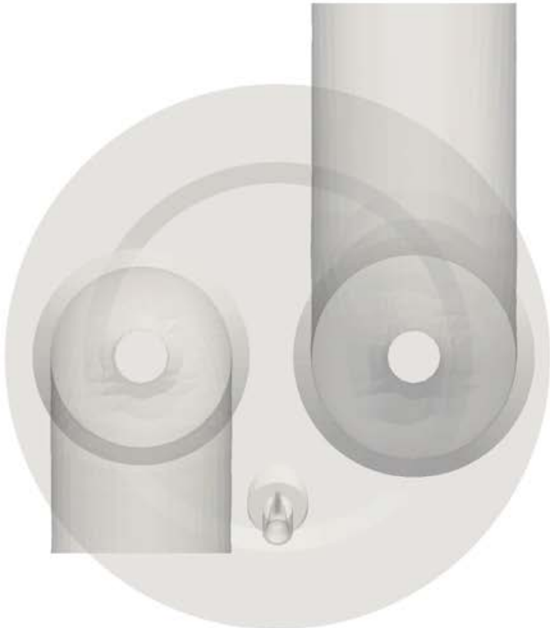


	Peak pressure (bar)		
A/F ratio	Homogeneous	PSC	Gain (%)
λ=1.53	33.26	34.68	4.27
λ=1.68	22.54	32.25	43.08

Flame propagation enhancement

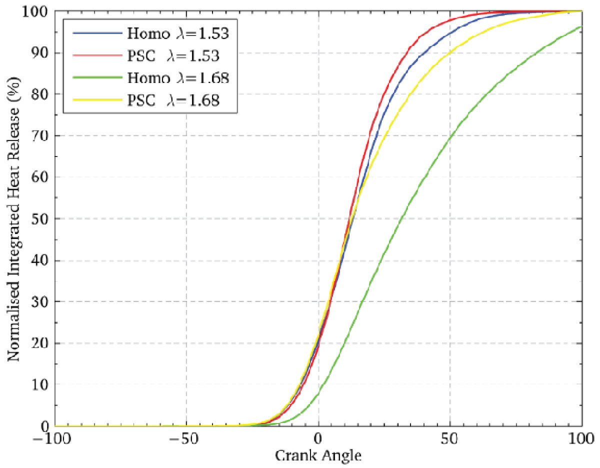
Homogeneous λ=1.68	PSC λ=1.68

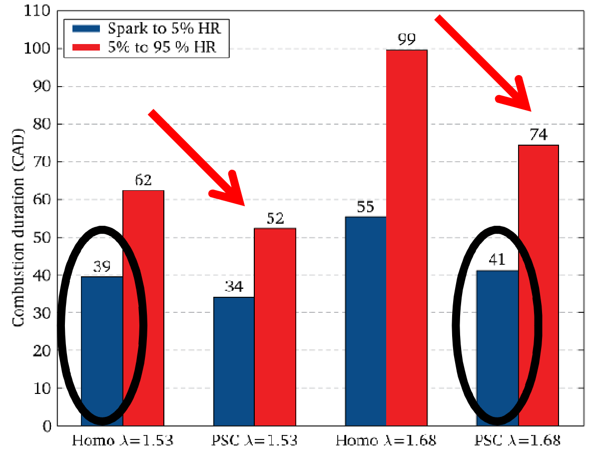




- PSC ignition strategy:
  - Faster flame propagation
  - Elongated flame towards the combustion chamber
- HOMOGENEOUS:
  - Slow propagation
  - Rather big amount of fuel unburned@EVO

Combustion duration analysis

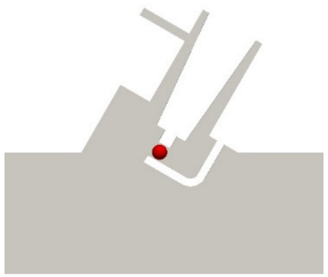




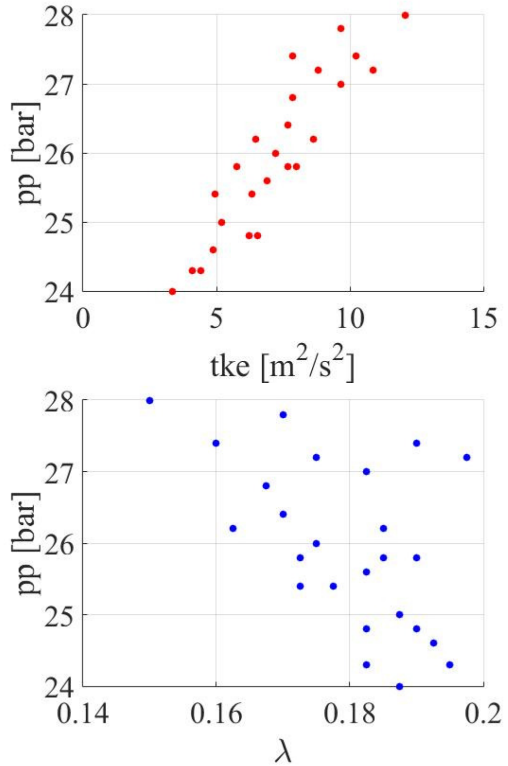
- CAD from Spark Timing to 5 % HR: flame kernel maturity time
- CAD from 5 % to 95 % HR: flame propagation time
- Effects of PSC:
  - Faster heat release
  - Lower flame kernel maturity time and flame propagation time

Preliminary LES results

- <u>Same</u> engine cycle
- <u>Perturbed</u> inflow BCs at the <u>PSC jet inlet</u>:
  - **Length scale** → 1/10 of the channel diameter
  - **Intensity** → 10% of the intake kinetic energy
- <u>Monitored volume</u> with a diameter of 1mm
- Monitored properties: <u>equivalent ratio and tke</u>



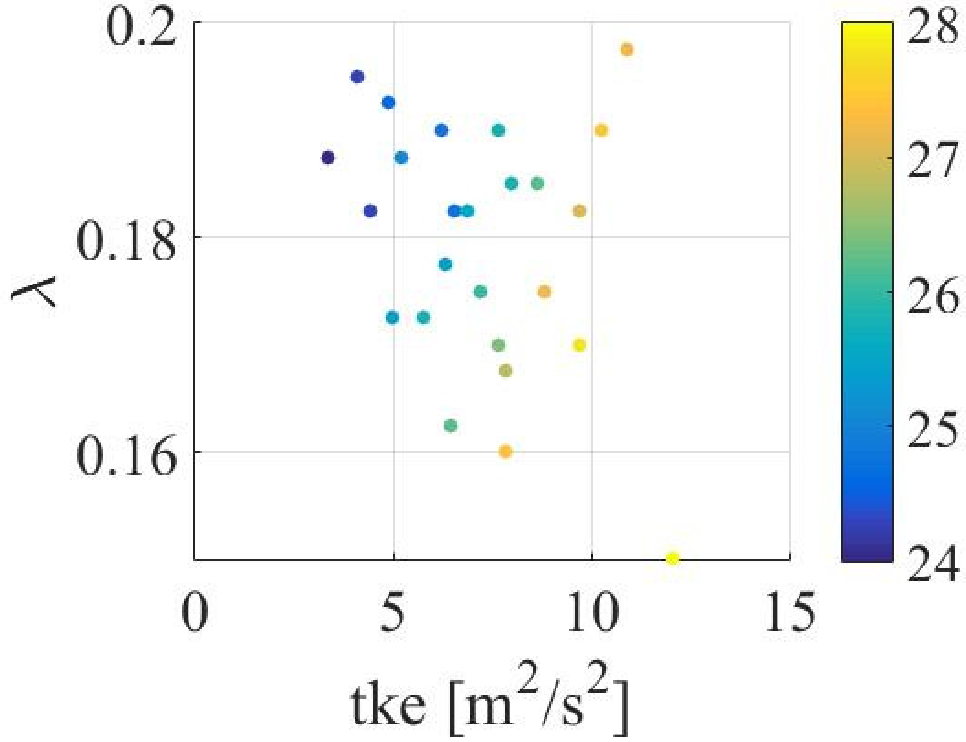
[2] **Correlation Coefficient: 0.9088**

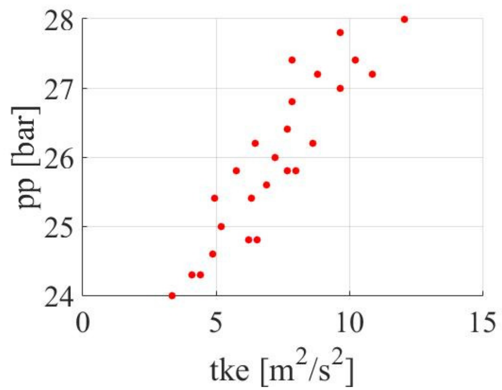


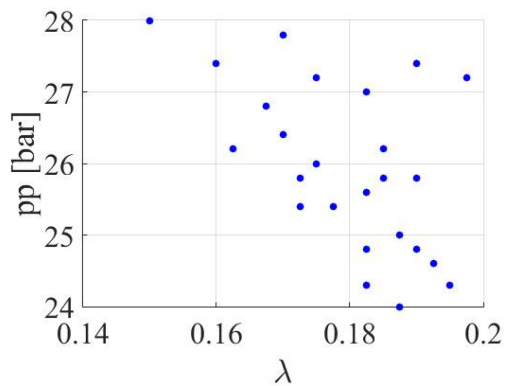
Correlation Coefficient: -0.5280

[2] L. Bartolucci, S. Cordiner, V. Mulone, V. Rocco, LES analysis of the mixing process in a natural gas fueled engine under Partial Stratified Charge operating conditions - comparison against the Constant Volume Combustion Chamber case, Energy Procedia, Volume 126, 2017, Pages 1019-1026, https://doi.org/10.1016/j.egypro.2017.08.308.

Preliminary LES results







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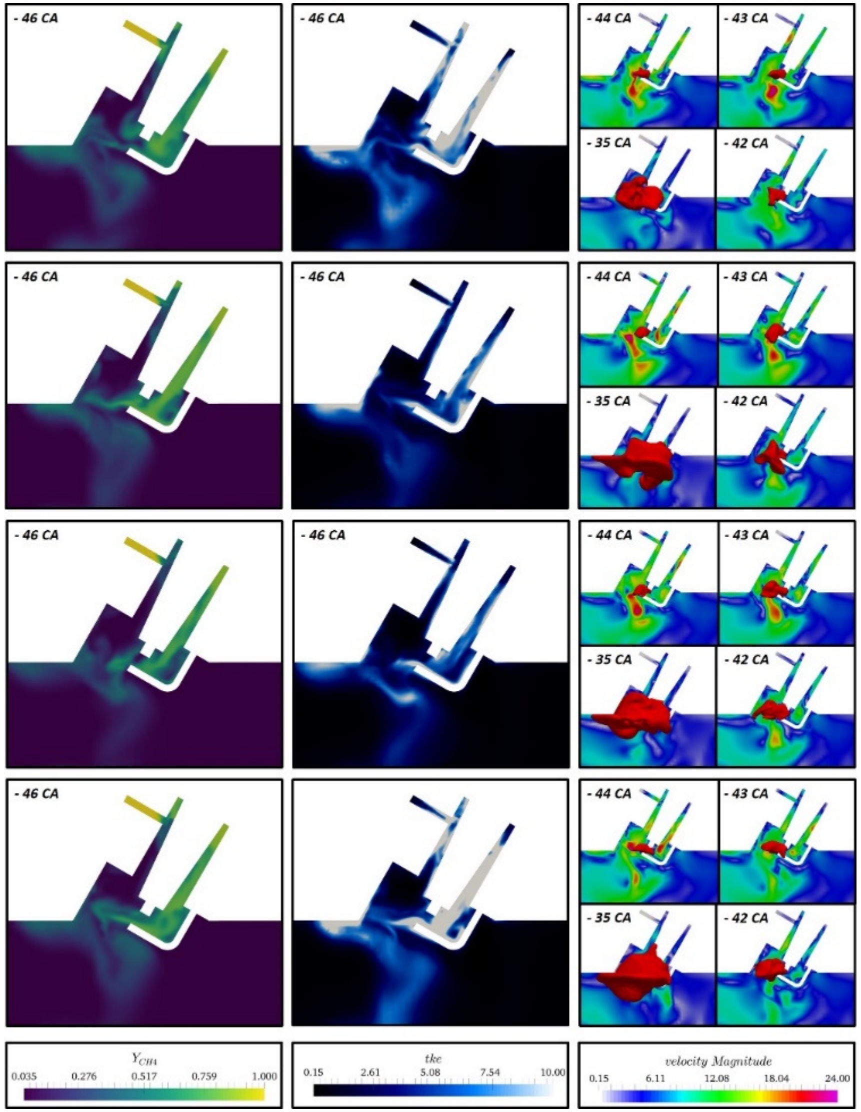
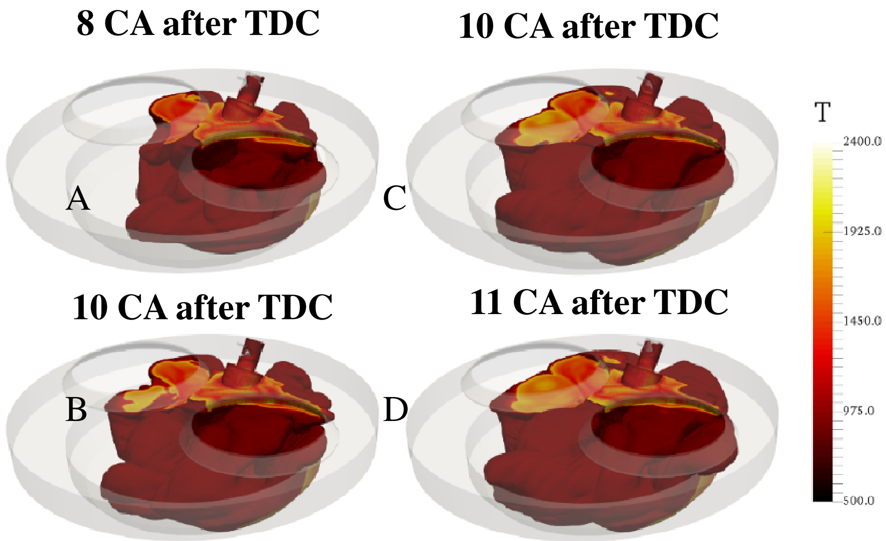


Observations:

- Coupled effect of Equivalent ratio and Turbulent Kinetic Energy
- TKE more effective than Equivalent ratio
- Higher Peak Pressure at Higher CA

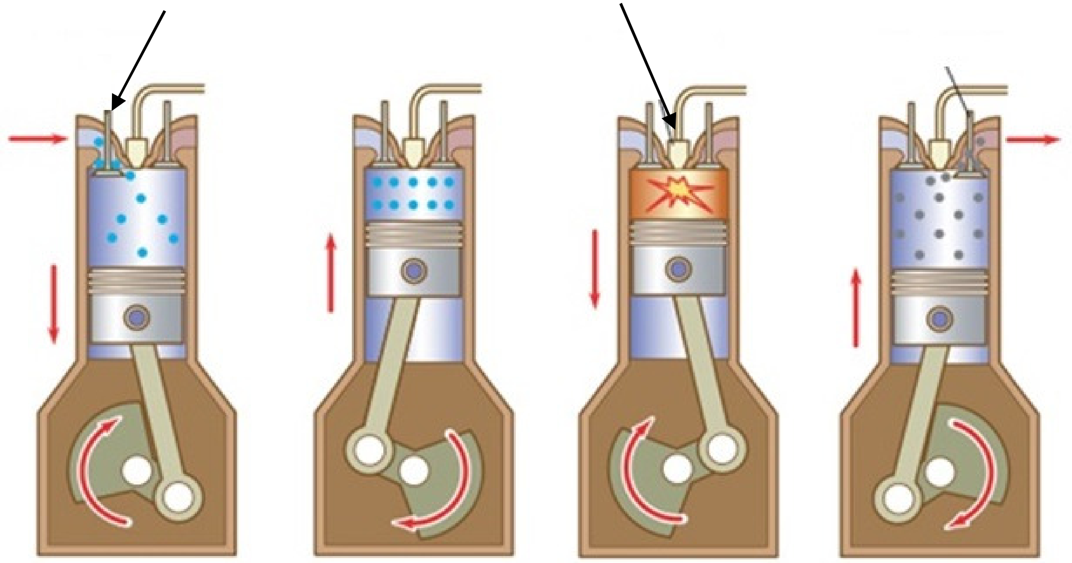


2. Dual Fuel Combustion

Basic principle of NG-PFI, DIESEL-DI dual-fuel engines

PFI of methane-air mixture

DI of DIESEL and combustion



$$PES = \frac{\dot{m}_g LHV_g}{\dot{m}_g LHV_g + \dot{m}_d LHV_d}$$

<u>Percentage of Energy Substitution</u>

$$\Phi = \frac{(A/F)_{st-tot}}{\frac{\dot{m}_a}{\dot{m}_d + \dot{m}_g}}$$

<u>Equivalence Ratio</u>

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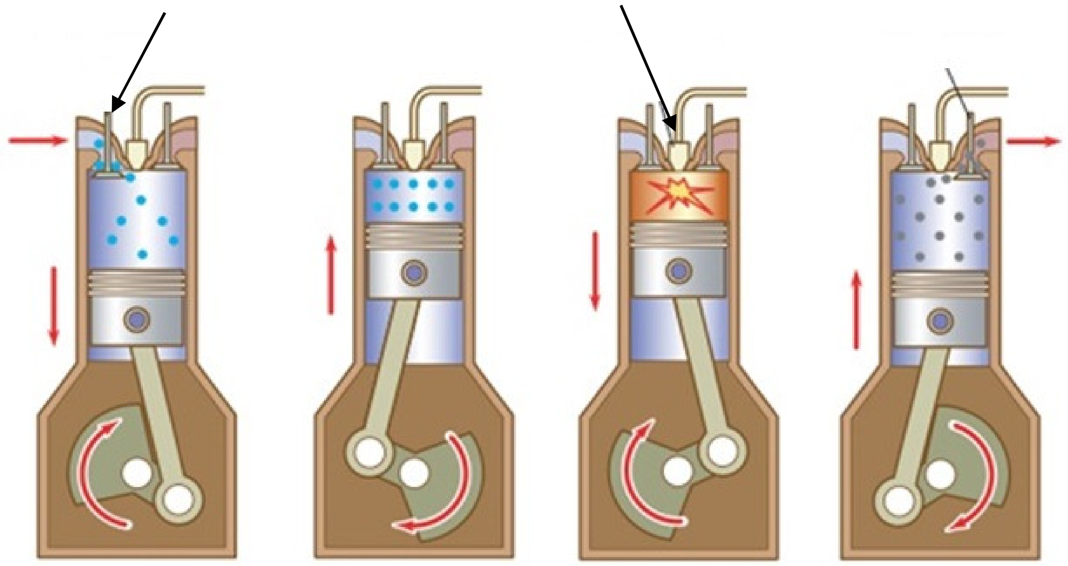

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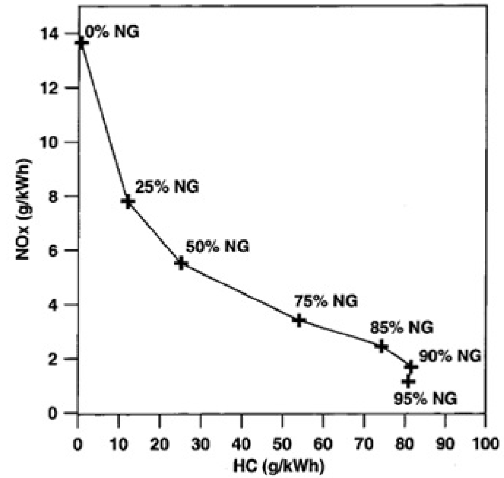
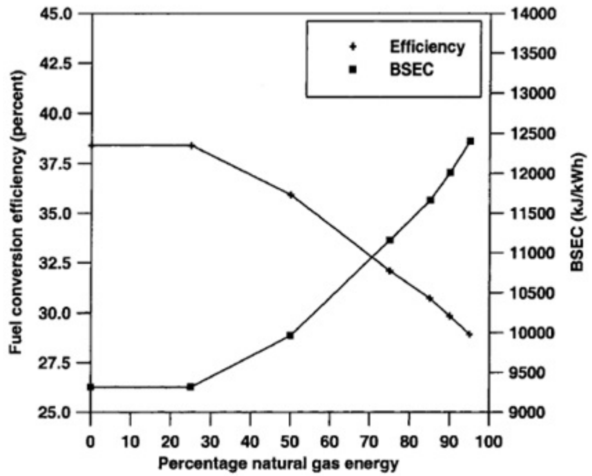
[3]

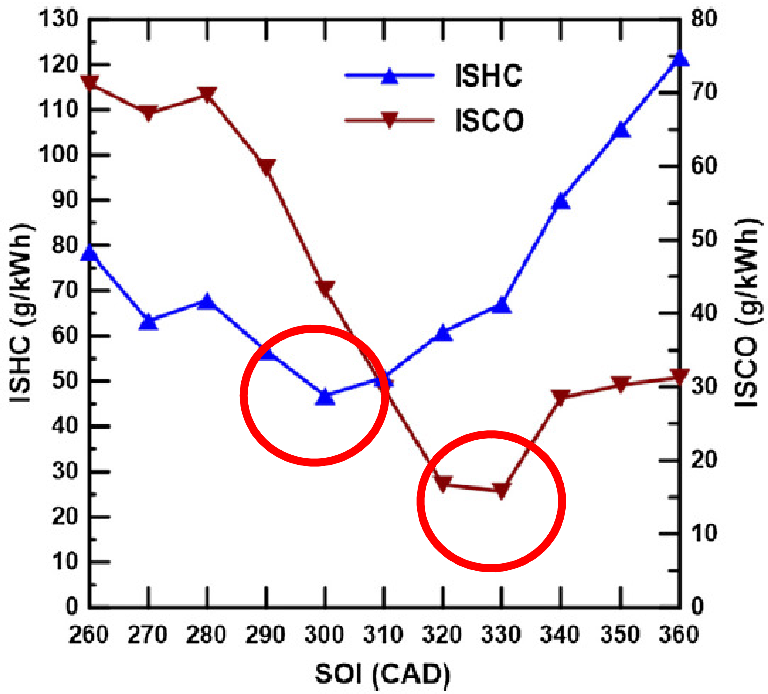




[3] Performance and heat release analysis of a pilot-ignited natural gas engine S. R. Krishnan, M Biruduganti, Y Mo, S. R. Bell, K. C. Midkiff International Journal of Engine Research Vol 3, Issue 3, pp. 171 – 184 June 1, 2002

Effect of DIESEL SOI

[4]



Parameter	Value
Engine type	RSi-130 DV11 single cylinder research engine, compression-ignition
Bore × stroke	128 mm × 142 mm
Connecting rod length	228 mm
Displaced volume	1827 cm^3
Compression ratio (nominal)	17.1:1
Valve train system	4-valve, OHV
Intake valve open[a]	32°
Intake valve close[a]	198°
Exhaust valve open[a]	531°
Exhaust valve close[a]	14°
Diesel fuel injection system	CP3 Bosch common-rail
Methane fuel system	Fumigation into intake manifold
Maximum speed	1900/min

- HC e CO emissions are affected by the DIESEL SOI – an optimum can be found.

[4] Injection timing effects on partially premixed diesel–methane dual fuel low temperature combustion - Guerry, E. Scott - Raihan, Mostafa S. - Srinivasan, Kalyan K. - Krishnan, Sundar R. - Sohail, Aamir - Applied Energy , 2016

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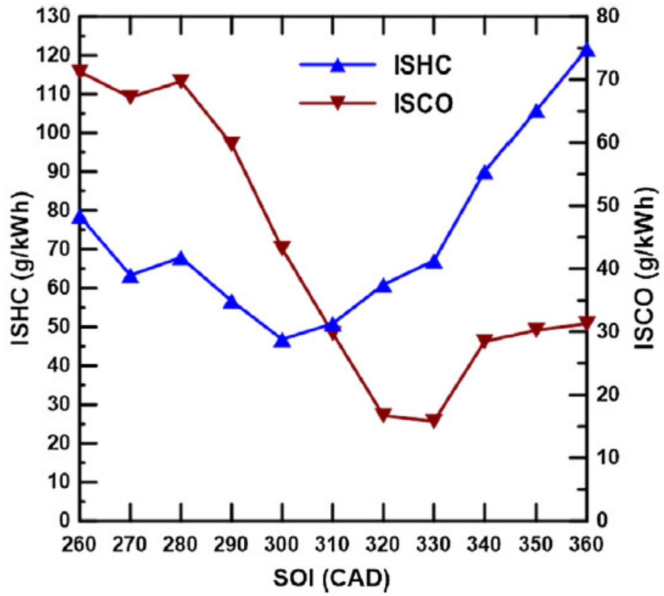

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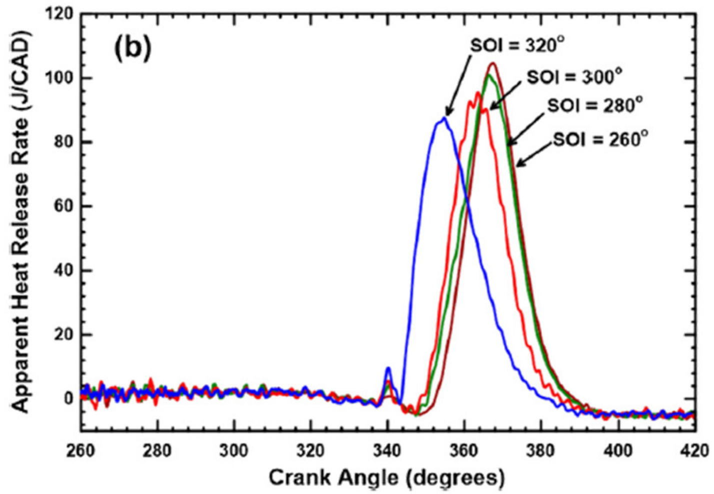
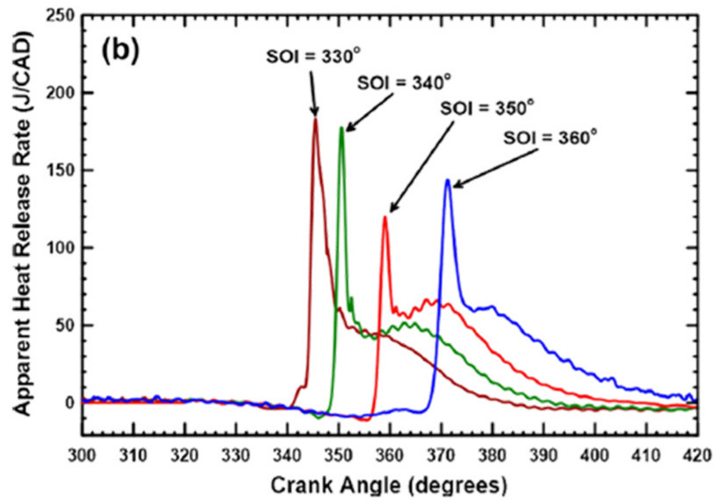
[9]



- The SOI affects the heat release rate, modifying the combustion process
- Delaying the injection process, the heat release rate profile switches from a one-stage to a twin-stage shape



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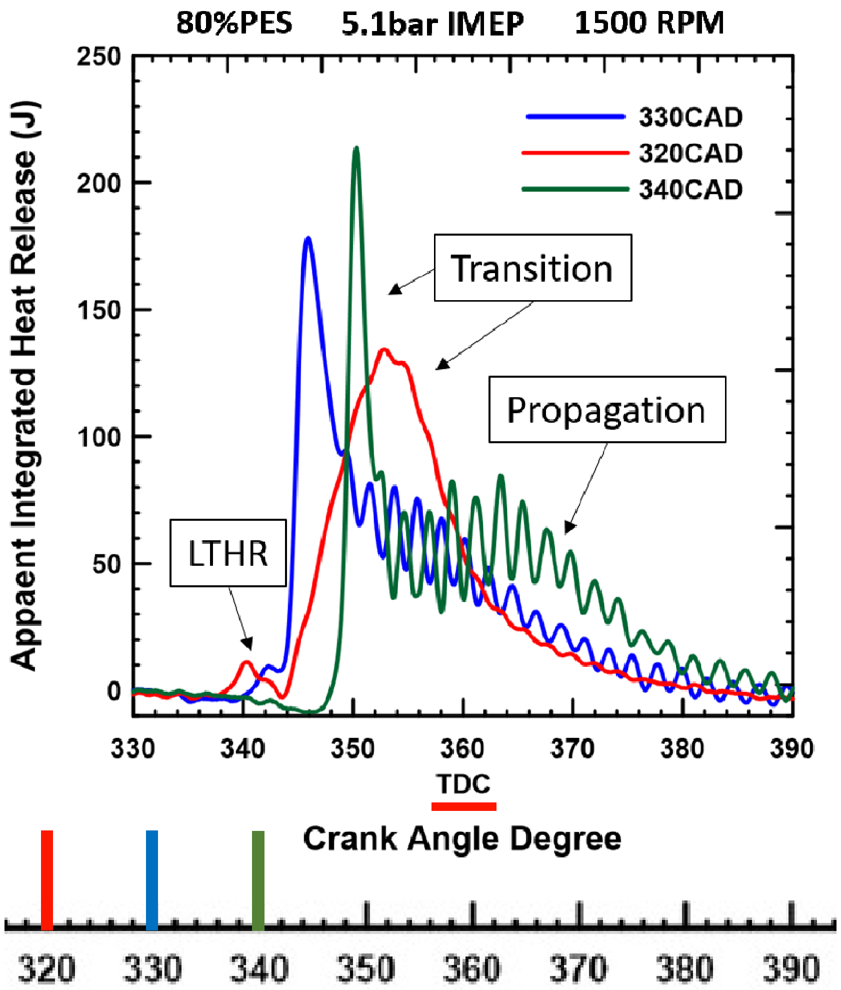
Objectives



Focusing on the transition-SOI, the CFD analysis of the HRR curves aims at thoroughly understand:

- the role of **each fuel** during the combustion process
- the reasons for the <u>transition</u> between the **one-stage** to the **two-stage** HRR curve
- The **LTHR** phase and its influence <u>on the combustion process</u>
- The combustion process itself, with particular focus <u>towards the end</u>.

Conclusions - PSC

- The implemented combustion model is accurate in lean conditions
- Good agreement between numerical and experimental results
- Small discrepancies due to uncertainties on the boundary conditions

- The PSC ignition system stabilizes and supports both mixture ignition and flame propagation
- Engine performance is enhanced thanks to mixture stratification
- The effects of PSC are more evident as the mixture is progressively leaned out
- A correlation has been found among the air fuel ratio, the turbulent kinetic energy and the cycle peak pressure, more sensitive to the tke

Conclusions – Dual Fuel

- The numerical approach proposed has been proved capable of capture accurately all the main phenomena occurring during the dual-fuel combustion at low load and high-percentage of energy substitution
- The LTHR phenomenon has represented by the model especially at late SOI allowing for a deep investigation of the local phenomena
- The role of each fuel has been highlighted while sweeping the SOI
- The numerical framework is then a reliable instrument for further development of dual-fuel engines in order to improve engine performance and reduce emissions.

References

- [1] L. Bartolucci, S. Cordiner, V. Mulone, V. Rocco, Natural Gas Partially Stratified Lean Combustion: Analysis of the Enhancing Mechanisms into a Constant Volume Combustion Chamber, Fuel, Volume 211, 2018, Pages 737-753, https://doi.org/10.1016/j.fuel.2017.09.100.
- [2]Bartolucci, L., Cordiner, S., Mulone, V., and Rocco, V., "Natural Gas Fueled Engines Modeling under Partial Stratified Charge Operating Conditions," SAE Technical Paper 2017-24-0093, 2017, doi:10.4271/2017-24-0093.
- [3] L. Bartolucci, S. Cordiner, V. Mulone, V. Rocco, LES analysis of the mixing process in a natural gas fueled engine under Partial Stratified Charge operating conditions - comparison against the Constant Volume Combustion Chamber case, Energy Procedia, Volume 126, 2017, Pages 1019-1026, https://doi.org/10.1016/j.egypro.2017.08.308.
- [4] Performance and Emissions Characteristics of Diesel-Ignited Gasoline Dual Fuel Combustion in a Single-Cylinder Research Engine - U. Dwivedi, C. D. Carpenter, E. S. Guerry, A. C. Polk, S. R. Krishnan and K. K. Srinivasan[1] *J. Eng. Gas Turbines Power*
- [5] Injection timing effects on partially premixed diesel–methane dual fuel low temperature combustion - Guerry, E. Scott - Raihan, Mostafa S. - Srinivasan, Kalyan K. - Krishnan, Sundar R. - Sohail, Aamir - Applied Energy

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Thanks for your attention

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