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Effects of Passive Pre-chamber Geometry and Ignition System on Engine Performance

Francesco Di Sabatino[1], Pablo Jose Martinez-Hernandiz[2], Ricardo Novella Rosa[2], Isaac Ekoto[1]

[1]Sandia National Laboratories, Livermore, CA

[2]CMT Motores Termicos, Valencia, Spain

Acknowledgements

DOE Program Managers: **Michael Weismiller, Kevin Stork, Gurpreet Singh**

ANL contributors: Toby Rockstroh, Taehoon Han

Sandia National Laboratories

Technical support: **Alberto Garcia**

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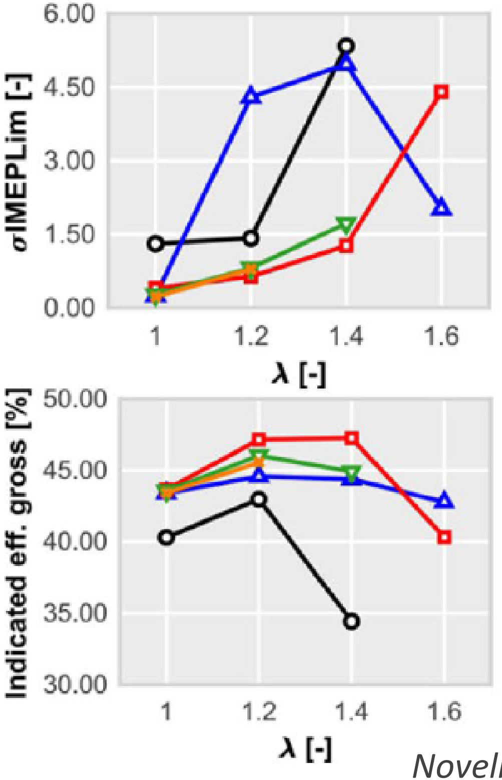
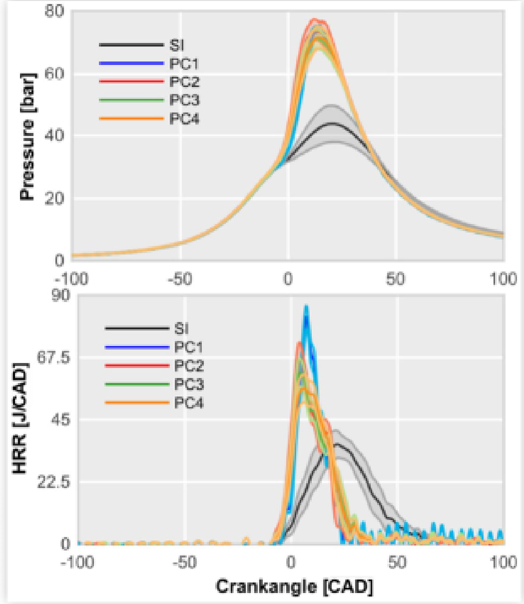
Background

Background: Why passive PC?

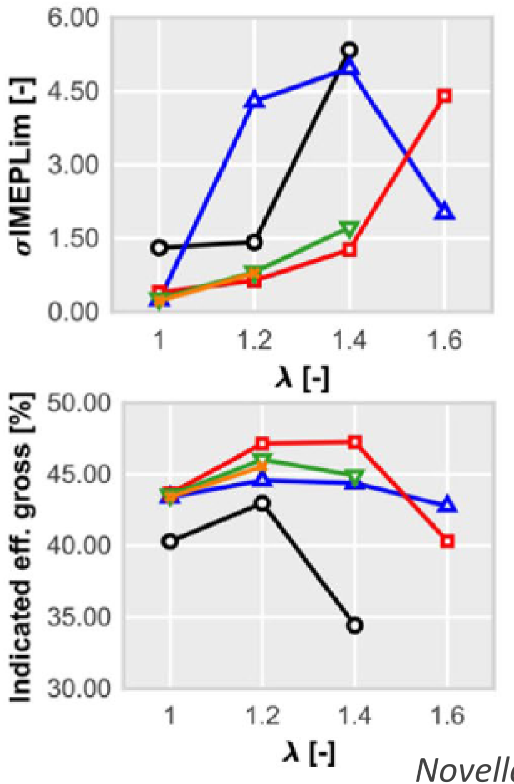


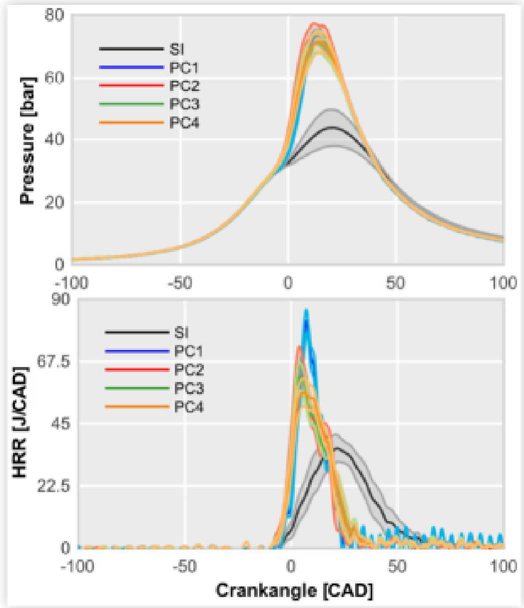


Novella et al., 2020

- Compared to conventional SI systems, PC ignition can lead to:
  - Faster Combustion
  - Smaller COV of IMEP
  - Extended lean limit
  - Higher efficiency
  - Easy implementation

Background: Why passive PC?





Novella et al., 2020

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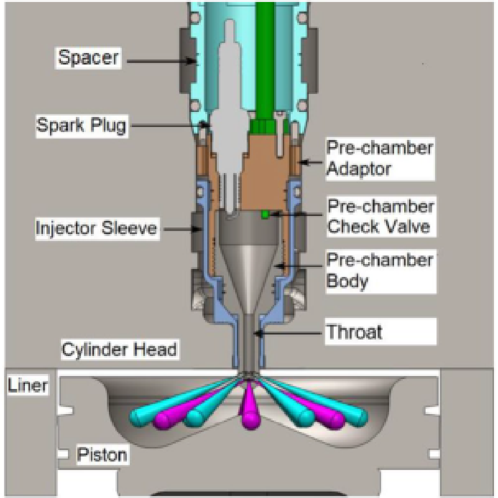
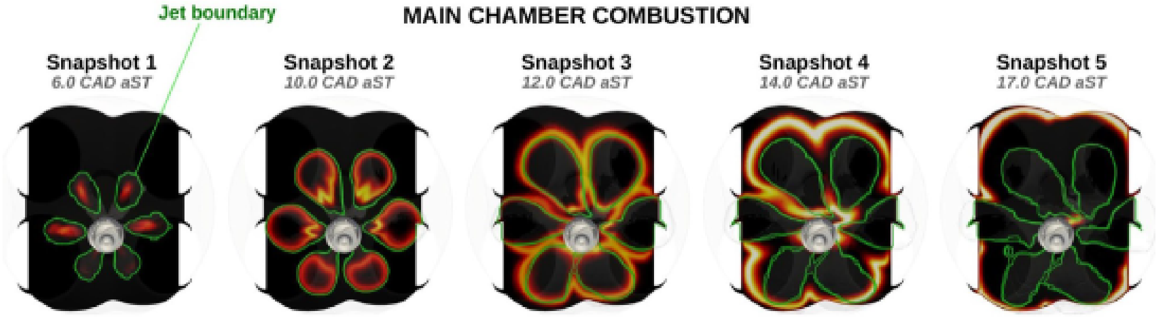
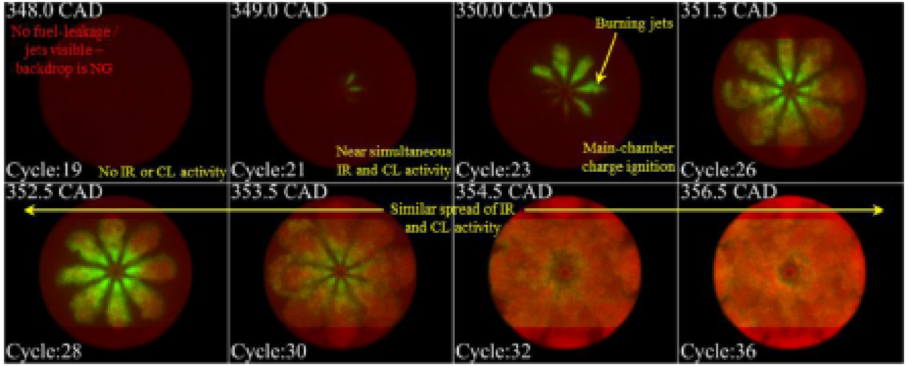
Background: Radial jets might not be the only way



Hlaing et al., 2021



Novella et al., 2020



Rajasegar et al., 2021

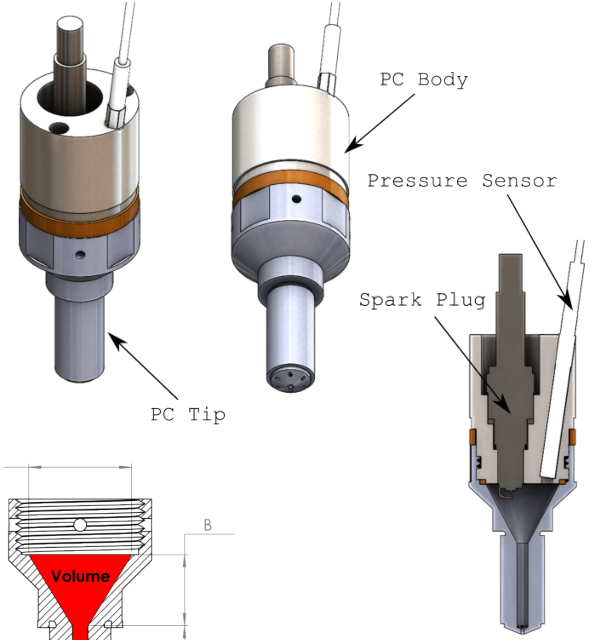
- Recent studies deal with:
  - PC with radial jets only
  - Conventional inductive spark ignition

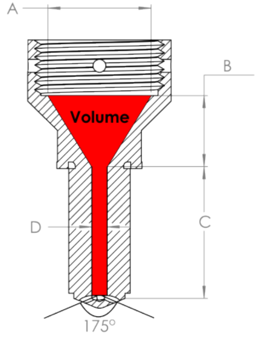
Objectives

- Investigate how PC geometry and ignition systems affect HRR trace

Experimental setup and diagnostics

Experimental setup: pre-chamber geometries and nozzle-patterns

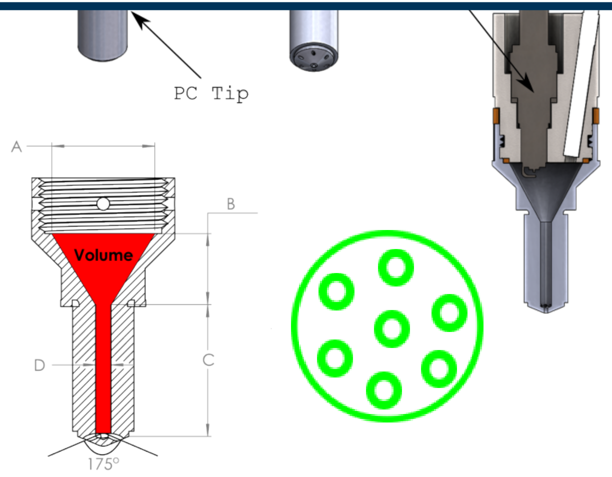




PC ID	Volume [cc]	Radial nozzle	Nozzles diam. [mm]	Axial nozzle	Nozzle diam. [mm]
1	2.0	6	0.8	1	1.0
2	1.7	6	0.8	1	1.0
3	1.7	6	1.2	0	0

Experimental setup: pre-chamber geometries and nozzle-patterns

Tangentially placed nozzles and narrow throat to enhance swirl in the PC



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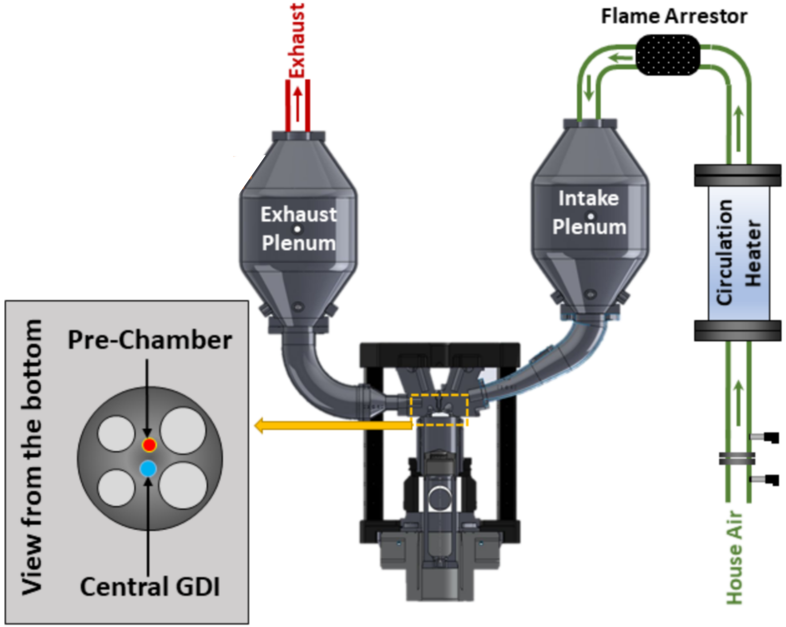
PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole

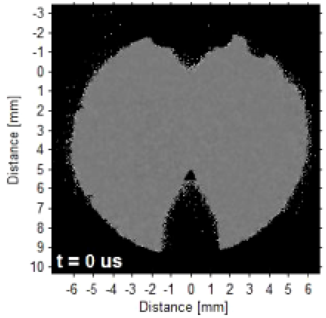
Experimental setup: the engine and ignition systems



Inductive spark discharges M8 spark plug (ISP)

Ford DG562

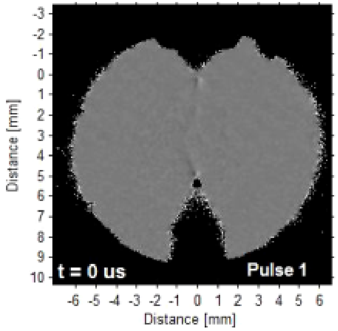
NGK ER9EHIX



Nanosecond spark discharges M10 spark plug (NRP)

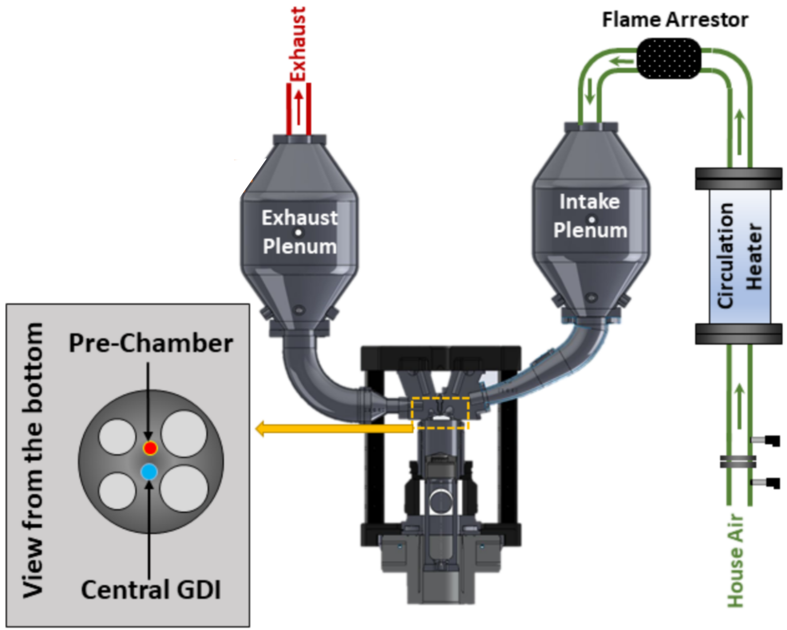
TPS SSPG-20X

NGK 7473

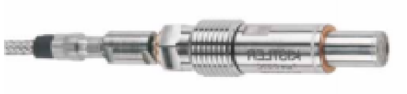


Faster flame development

Diagnostics: pressure sensors



Kistler 6135A

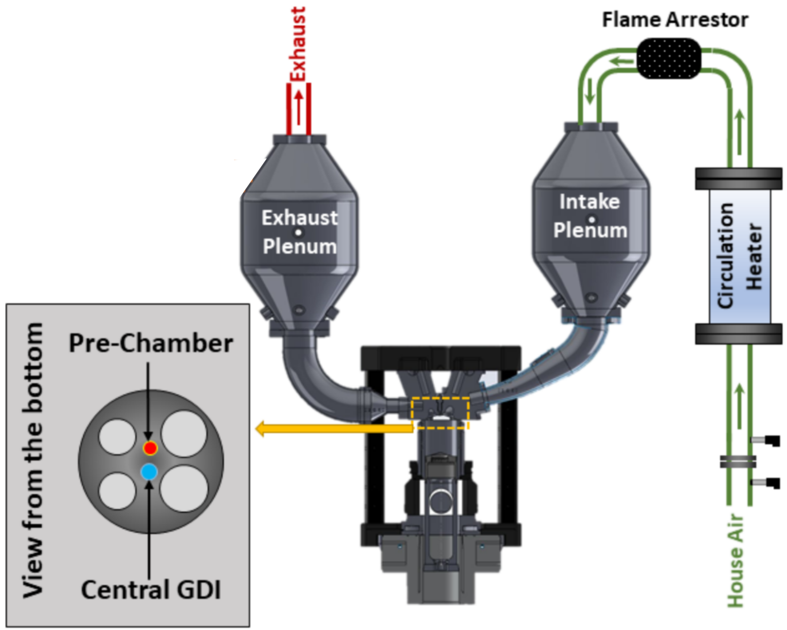


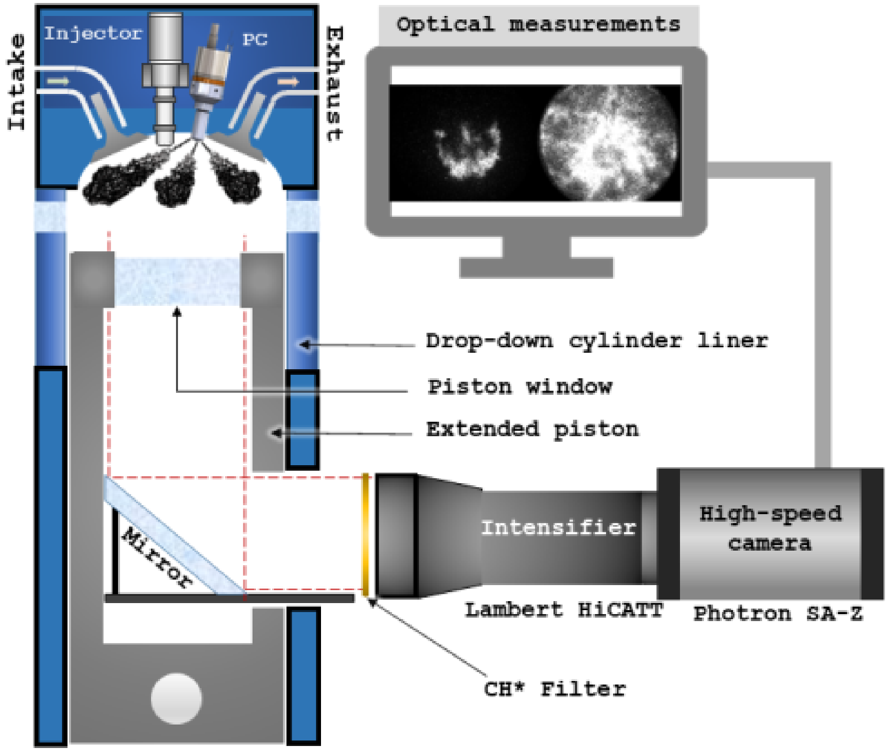
MC/Cylinder pressure

AVL GH14P

PC pressure

Diagnostics: high-speed CH* chemiluminescence imaging systems





Experimental conditions and procedure

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Experimental conditions

- Fuel: RD5-87 single injection
- Fuel injection pressure: 100 bar
- Homogeneous charge
- IMEP: 3.5 bar (constant)
- RPM: 1300
- T_{int}: 62°C
- P_{int}: 51 – 61 kPa

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ISP

- Coil charge dur. = 4 ms
- Discharge gap = 0.7 mm
- Secondary Energy = 61.5 mJ

NRP

- 2-5 pulses at 10 kHz
- Pulse width ≈ 10 ns
- Primary voltage = 19-26 kV
- Secondary Energy = 3-18 mJ
- Discharge gap = 0.9 mm

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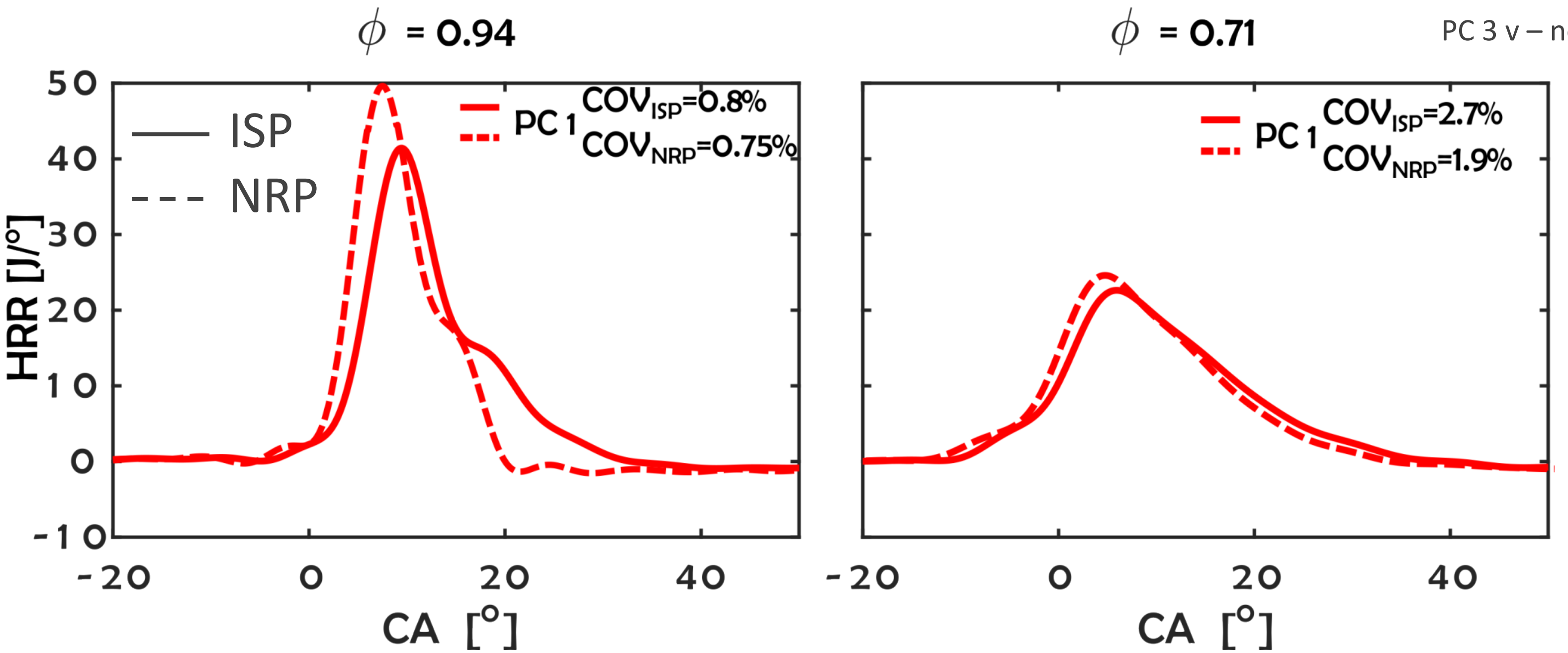
Experimental procedure

- Flow rate of combustion air was increased to reduce Φ, while the flow rate of fuel was adjusted to obtain IMEP = 3.5 bar
- Spark timing was adjusted to obtain stable combustion
- The engine was run in a continuous firing configuration with a moderate valve overlap. 100 cycles of measurements were collected
- Primary voltage and number of pulses were adjusted to obtain stable combustion when NRP is used
- CH* chemiluminescence images were collected:
  - 20 kHz 896x896 pixels
  - 40 kHz 896x448 pixels (closer look at the PC jets)

Results and discussion

Results: ISP vs NRP main chamber heat release rate

PC 1 V – axial hole
PC 2 v – axial hole
PC 3 v – no axial hole



- Bi-modal profile of heat release was observed
- NRP increased peak and made the profile narrower

- No bi-modal profile observed
- NRP increased peak

Results: ISP vs NRP main chamber heat release rate

PC 1 V – axial hole
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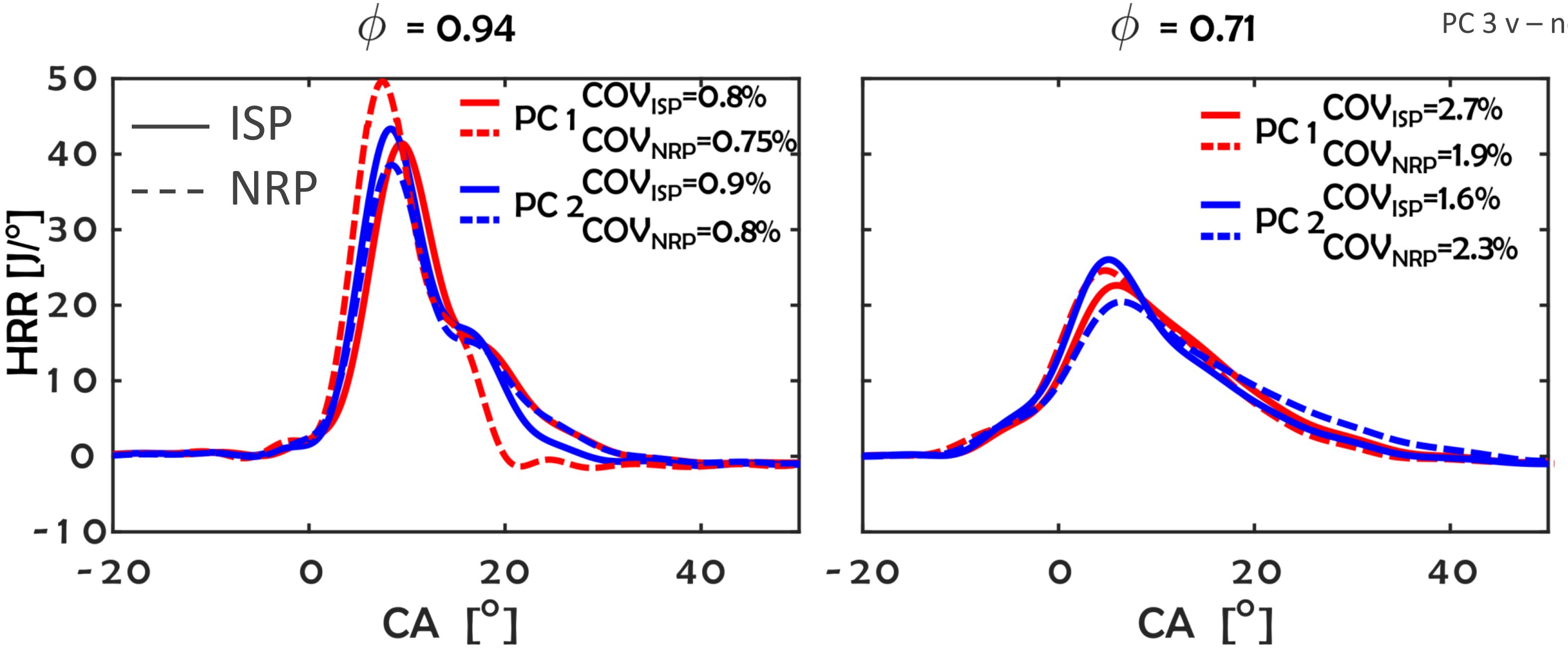
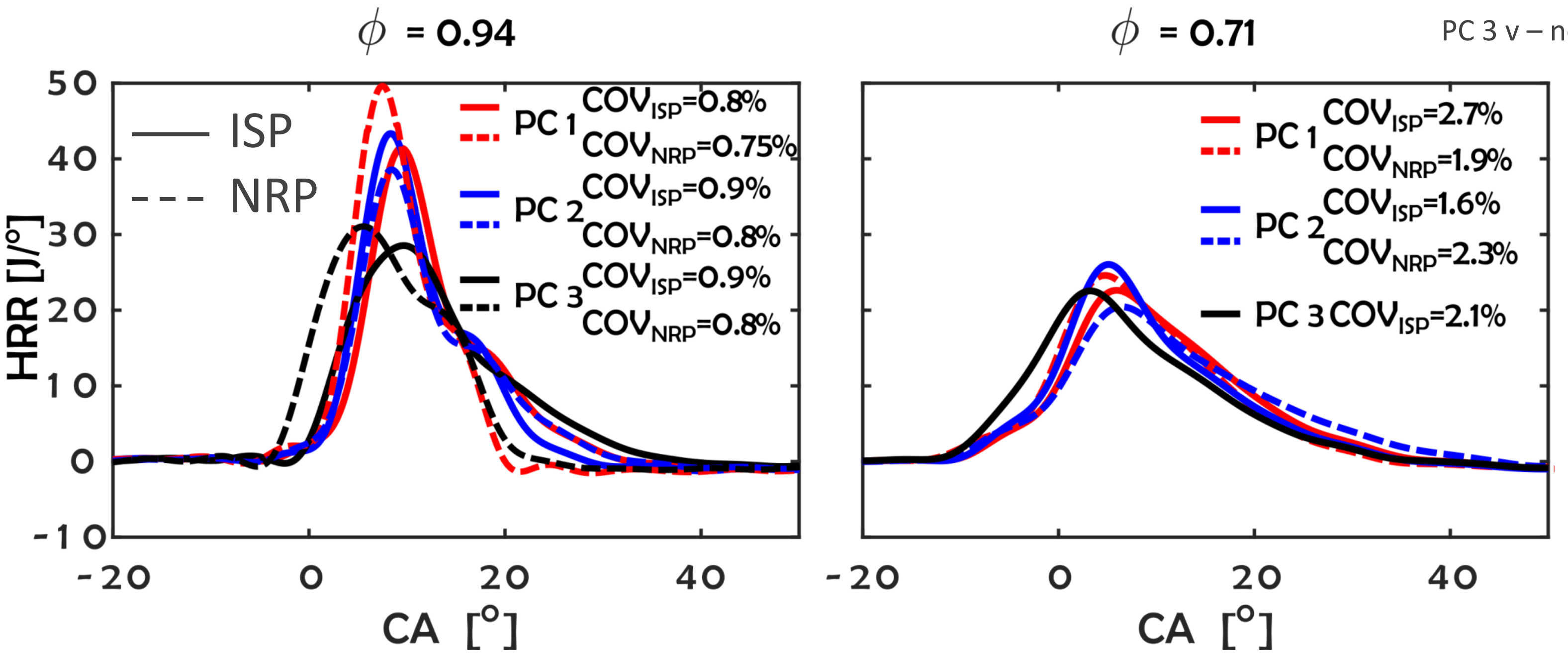


- Bi-modal profile of heat release was observed
- NRP decreased peak and made the profile broader

- No bi-modal profile observed
- NRP decreased peak

Results: ISP vs NRP main chamber heat release rate

PC 1 V – axial hole
PC 2 v – axial hole
PC 3 v – no axial hole



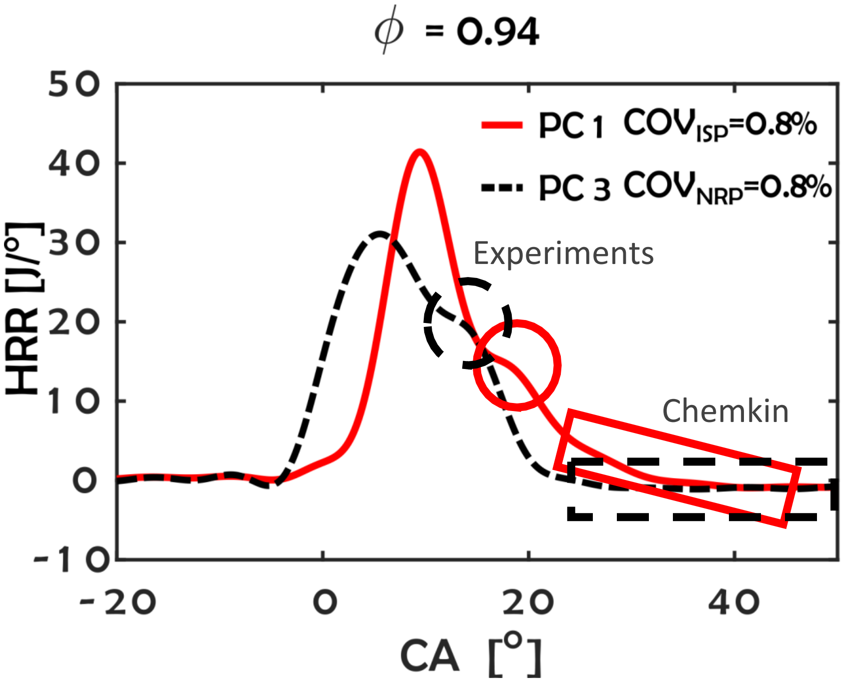
- Bi-modal profile of heat release was observed for NRP, but not for ISP
- NRP slightly increased peak and made the profile narrower

- No bi-modal profile observed
- No stable combustion at these conditions for the NRP

CRF

Results: Chemkin simulations showed very retarded end gas auto-ignition

- Numerical setup for Chemkin (ϕ = 0.94):
  - Pressure set to TDC and max P
  - Temperature set to TDC and max + 0-100 K
  - PACE-20 as surrogate for RD5-87
  - Closed homogeneous batch reactor with no heat losses at constant pressure
    - PC showed possibility of end gas auto-ignition but very retarded compared to the second peak of AHHR



PC 1 V – axial hole

PC 2 v – axial hole

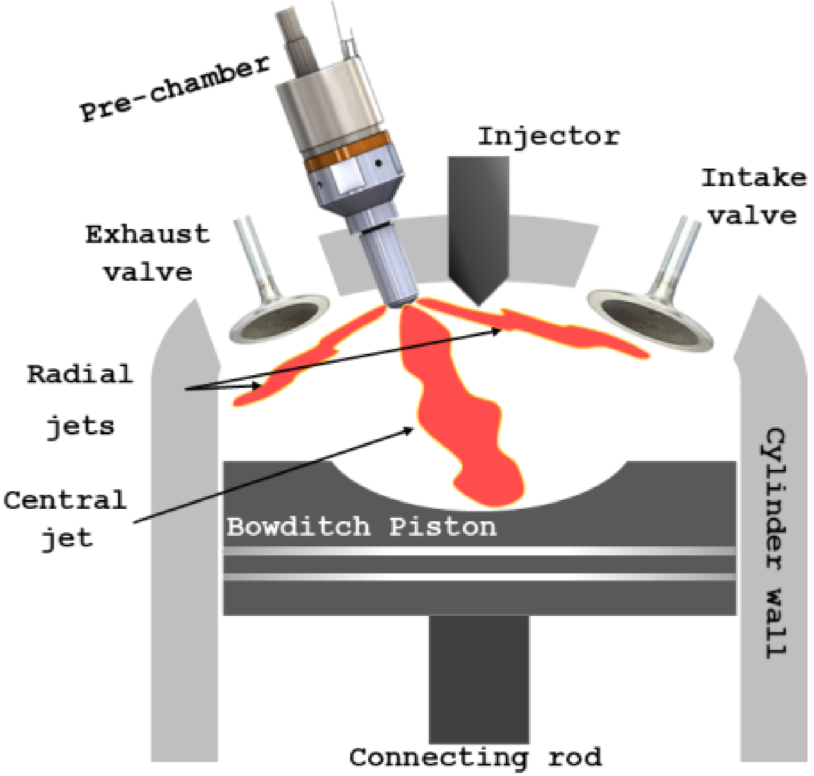
PC 3 v – no axial hole

Results: what other phenomena can explain the bi-modal trend?

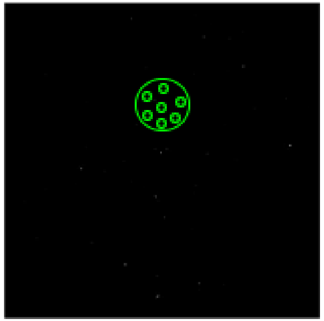
PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole



PC 1 Φ = 0.94 ISP



- Succession of core and squish volume combustion generated by the combined axial and radial jets

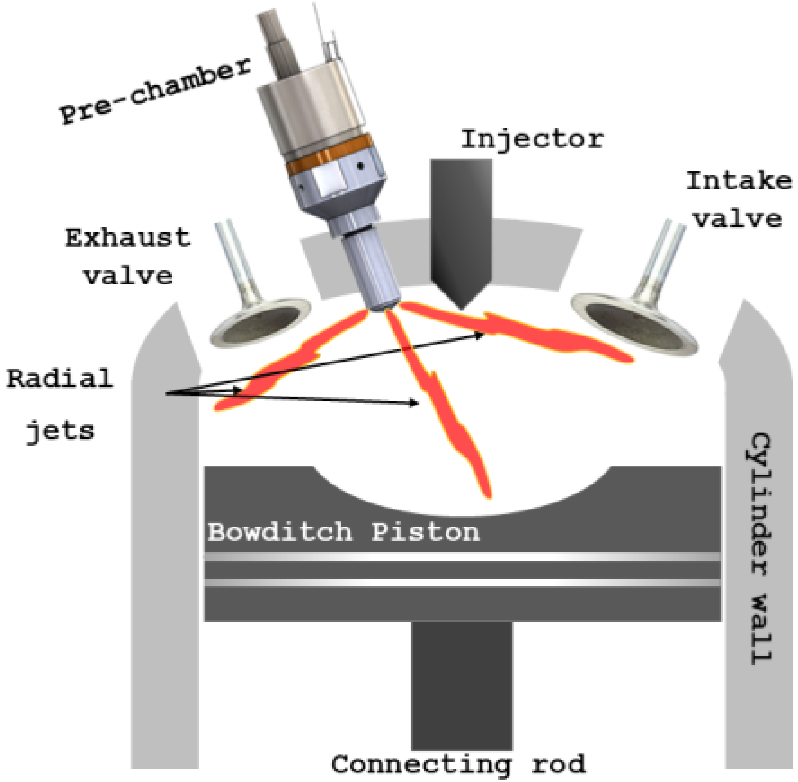
- No axial jets for PC 3 so slower HRR and no second peak

Results: what other phenomena can explain the bi-modal trend?

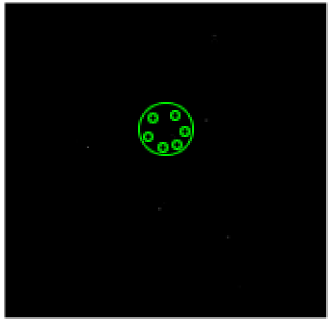
PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole



PC 3 Φ = 0.94 NRP



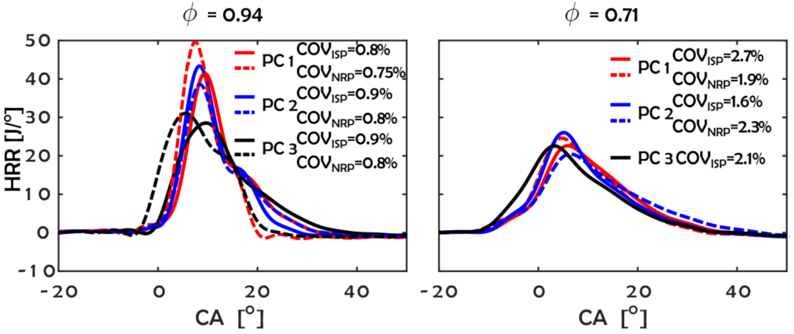
- Radial jets might serve as even hotter hotspots
- More "turbulent" kernel might generate faster flame and stronger jets
- Stronger jets might activate these phenomena

Results: no bi-modal profiles for the leanest equivalence ratios

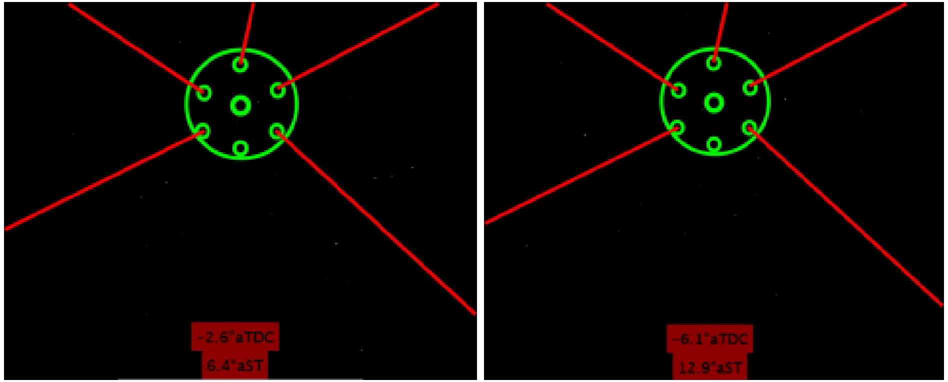
PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole



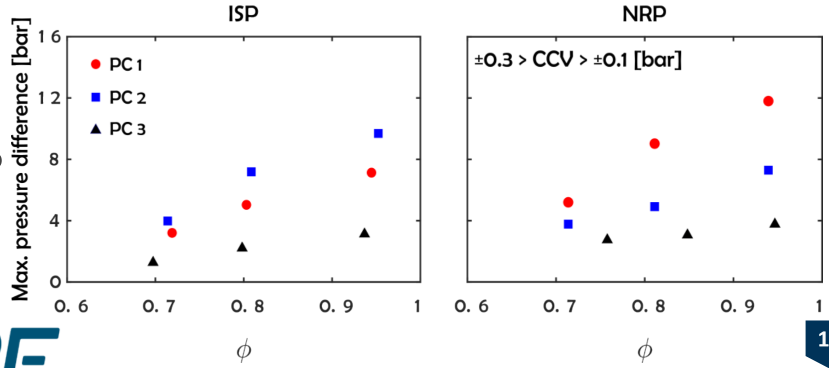
PC 1 Φ = 0.94 NRP   PC 1 Φ = 0.71 NRP



- The deflagration/ignition generated by radial jets disappeared in the leaner cases (no or weak jets)

- The bi-modal trend disappeared as well

  - What controls the strength of the radial jets?



Take home messages

Take home messages

PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole

- Bi-modal AHRR profile was observed for almost all conditions close to stoichiometry
- End gas auto-ignition was unlikely to be the cause for the second peak of AHRR
- Succession of ignition from the axial and radial jest might be the cause together with radial jets-generated hot spots
- Bi-modal trend disappeared for lean conditions possibly due to the absence or weakness of the radial jets
- The use of the NRP ignition system resulted in a faster combustion process and stronger radial jets

Thank you for your attention!

Contact: fdisaba@sandia.gov

F. Di Sabatino, P. J. Martinez-Hernandiz, R. Novella Rosa, I. Ekoto. *Investigation of the Effects of Passive Pre-chamber Nozzle-hole Pattern and Ignition System on Engine Performance and Emissions*. International Journal of Engine Research. Under review.

F. Di Sabatino, P. J. Martinez-Hernandiz, R. Novella Rosa, I. Ekoto. *INVESTIGATION ON THE EFFECTS OF PASSIVE PRE-CHAMBER IGNITION SYSTEM AND GEOMETRY ON ENGINE KNOCK INTENSITY*. ICEF 2022. ICEF2022-95118

P. J. Martinez-Hernandiz, F. Di Sabatino, R. Novella Rosa, I. Ekoto. *A numerical and experimental investigation on different strategies to evaluate heat release rate and performance of a passive pre-chamber ignition system.* SAE Technical Paper: 2022-01-0386.

Backup slides

Engine and fuel characteristics

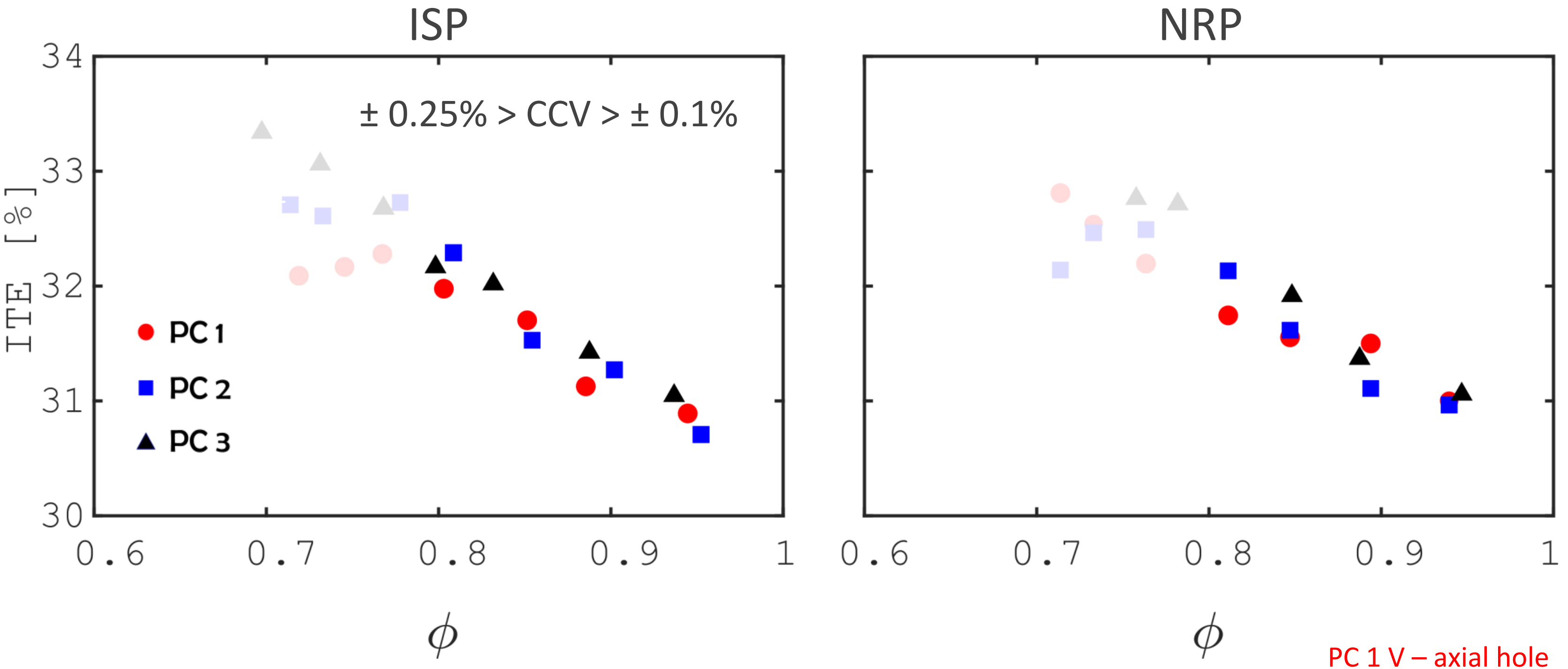
Engine: single cylinder optical

Displaced volume w/o PC [cm3]	551
Bore/Stroke/Connecting Rod [mm]	86/95.1/ 166.7
Geometric Compression Ratio w/o PC	13:1
Intake Valve Open/Close [ºTDC]	343 / -145
Exhaust Valve Open/Close [ºTDC]	160 / -343
Maximum Valve Lift [mm]	9.7
Fuel Injection Pressure [bar]	100
Injector Hole Number	8
Injector Cone Angle [°]	60
Injector Orifice Diameter [µm]	125
Intake Pressure [kPa]	51 – 61
Exhaust Pressure [kPa]	104
Intake Temperature [°C]	62
Engine Speed [rpm]	1300
Cycle fueling rates [mg/cycle]	14.3 – 14.9
Equivalence ratio	0.7 – 0.95
Spark Timing [ºTDC]	-24 – -5

Fuel: RD5-87

Liquid Density @15 °C [g/L]	748
LHV [MJ/kg]	41.9
H/C ratio	1.972
O/C ratio	0.033
Research Octane Number	92.1
Octane Sensitivity	7.3
T10 / T50 / T90 [°C]	57 / 98 / 156

Results, ITE: similar values between tips down to phi = 0.8



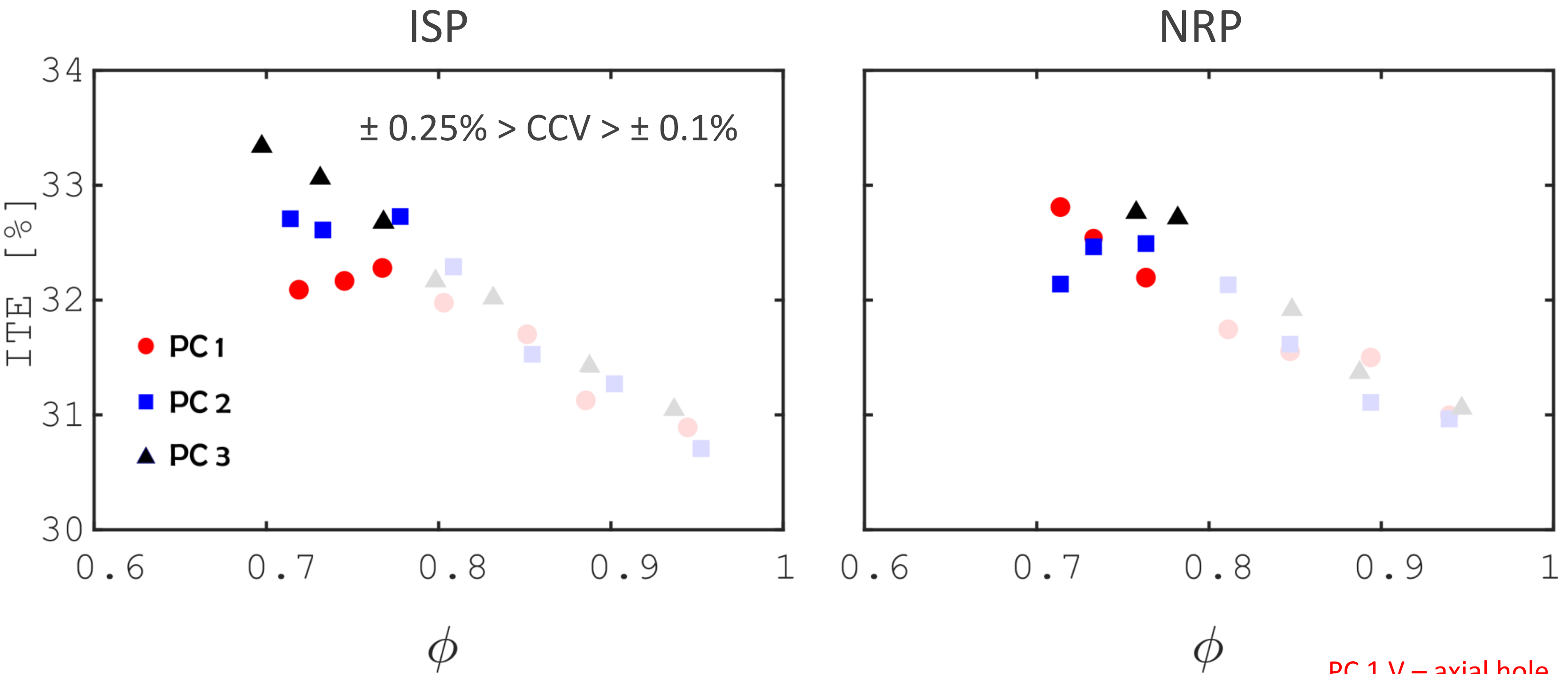
- Similar trend between ISP and NRP

PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole

Results, ITE: leanest conditions show different efficiency values



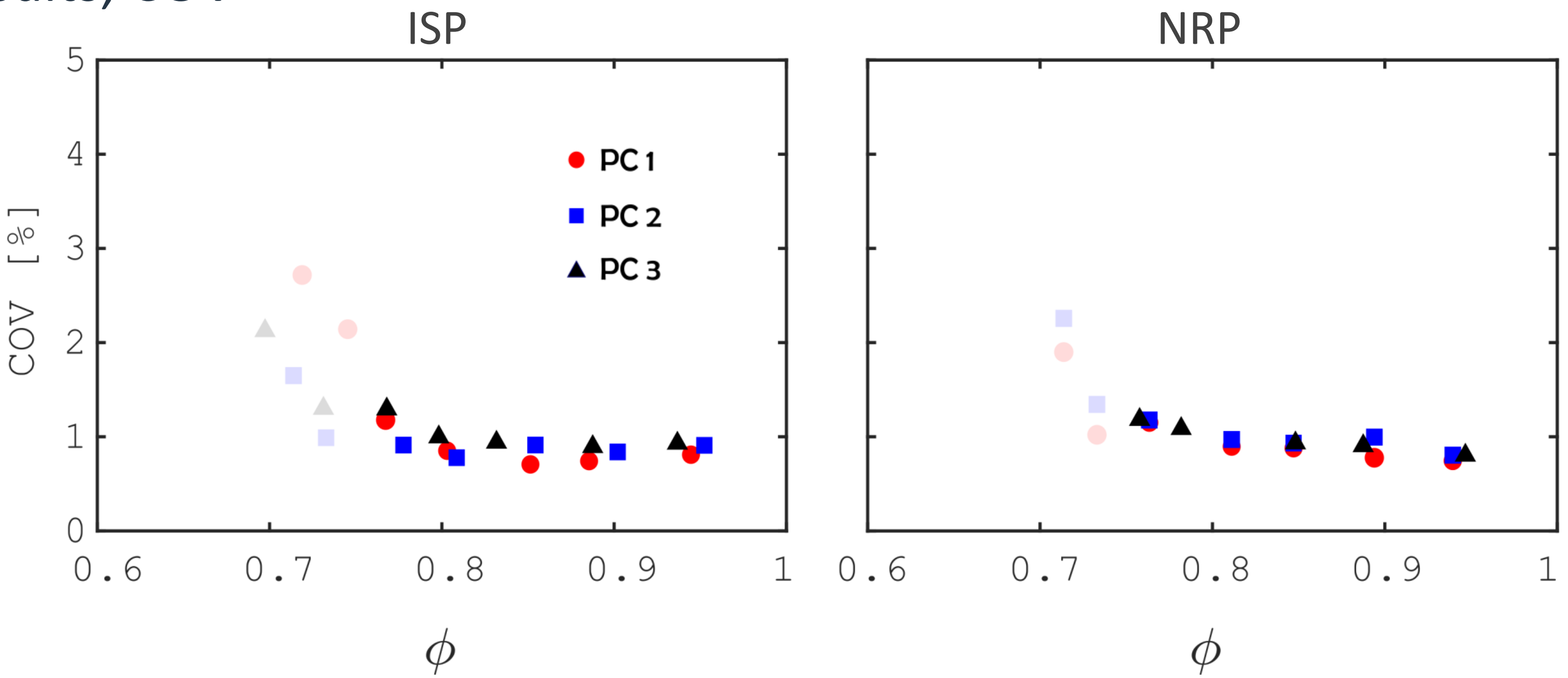
- Substantial difference between tips and for ISP and NRP
- No stable combustion is reached for NRP PC 3

PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole

Results, COV



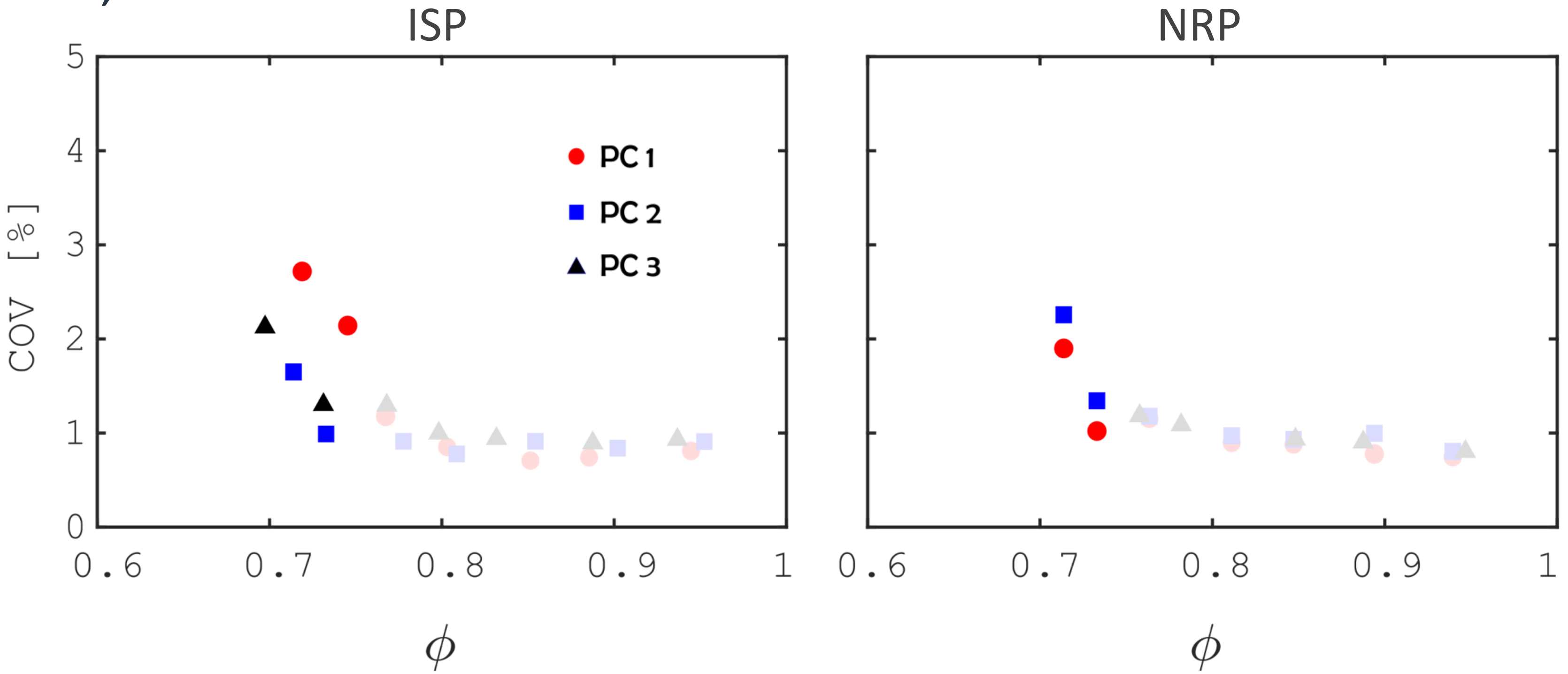
- Similar trend between tips for ISP and NRP

PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole

Results, COV



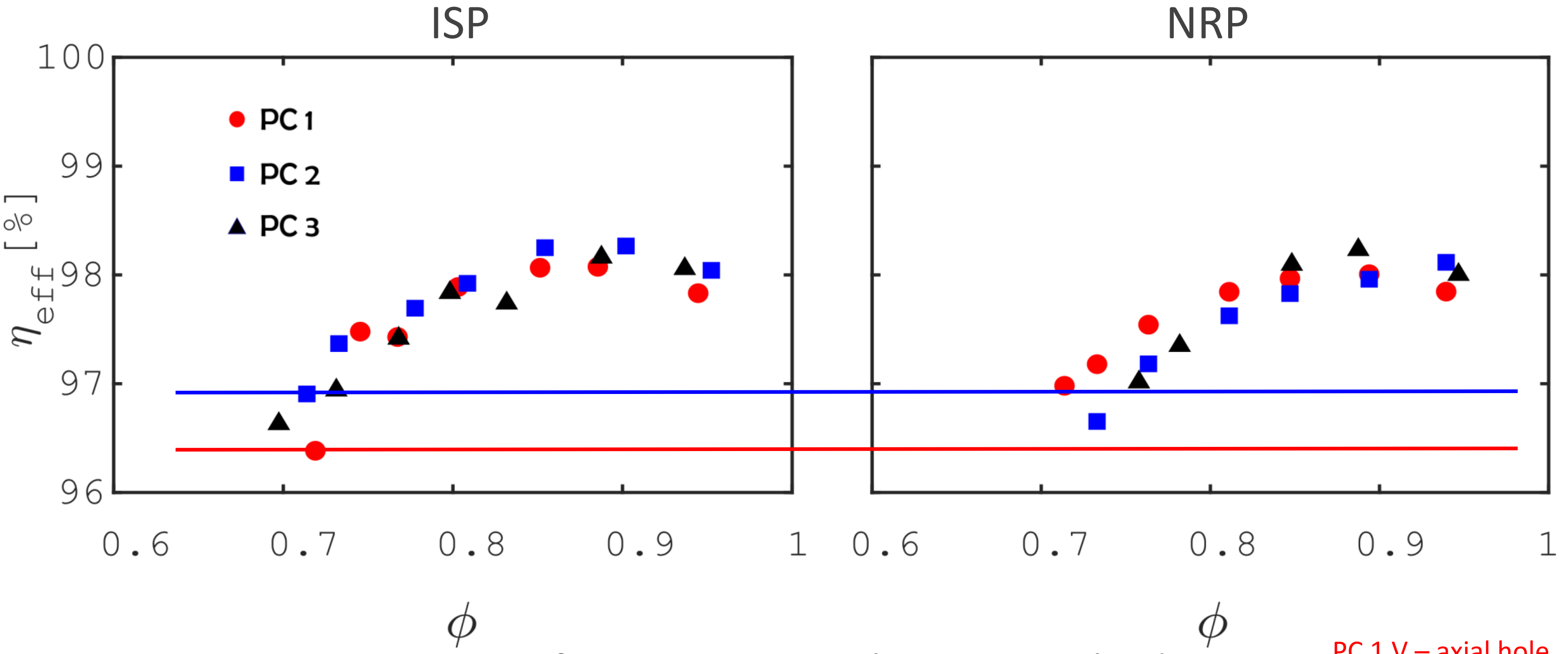
- Substantial difference between tips and for ISP and NRP
- PC 1 more stable when NRP are utilized

PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole

Results, Combustion efficiency



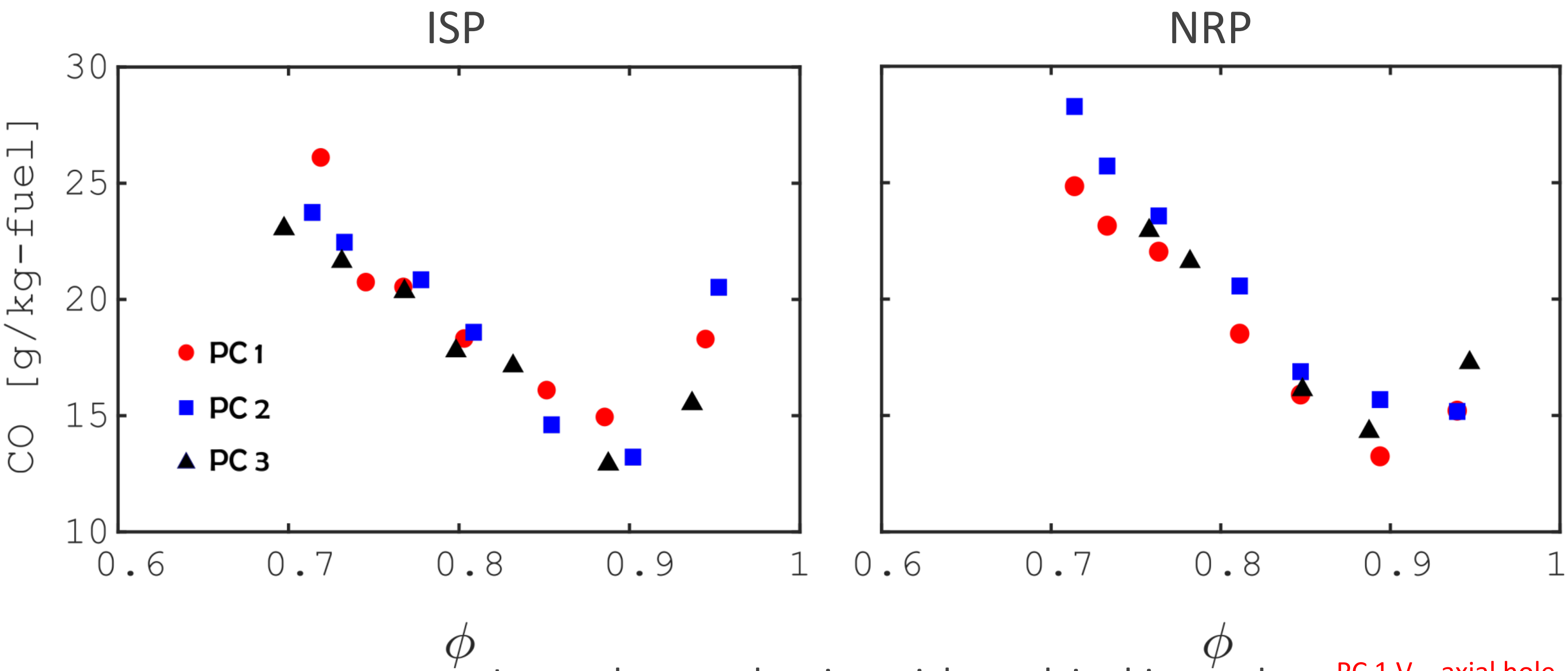
- η_{eff} for PC 1 increases when NRP is utilized
- η_{eff} for PC 2 decreases when NRP is utilized

PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole

Results, emissions, CO



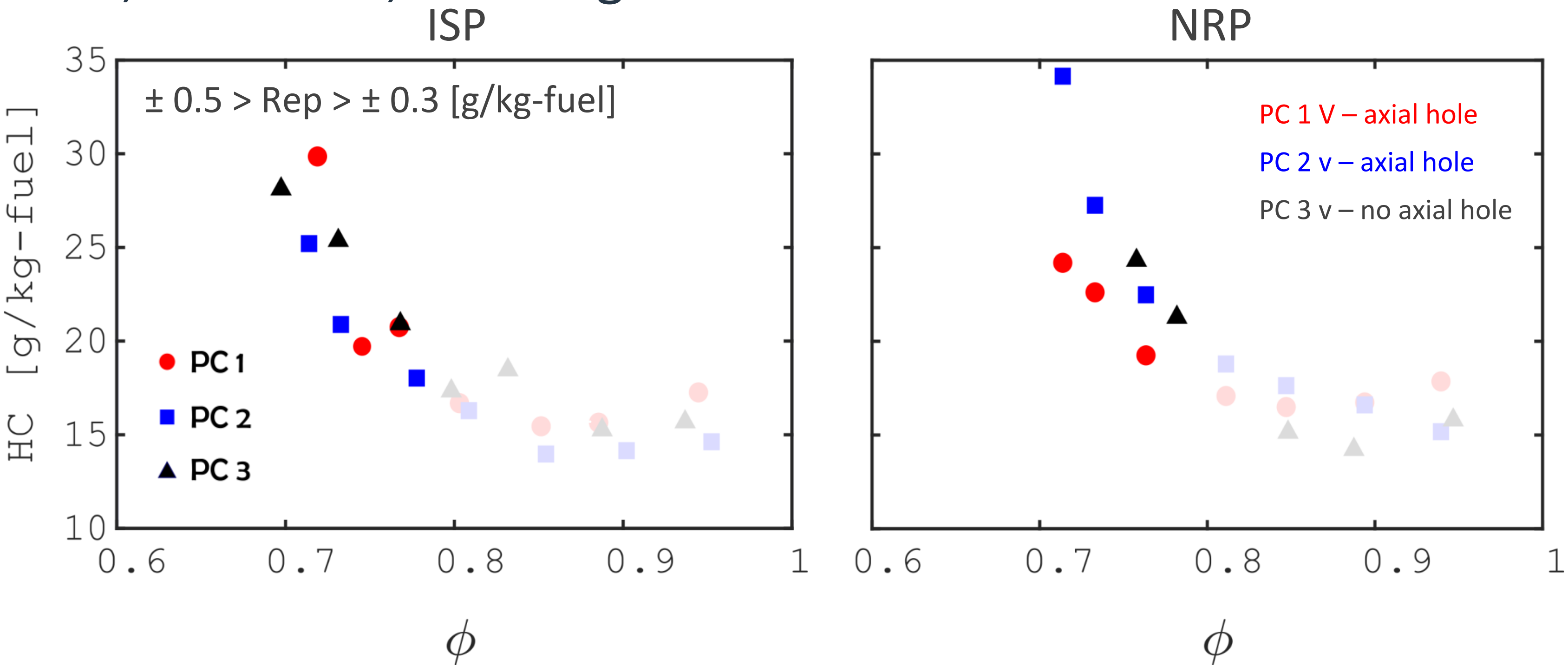
- Incomplete combustion might explain this trend
- Are there other phenomena involved?

PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole

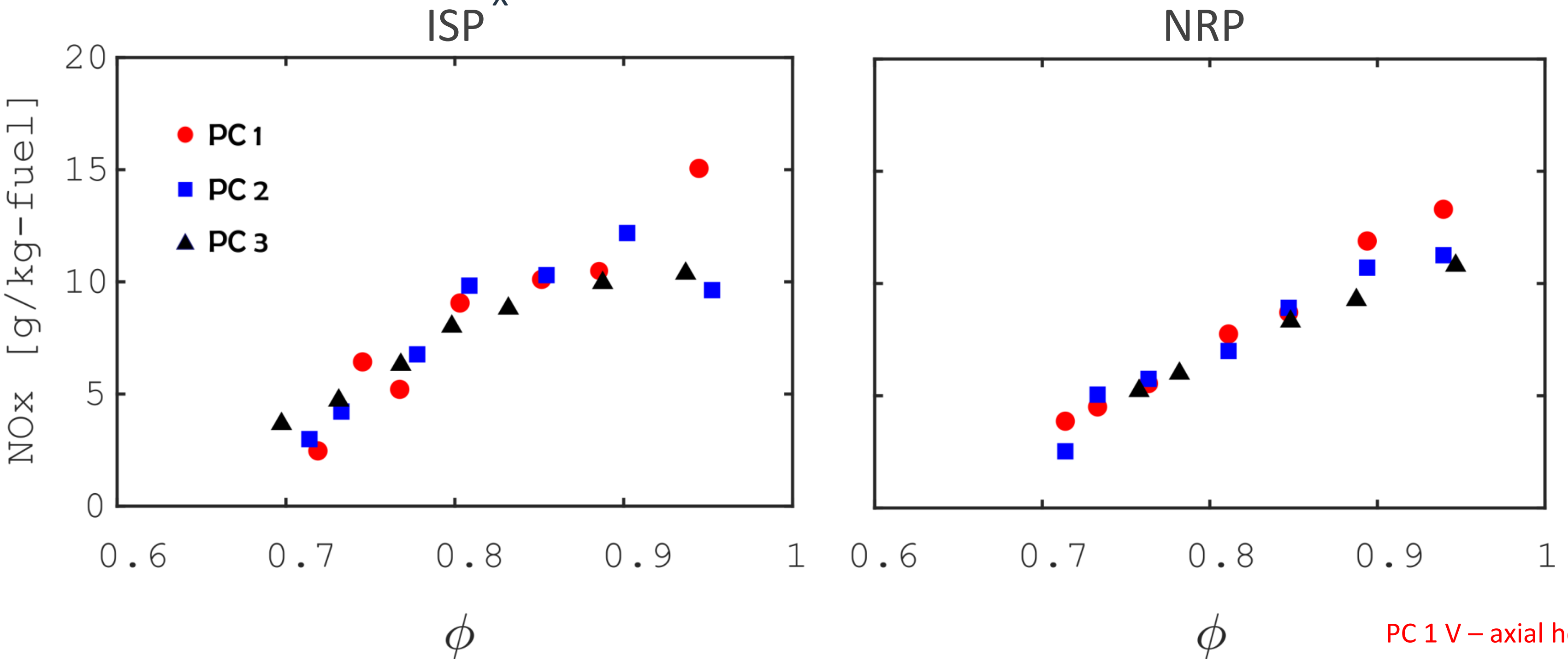
Results, emissions, UHC: high level of UHC emissions for leaner cases



- Incomplete combustion might explain this trend
- PC 1 features lower UCH emissions when NRP is utilized

- An opposite trend is observed for PC 2
- Are there other phenomena involved?

Results, emissions, NO_x



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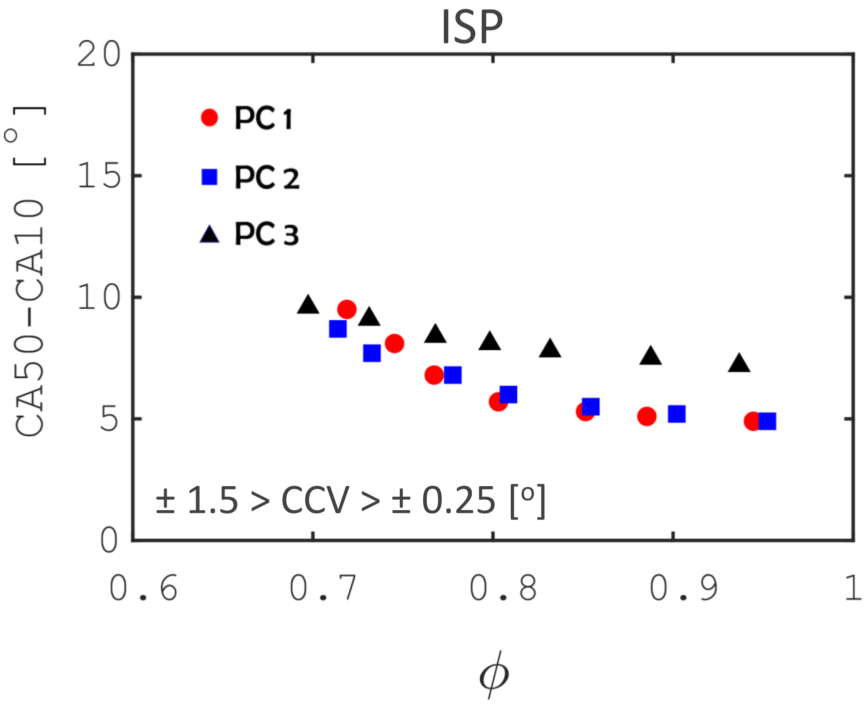
PC 3 v – no axial hole

- Lower emissions than direct spark ignition (14 g/kg-f constant)

Result, comb. dur.: CA50-CA10: non-linear trend for PC 1 and 2



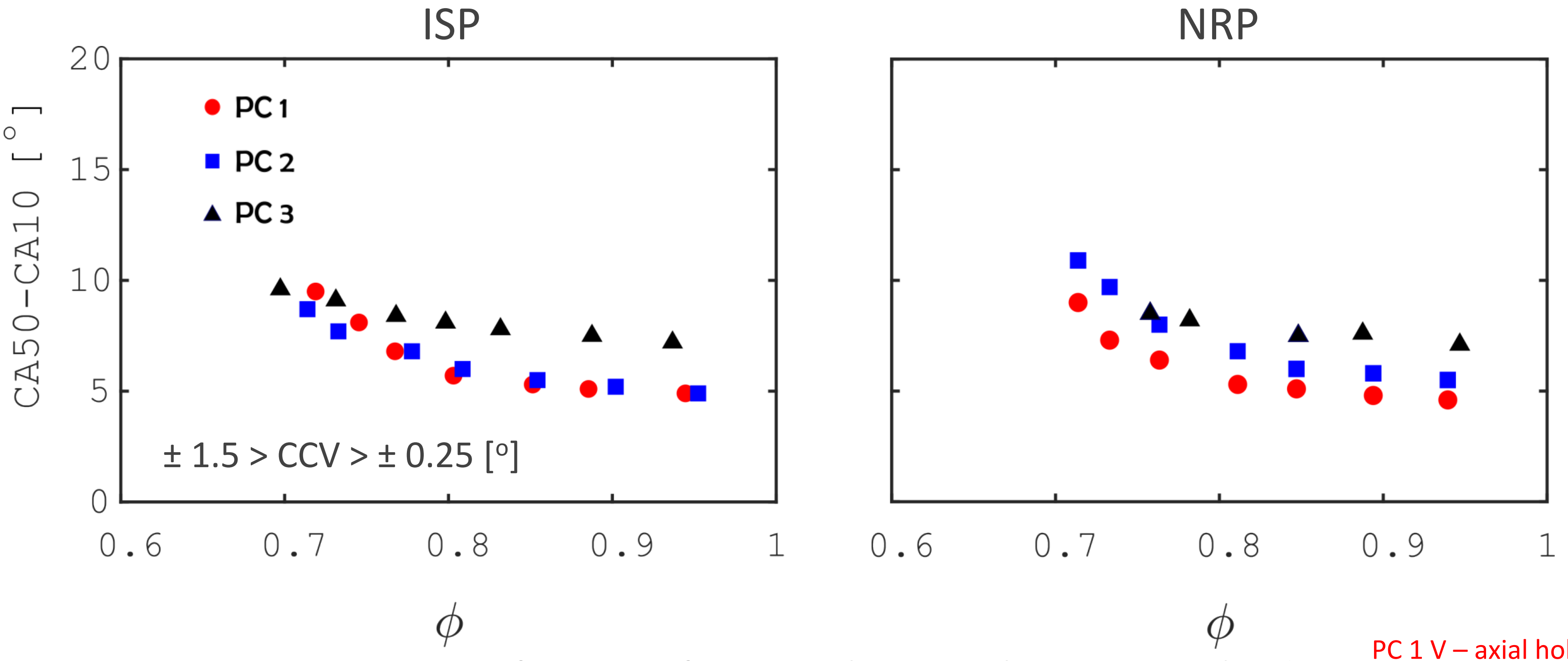
- PC 3 shows an increasing linear trend
- PC 1 and 2 show an increasing non-linear trend, highlighting the presence of possible multiple ignition/combustion phenomena

PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole

Result, comb. dur.: CA50-CA10: non-linear trend for PC 1 and 2



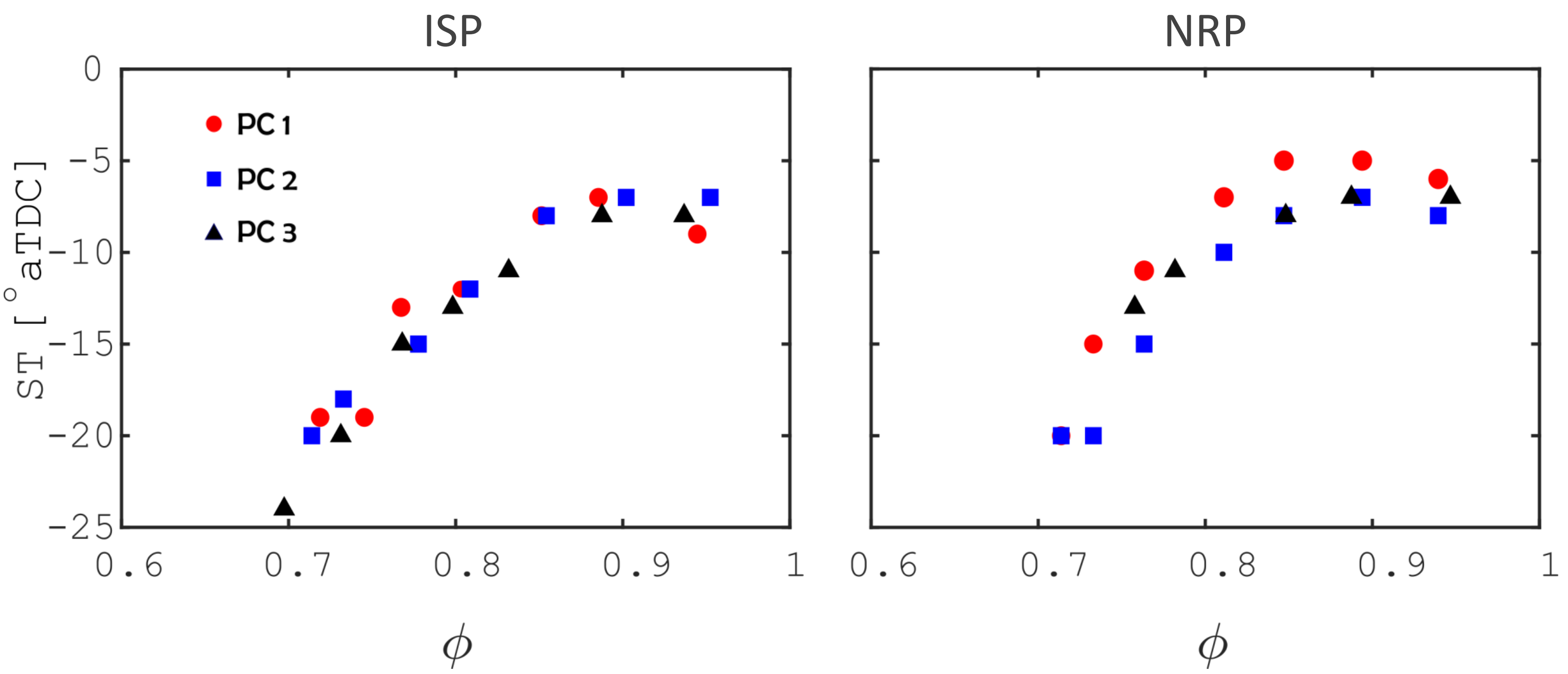
- PC 1 features a faster combustion when NRP is utilized
- Apposite trend is observed for PC 2

PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole

Results, spark timing

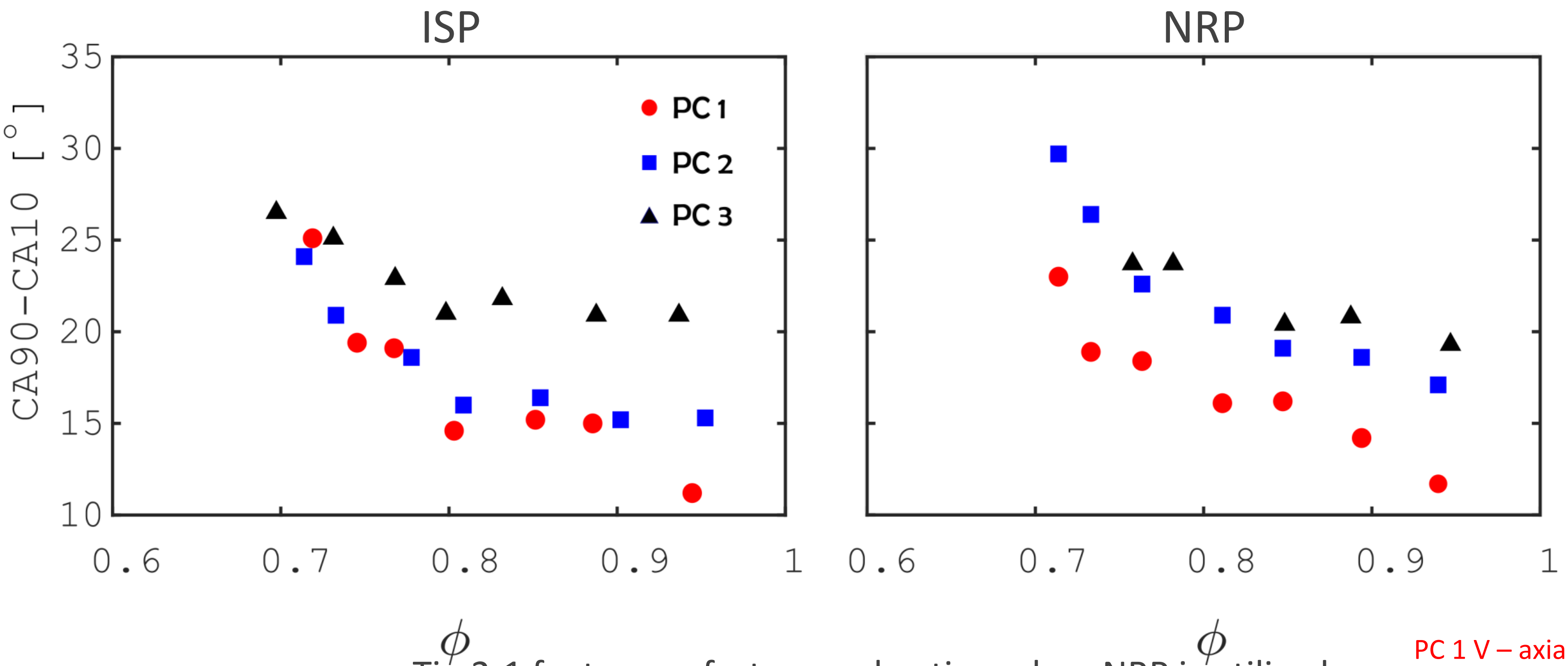


PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole

Results, CA90-CA10



- Tip 2-1 features a faster combustion when NRP is utilized
- Apposite trend is observed for PC 2

PC 1 V – axial hole

PC 2 v – axial hole

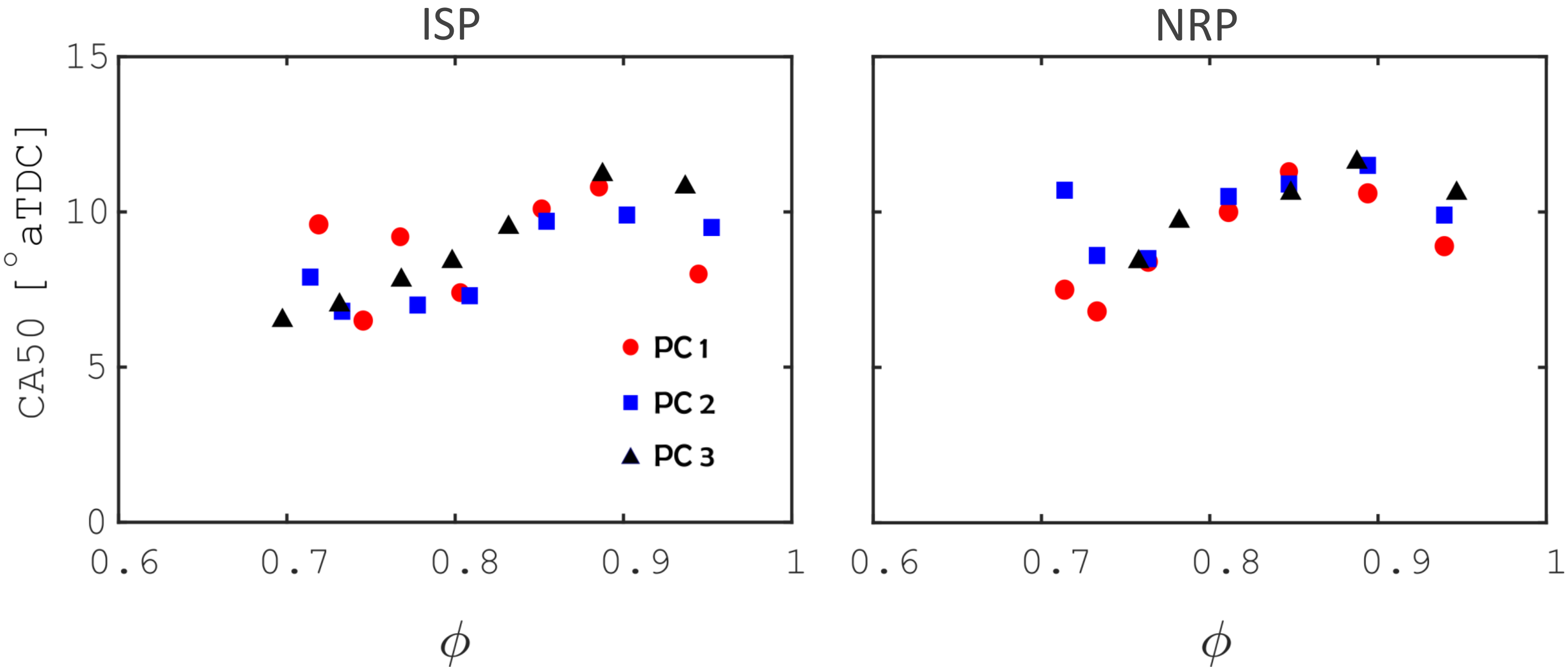
PC 3 v – no axial hole

Results, CA50 (combustion phasing)

PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole

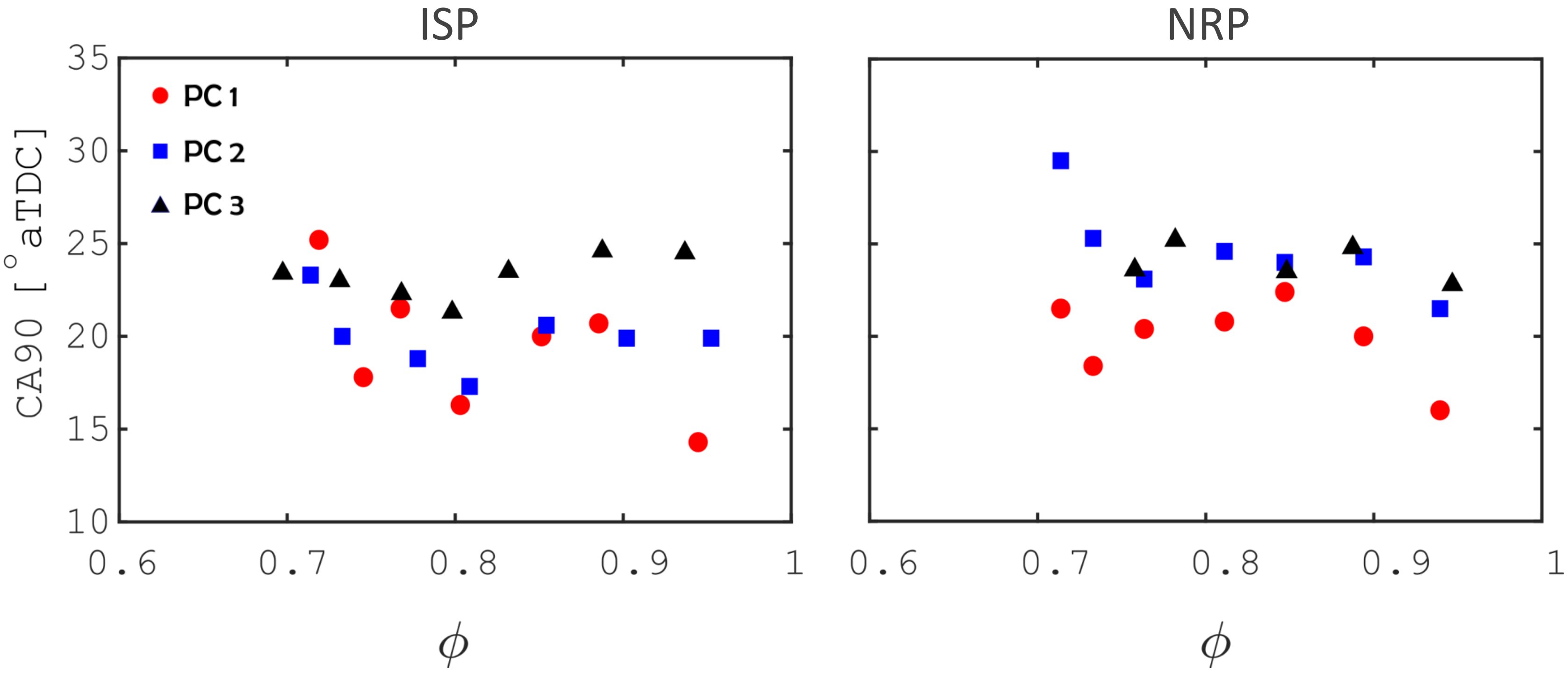


Results, CA90 (combustion duration)

PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole



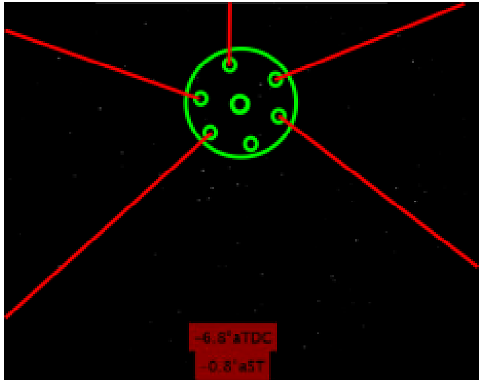
NRP generates stronger radial jets

PC 1 V – axial hole

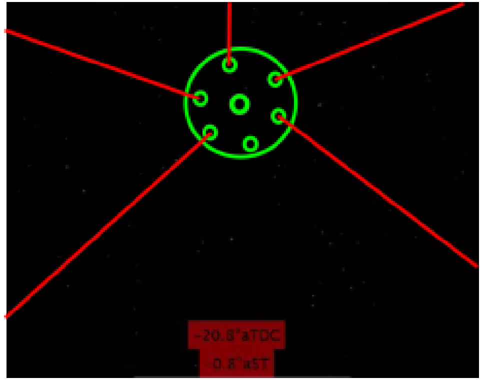
PC 2 v – axial hole

PC 3 v – no axial hole

$\Phi = 0.94$



$\Phi = 0.71$



- Radial jets are still active in leaner cases

Results: Chemkin simulations show very retarded end gas auto-ignition

- Numerical setup for Chemkin (ϕ = 0.94):
  - Pressure set to TDC and max P
  - Temperature set to TDC and max + 0-100 K
  - PACE-20 as surrogate for RD5-87
  - Closed homogeneous batch reactor with no heat losses at constant pressure
    - All PC showed possibility of end gas auto-ignition but very retarded compared to the second peak of AHHR

PC	Second peak (CAD)	ISP (CAD)
1	17.6 ± 2	20.5-40
2	15.2 ± 2	24.6-55.5
3	NA	27.7-61.3

PC	Second peak (CAD)	NRP (CAD)
1	15.1 ± 2	22.8-46.2
2	18.1 ± 2	25.8-59.6
3	15.3 ± 2	26.6-58.2

PC 1 V – axial hole

PC 2 v – axial hole

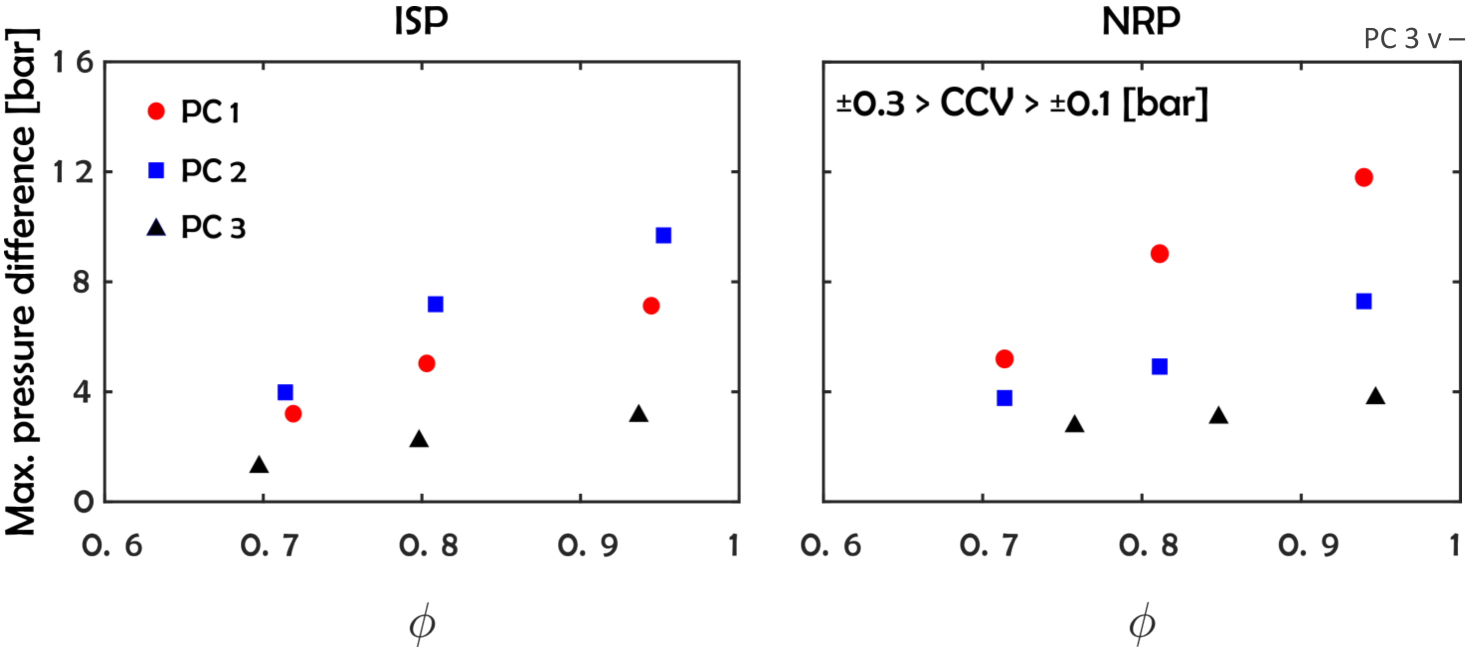
PC 3 v – no axial hole

Results: Higher pressure differential might be the answer

PC 1 V – axial hole

PC 2 v – axial hole

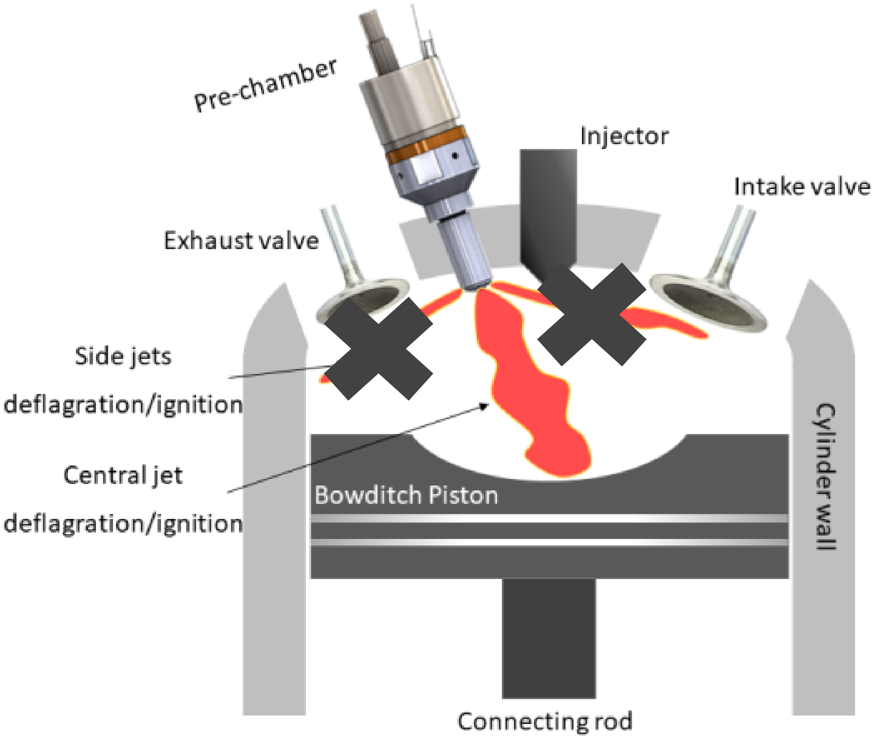
PC 3 v – no axial hole



- Diff. in P decreases with decreasing Φ
- Bi-modal profile disappears at lean Φ

- Higher peak pressure might result from higher deposited electrical power and more a faster flame propagation for NRP, and might generate stronger jets

Radial jets might be crucial for complete combustion of the charge in the cylinder



- Charge in the area close to the cylinder wall might remain unburned due to the slow propagation of the central jet and the absence of the radial jets
- To obtain a constant IMEP (3.5 bar), more fuel needs to be burned so a lower ITE is observed
- Performances of PC 1 and 2 might strongly depend on the presence of the radial jets
- The radial jets are always active for PC 3 so this phenomenon is not observed

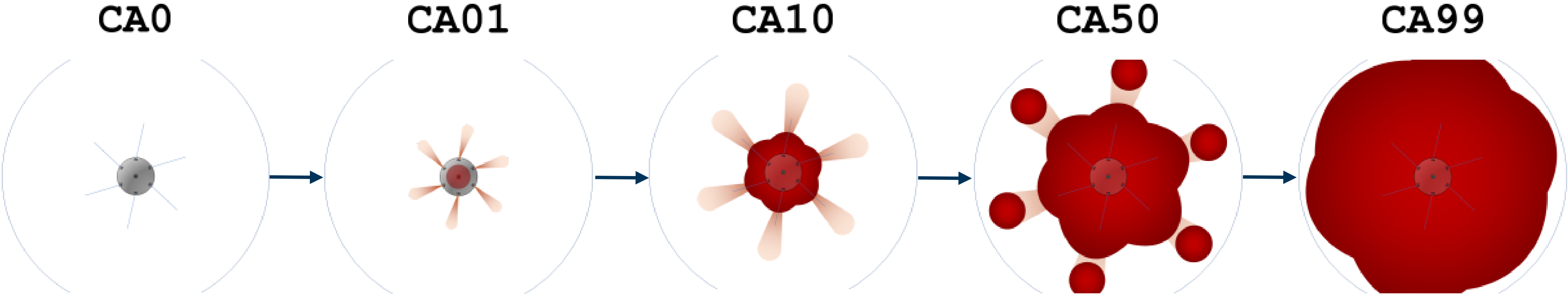
PC 1 V – axial hole

PC 2 v – axial hole

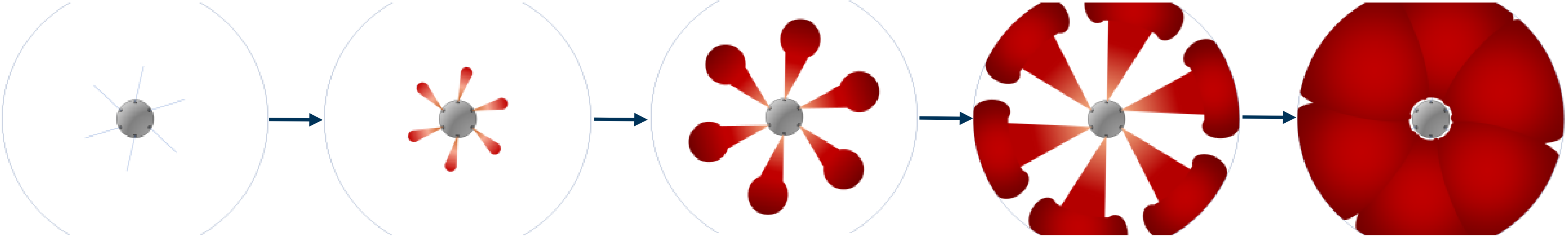
PC 3 v – no axial hole

Results: schematic of the combustion process in the MC

PC 1-2 Φ = 0.94 ISP-NRP



PC 3 Φ = 0.95 ISP-NRP



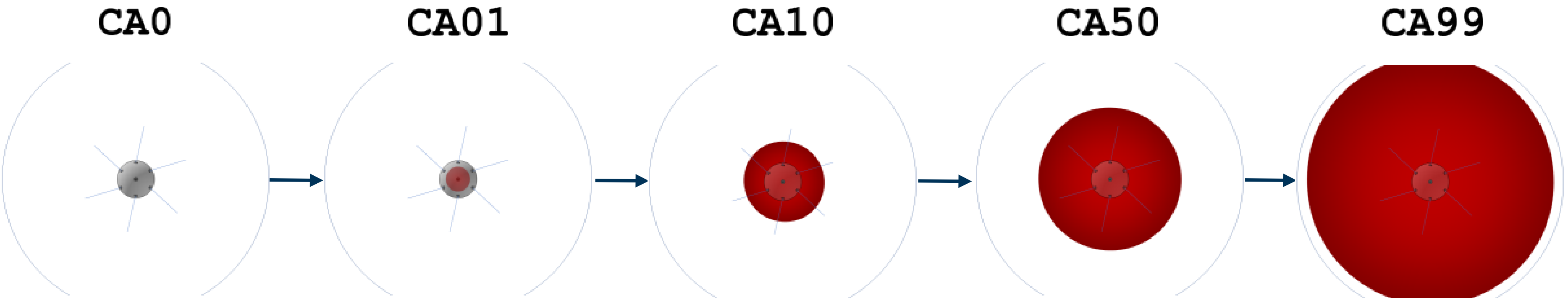
PC 1 V – axial hole

PC 2 v – axial hole

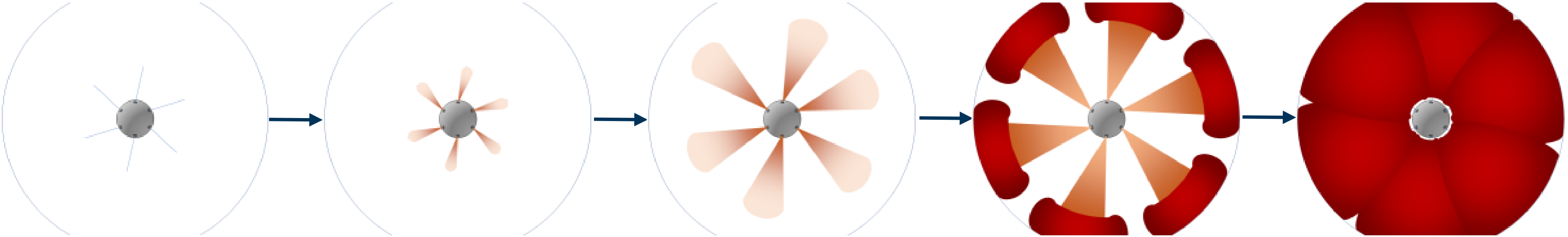
PC 3 v – no axial hole

Results: schematic of the combustion process in the MC

PC 1-2 Φ = 0.71 ISP



PC 3 Φ = 0.7 ISP



PC 1 V – axial hole

PC 2 v – axial hole

PC 3 v – no axial hole