Sharif University of Technology
Department of Mechanical Engineering
Fuel, Combustion and Emission (FCE) Research Center

Investigation of Non-volatile Nanoparticle Emissions of Diesel-Natural Gas RCCI Combustion Engine

(RCCI: Reactivity-Controlled Combustion Ignition)

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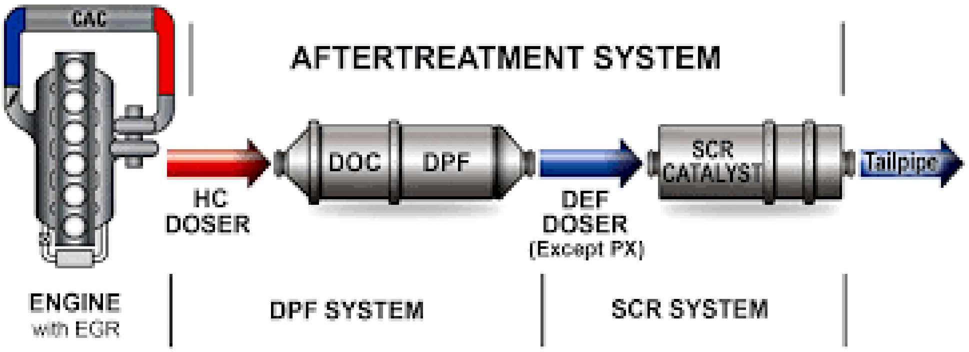
23rd ETH-Conference on Combustion Generated Nanoparticles
June 2019, ETH Zurich, Switzerland

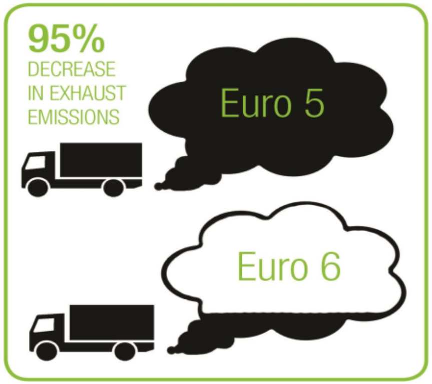
Table of Contents

Introduction: Emission Control Strategies

- The target of examining alternative combustion strategies (in this case low-temperature partially homogeneous mixture) is to reduce emissions (focusing on NOx, PM, and PN) while keeping the efficiency high enough.
- After-treatment systems are expensive and reduce the efficiency.
- The question is, how does RCCI combustion affect PM and PN emission of a dual-fuel CNG-diesel engine?



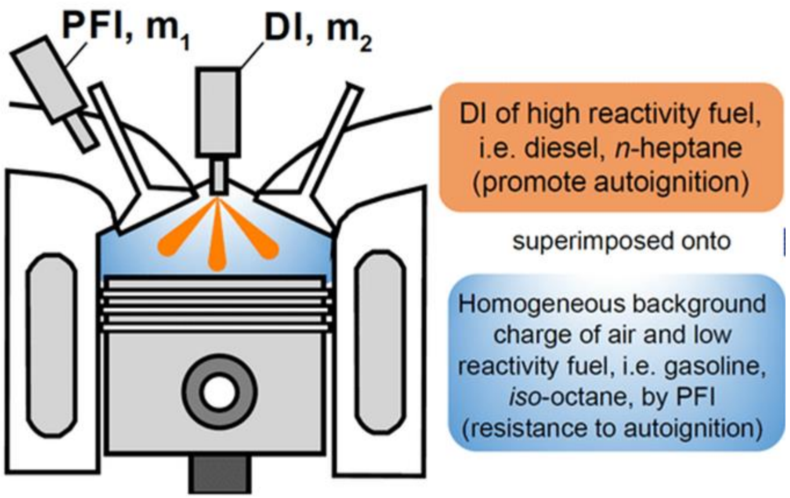
PACCAR Engine Aftertreatment Systems (TTS) Operator's Manual



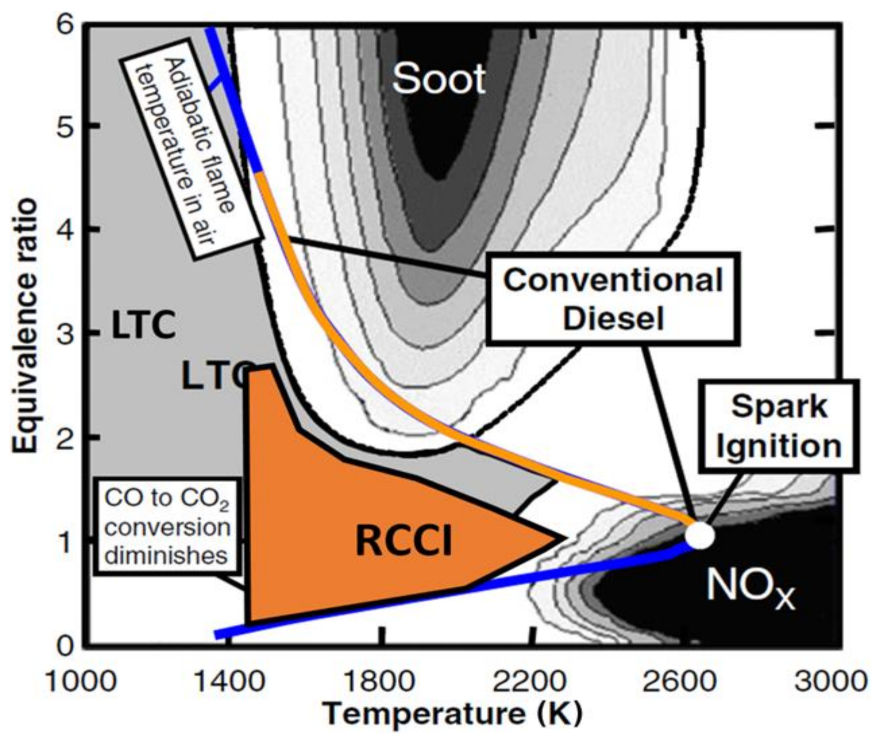
https://www.toxfree.com.au/australias-first-euro-6/

Introduction: RCCI Combustion

- Novel combustion strategy with two different fuels with opposite reactivities (i.e. autoignition properties)
- Extended combustion duration → low temperature → low NOx
- Retained benefits of CI combustion: efficiency and controllability
- Less heat loss → more efficiency
- Low soot amount



https://www.researchgate.net/figure/Illustration-of-RCCI-combustion-concept-PFI-and-DI-denote-port-fuel-injection-and-direct_fig3_317481348 [accessed 27 May, 2019]

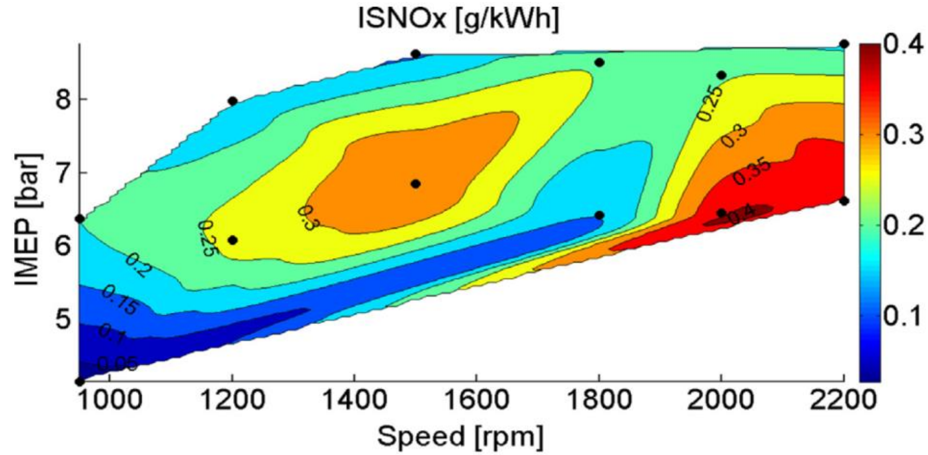


Jing Li et al. ASME. *J. Eng. Gas Turbines Power.* 2016;138(9)

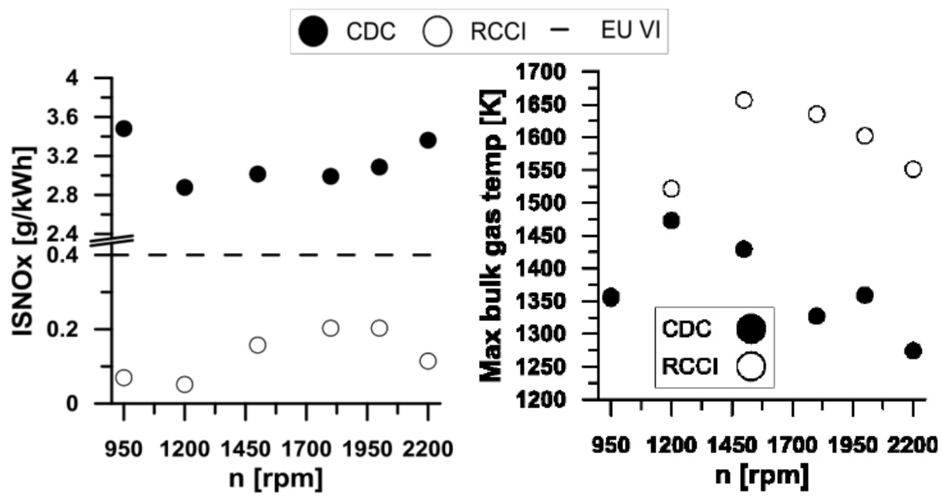
Literature Survey: NOx Emission

RCCI 4.0 bar BMEP/2000 rpm	**Pre-DOC**
Gas Temp. [°C]	269
UHC – FID [ppm]	2165
CO – NDIR [ppm]	1733
NOx – CLD [ppm]	26.4
NOx – FTIR [ppm]	30.9
NO/NO2 – FTIR [ppm]	22.0 / 8.9
BSHC – FID [g/kW-hr]	7.3
BSCO – NDIR [g/kW-hr]	11.8
BSNOx – CLD [g/kW-hr]	0.29
Combustion Eff. [%]	95.7%
Soot Concentration – AVL 415S [mg/m^3]	0.1
PM Concentration – Filters [mg/m^3]	2.2

Dempsey, A. et al., SAE Technical Paper 2014-01-1596



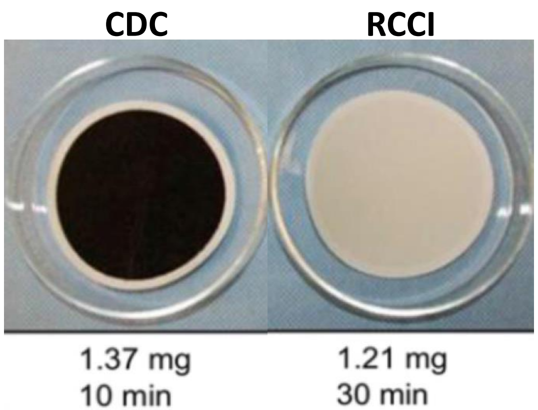
Benajes, J. et al., Energy Conversion and Management, 123 (2016), 381-391



Benajes, J. et al., *SAE Int. J. Engines* 10(5):2017

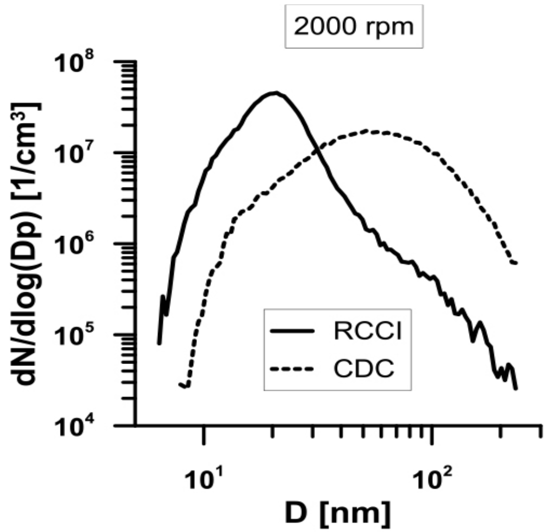
- No need to NOx after-treatment
- Less exhaust complexity
- Easy development of DPF and DOC

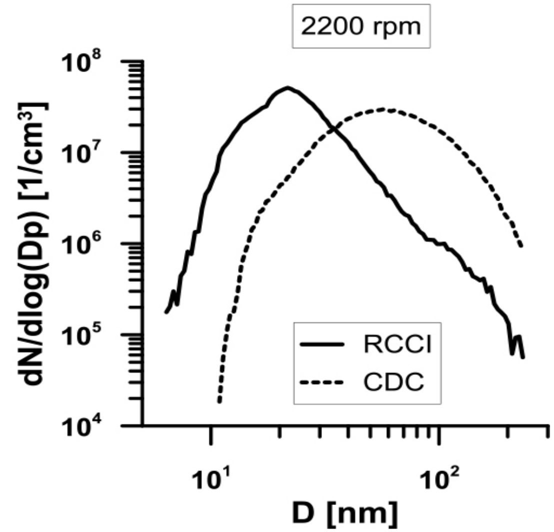
Literature Survey: PM, CO and HC Emissions

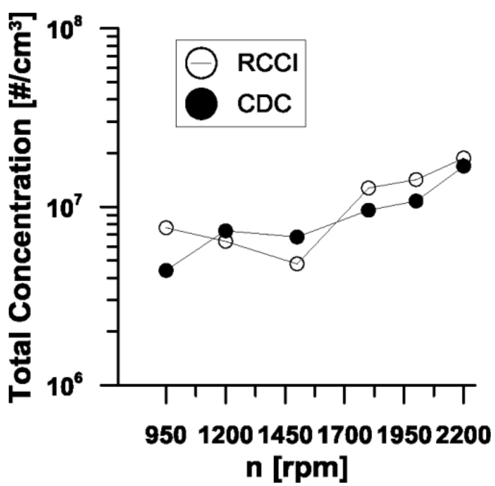


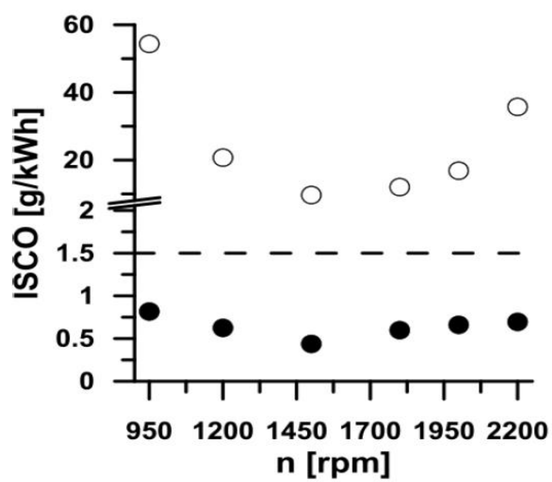
Teflon-coated quartz-fiber filters

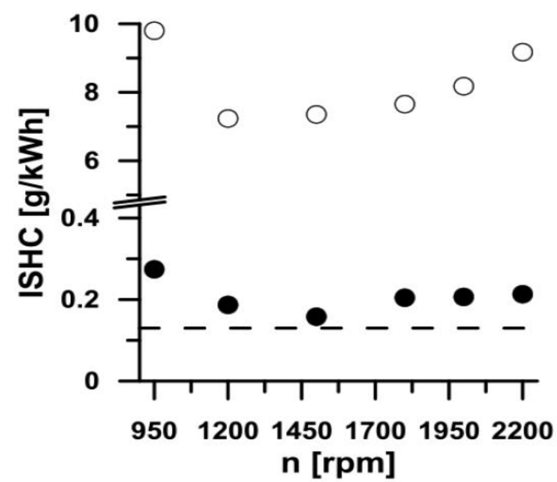
Dempsey, A et al., SAE Technical Paper 2014-01-1596





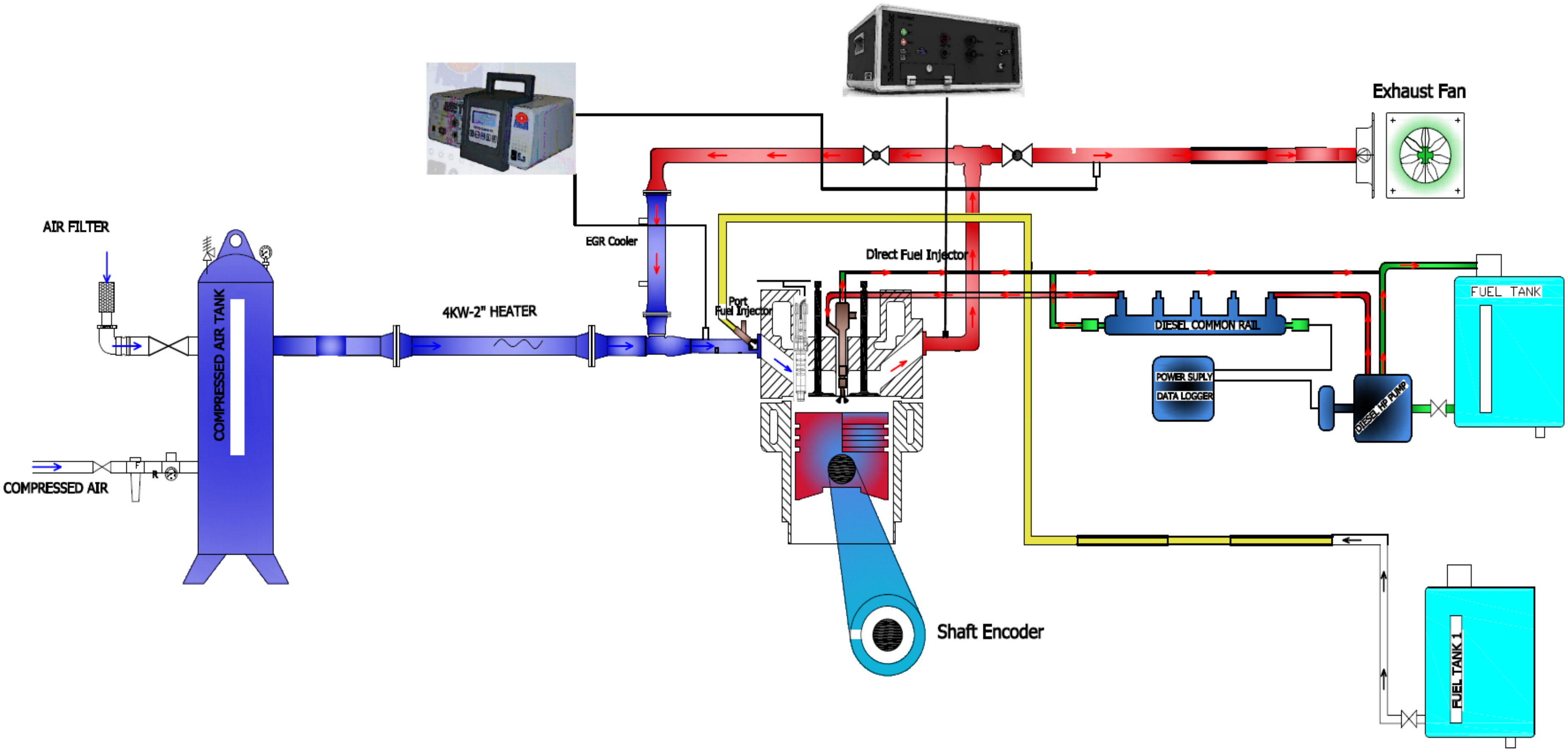






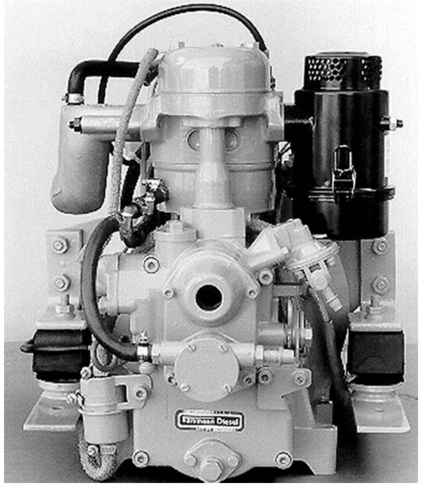
Benajes, J. et al., SAE Int. J. Engines 10(5):2017

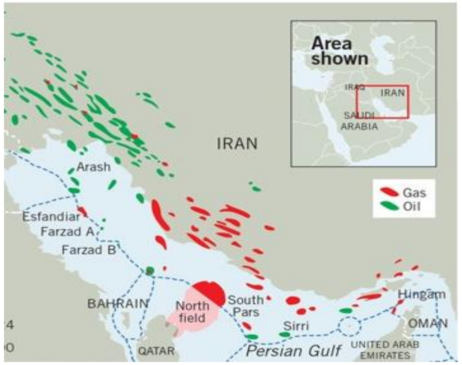
Methodology: Experimental Setup



Methodology: Engine and Fuels

Farymann 18W Engine	
Number of Cylinders	1
Output Power	4.7 kW @ 3000 rpm
Displacement Volume	290 ccm
Bore × Stroke	82 × 55 mm
Compression Ratio	16.5
Maximum speed	3600 rpm
DI Fuel	Diesel
Premixed Fuel	Natural Gas (CNG) Iran has large reserves of natural gas in the middle east

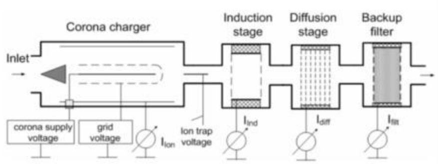


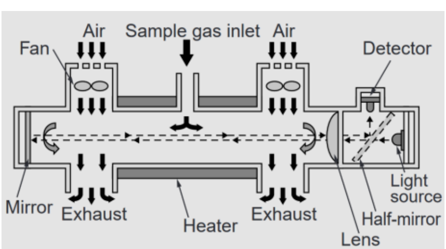


https://www.quora.com/What-are-Irans-natural-resources

The engine combustion chamber and fuel injector is not optimized for any emission level. The idea is to look for trends.

Methodology: Emission Measurement Devices





Nobutaka Kihara, Opacimeter MEXA-130S, Feature Article

Testo NanoMet3

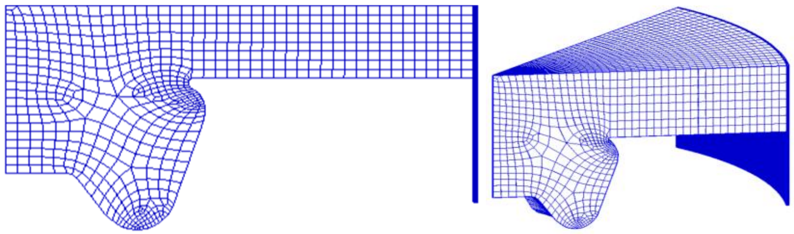
- Thermo-diluted sampling → solid and non-volatile particle measurement
- Diffusion size classifier mechanism
- PN, mean size, PM and LDSA of non-volatile particles

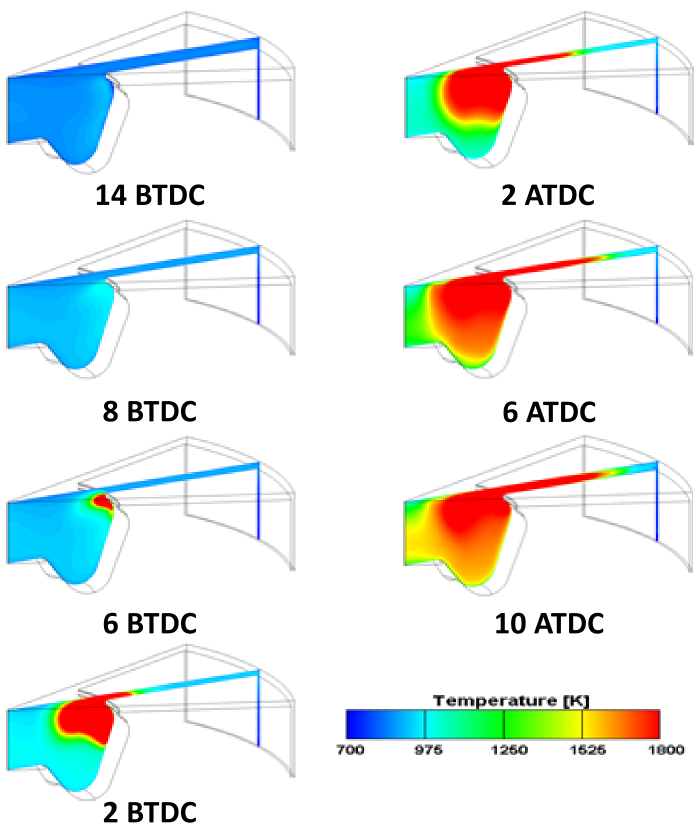
MAHA MET 6.3

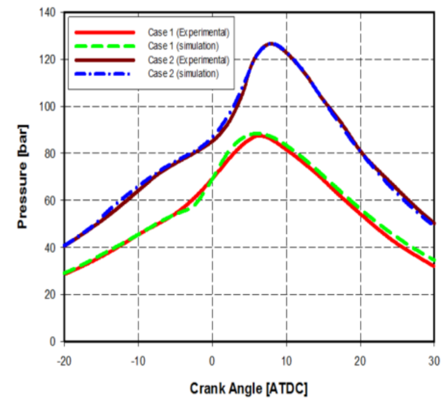
- Total PM by opacimeter

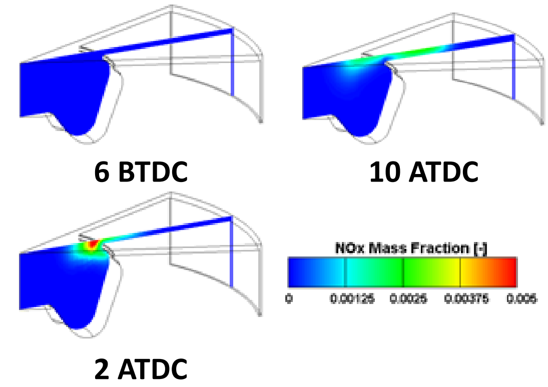
$$\text{Non}-\text{volatile Particle Fraction} = \frac{\text{Solid PM calculated by NanoMet3}}{\text{Total PM measured by MAHA MET}}$$

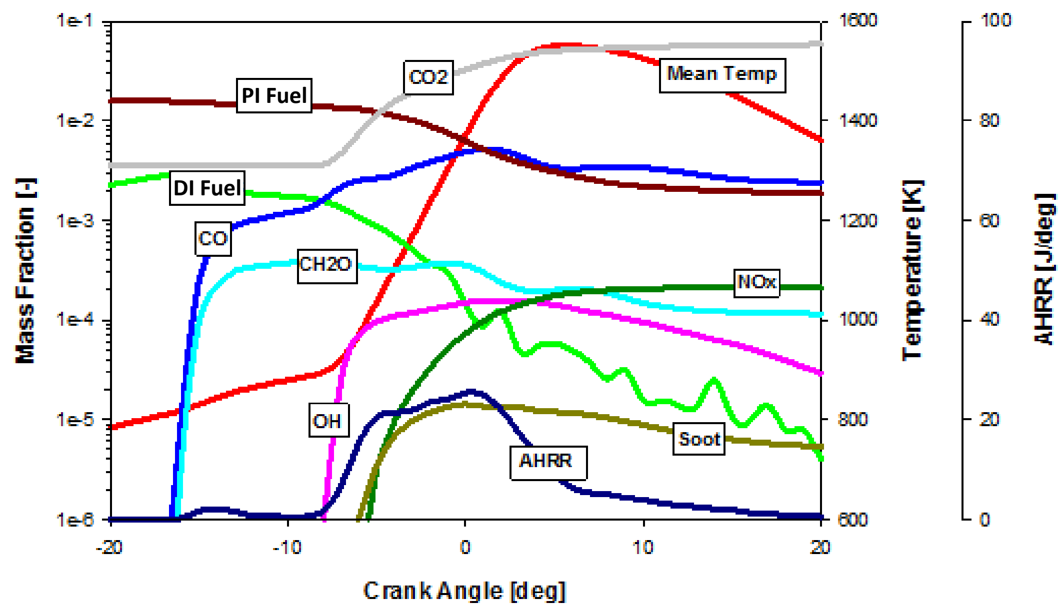
Methodology: CFD Analysis by AVL FIRE^{TM}



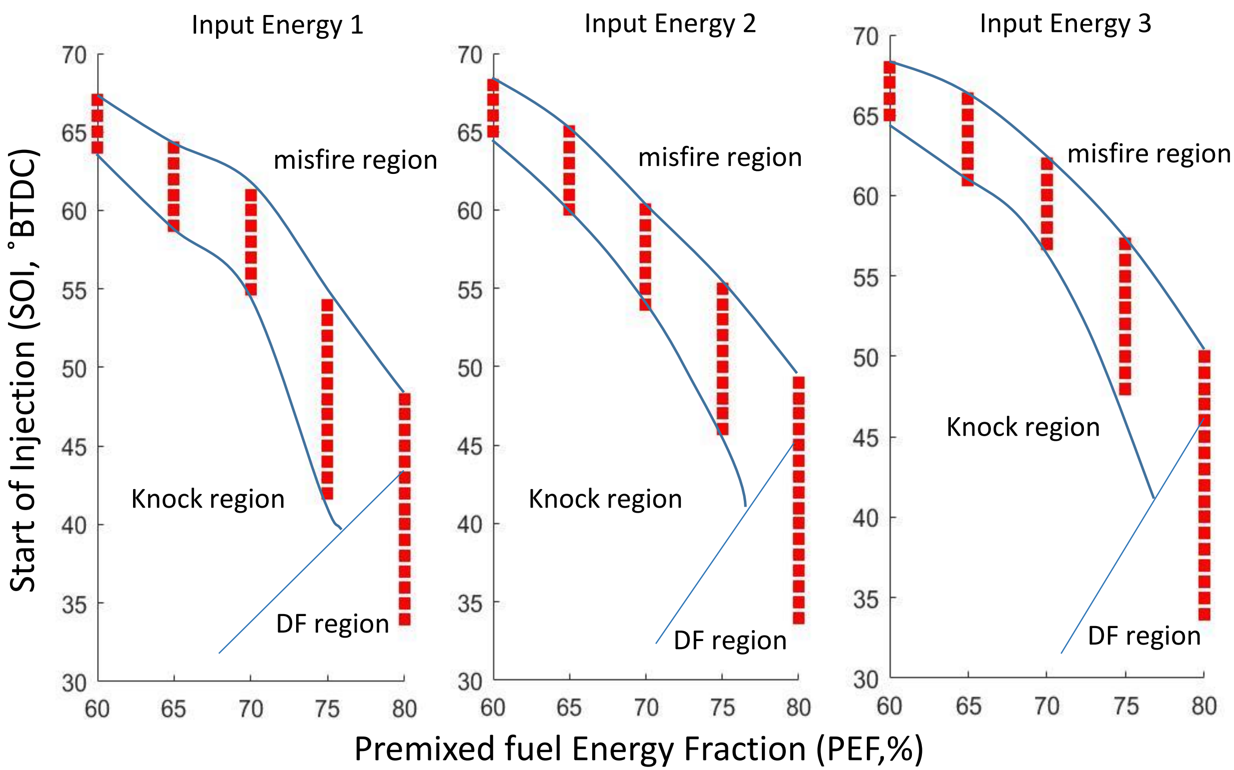




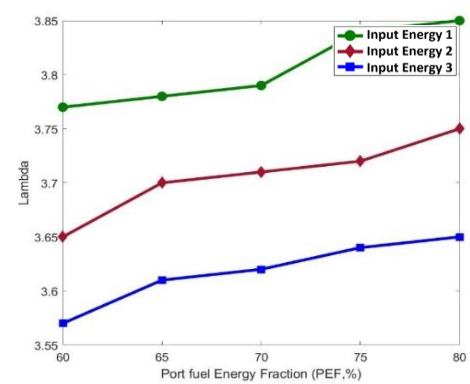




Methodology: Test Procedure



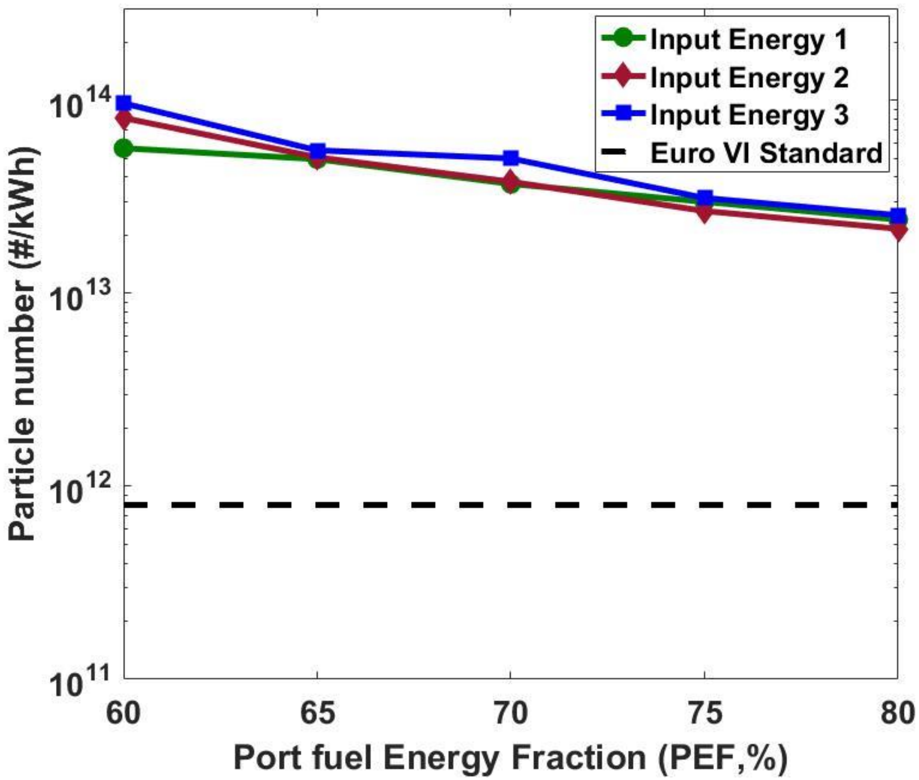
Test Parameters	
Constant Speed	1800 rpm
Diesel Injection Pressure	400 bar
EGR Ratio	0
PEF	60-80%
Input Energy 1	334 J/cycle
Input Energy 2	344 J/cycle
Input Energy 3	353 J/cycle



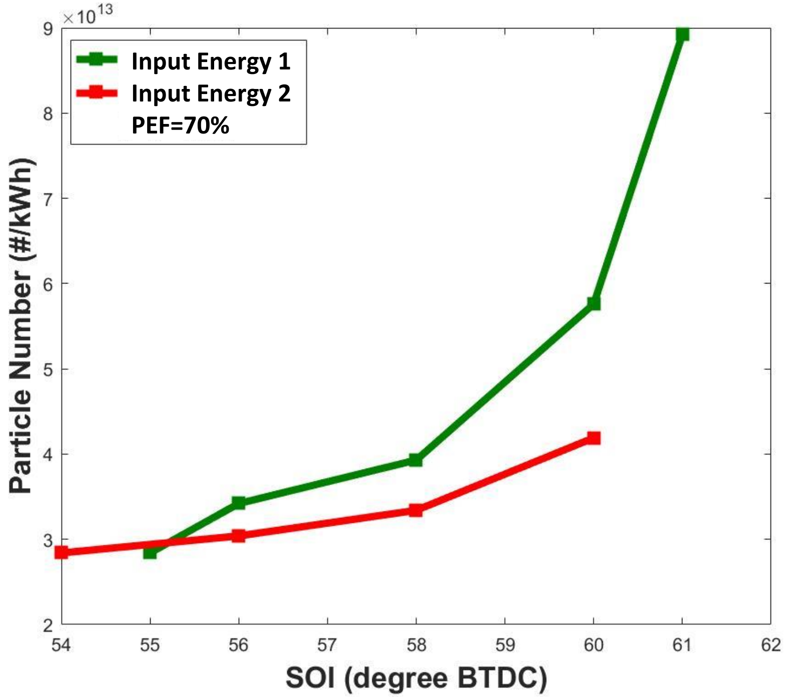
Knock region: high and unacceptable pressure rise rate
Misfire region: high and unacceptable COV of IMEP
DF region: Dual Fuel diesel-natural gas combustion

$$\text{PEF} = \frac{m_{premixed\ fuel} \times LHV_{premixed\ fuel}}{m_{premixed\ fuel} \times LHV_{premixed\ fuel} + m_{DI\ fuel} \times LHV_{DI\ fuel}}$$

Results: Particle Number

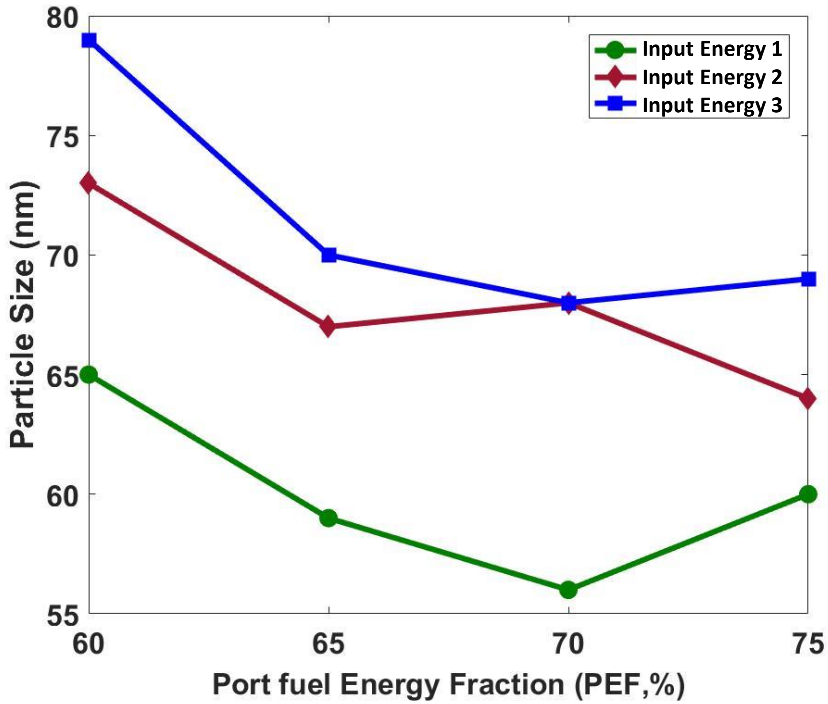


- Higher PEF → more premixed combustion & lower precursors to nucleate carbonaceous particles
- Higher Input Energy → less oxygen for soot oxidation

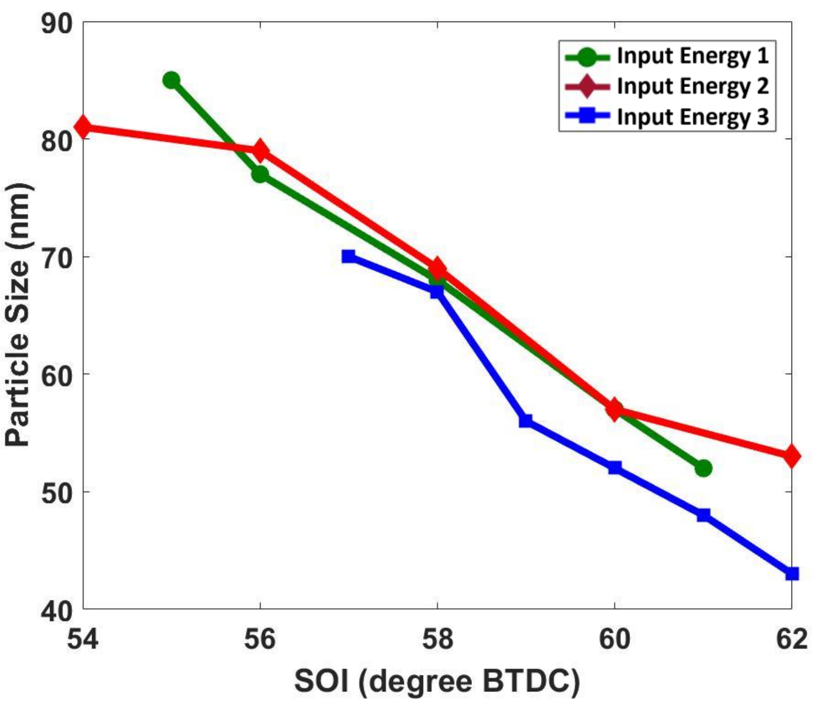


- Earlier SOI → homogeneous-distributed precursors → more possibility of particle nucleation

Results: Particle Size

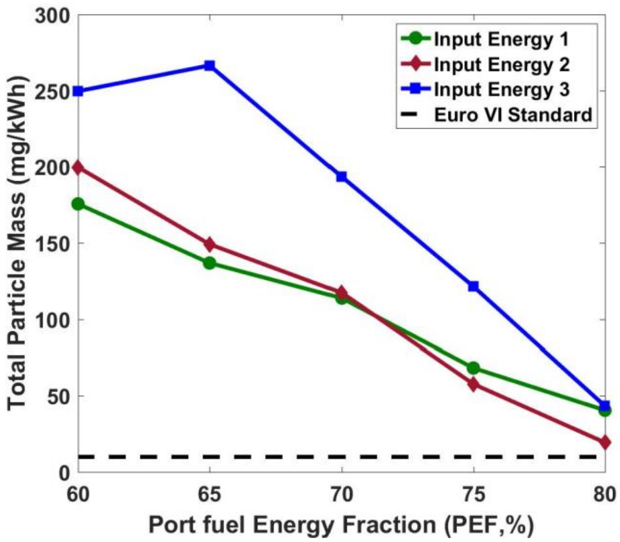


- Higher PEF → particle agglomeration caused by diffusion flame is reduced and further particles are in the nucleation mode

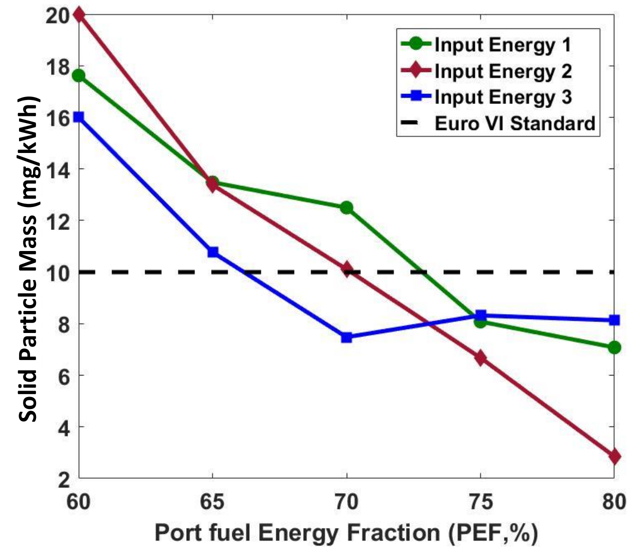


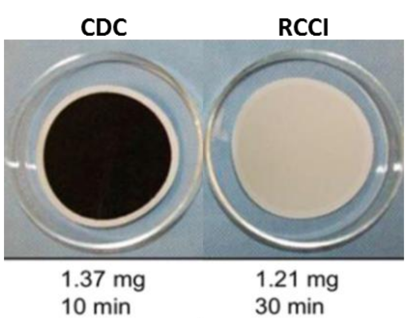
- Retarded injection → There is more diffusion flame and accumulated fuel → more agglomerated particles

Results: Non-volatile Particle Fraction



More Energy Level
More total PM
Less non-volatile PM fraction





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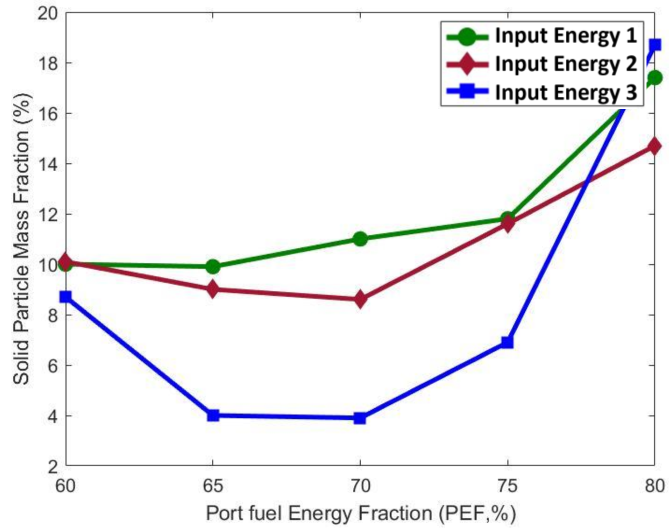
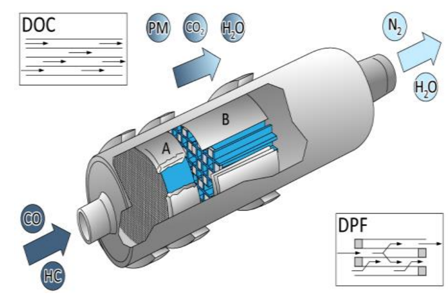
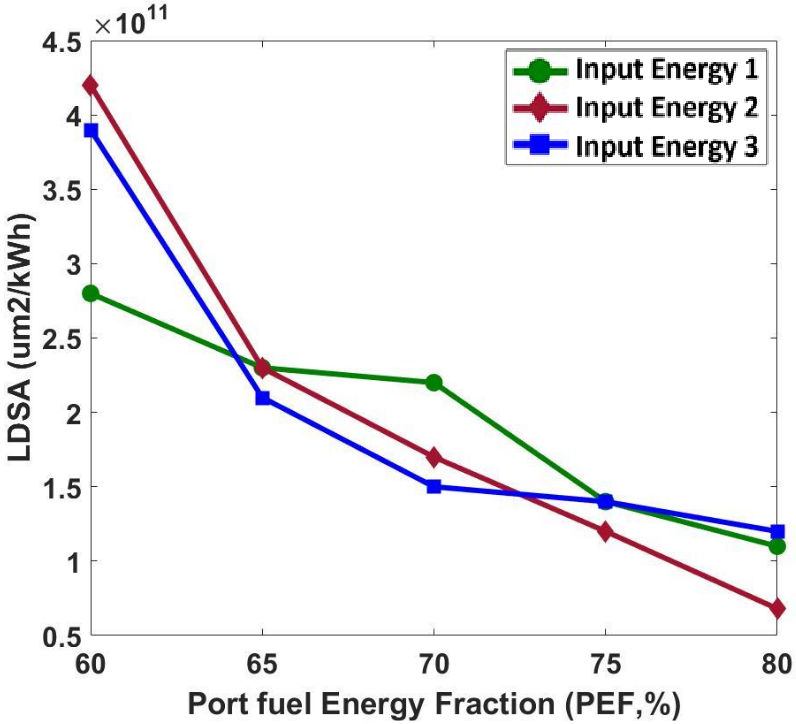


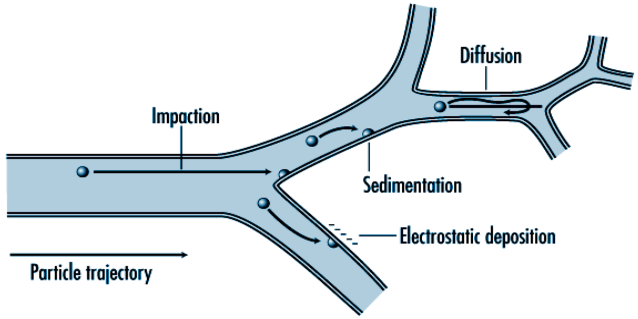


http://www.drawfolio.com/en/portfolios/ramongarciagonzalez/engine-technical-data

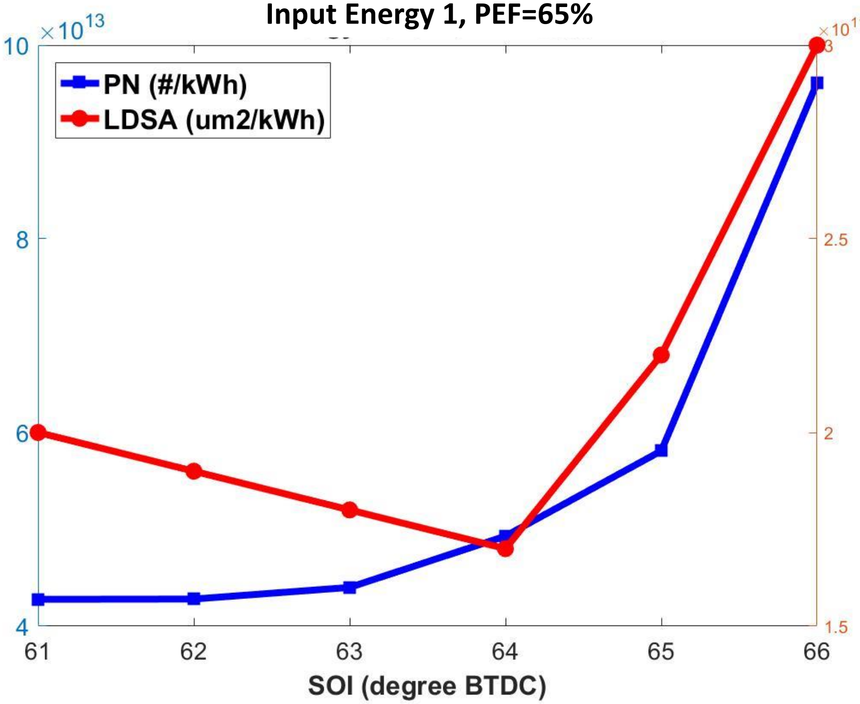
Results: LDSA



PN, PM or Particle Size?



http://www.ilocis.org/documents/chpt10e.htm



Summary and Conclusion

- RCCI combustion strategy is an efficient solution for ultra-low NOx emission with no after-treatment.
- CO and unburned HC emissions are increased compared to CDC. So diesel oxidation after-treatment is required to meet standard emission levels.
- Switching from CDC to RCCI, PM is reduced. There are some other parameters to consider; composition, number and size.
- Non-volatile particle mass is low enough to meet strengthen emission levels. Traditional NOx-PM trade-off is not valid any more at RCCI combustion.
- Low PM/PN emission RCCI combustion requires high fraction of port fuel injection (more than 80% in this case). This could potentially lead to very low PM/PN to reduce after-treatment requirements.
- FCE research lab at Sharif University is considering use of modern production-type engine at RCCI combustion mode to meet Euro VI PM/PN limits.

Acknowledgements

- VERT association, Dr. Andreas Mayer, and Mr. Volker Hensel
- Tehran Air Quality Control Co. (AQCC)

Thanks for your attention

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