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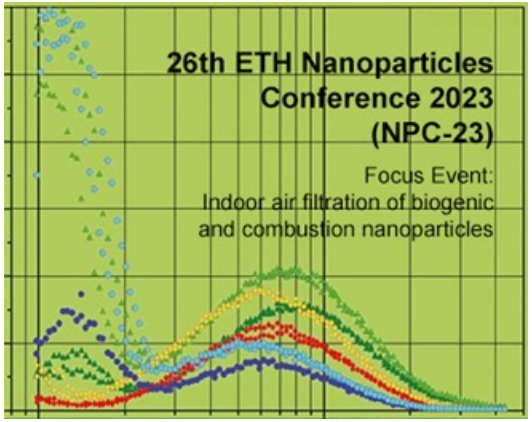


An updated mechanism of particle formation in non-premixed hydrogen combustion in internal combustion engines

Leonid Tartakovsky, Andy Thawko, Ben Holtzer and Michael Shapiro

26th ETH Nanoparticles Conference, Zurich, June 21 2023

Electric vehicle is not really the “silver bullet” solution

- Particle (PM) emissions – similar to those of motor vehicles
  - Non-exhaust PM emission - proportional to vehicle weight
  - Electric vehicle in average is heavier by 24% than the motor counterpart
- Major ecologic burden of battery materials production (human toxicity, soil acidification, water eutrophication…)
- Environmental impact of electricity production

Hydrogen is a great sustainable fuel for IC engine

- ✓ **Wide flammability limits**
- ✓ **High burning velocity**
- ✓ **Contributes to better antiknock performance**

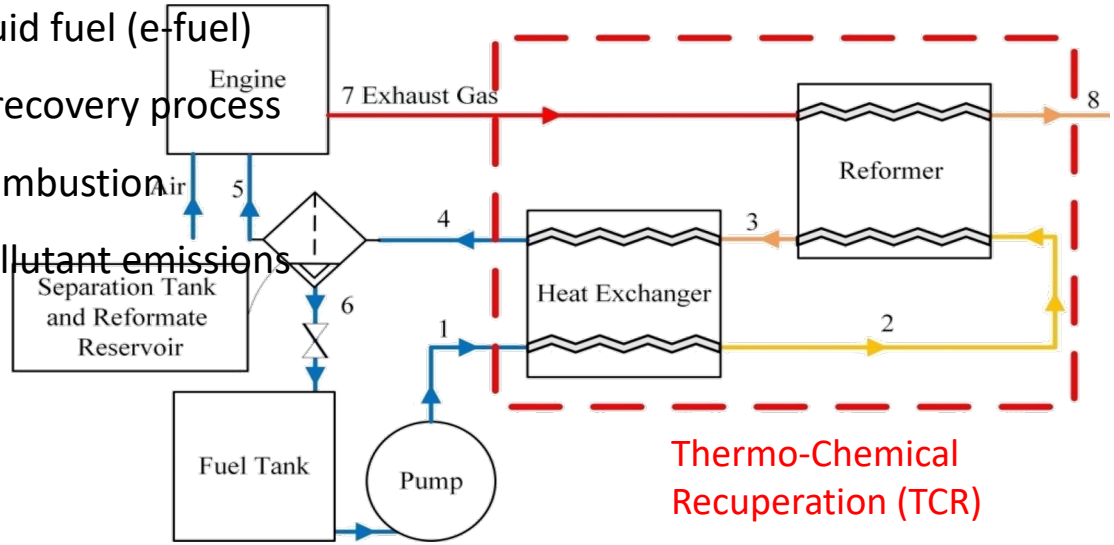
However:

- ✓ **No fueling infrastructure available**
- ✓ **Onboard storage is problematic**

To remind: M_{H2} = 2.016 g/mol, Boiling T = -253C

Onboard on-demand hydrogen production
High-Pressure ThermoChemical Recuperation

- ✓Primary renewable low-carbon intensity liquid fuel (e-fuel)
- ✓Waste heat recovery process
- ✓Hydrogen combustion
- ✓Ultra-low pollutant emissions



Thermo-Chemical Recuperation (TCR)

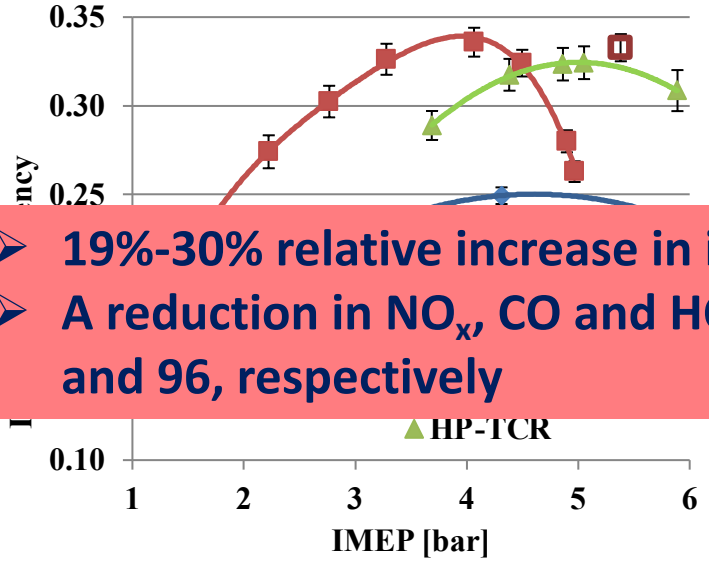
Methanol Steam Reforming (MSR)

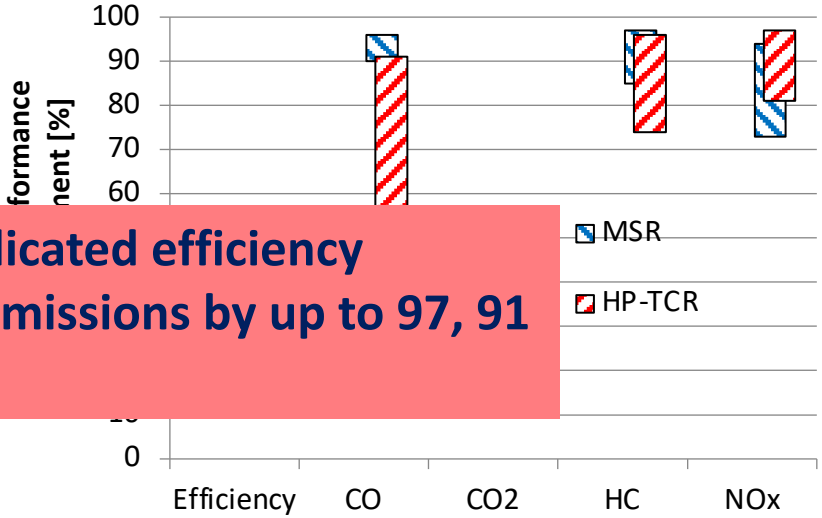
$CH_3OH+H_2O \rightarrow 3H_2+CO_2$ $\Delta H \approx 50$ kJ/mol

Low reforming temperatures- 250-300 C

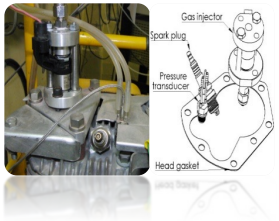
Tartakovsky L., Sheintuch M., Veinblat M., Thawko A., International Patent Application No. PCT/IB2020/056382, 2021

High-Pressure ThermoChemical Recuperation Performance



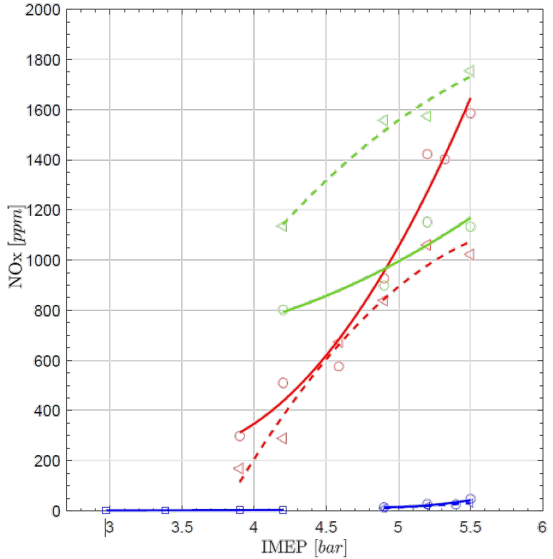


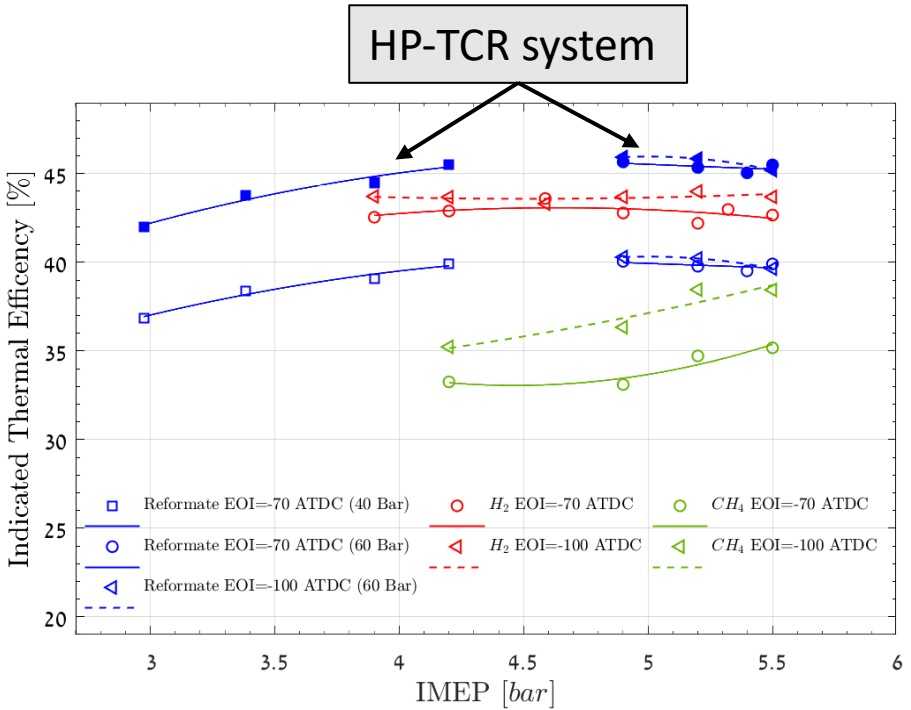
- 19%-30% relative increase in indicated efficiency
- A reduction in NO_x, CO and HC emissions by up to 97, 91 and 96, respectively



Poran, Thawko et al., Int. J Hydrogen Energy, 2018

Hydrogen vs Reformate combustion





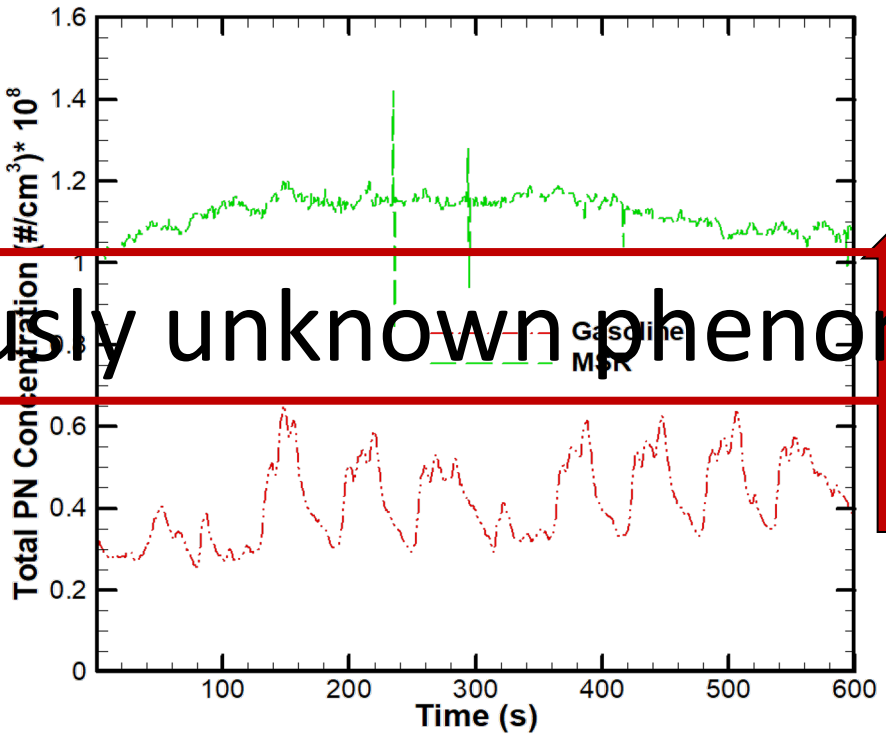
- HP-TCR system efficiency is higher than H_2
- NO_x emission is near-zero for the reformate due to CO_2 presence
- Advanced EOI is favored because of better Fuel-air mixing

Thawko et al., Energy Conversion and Management, 2022

Total particle concentration comparison

MSR

$$CH_3OH + H_2O \rightarrow 3H_2 + CO_2$$

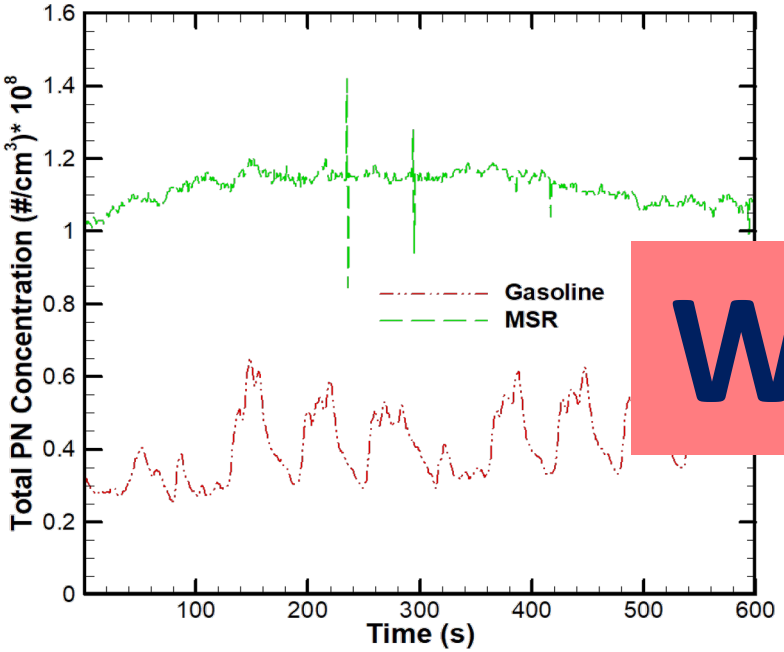


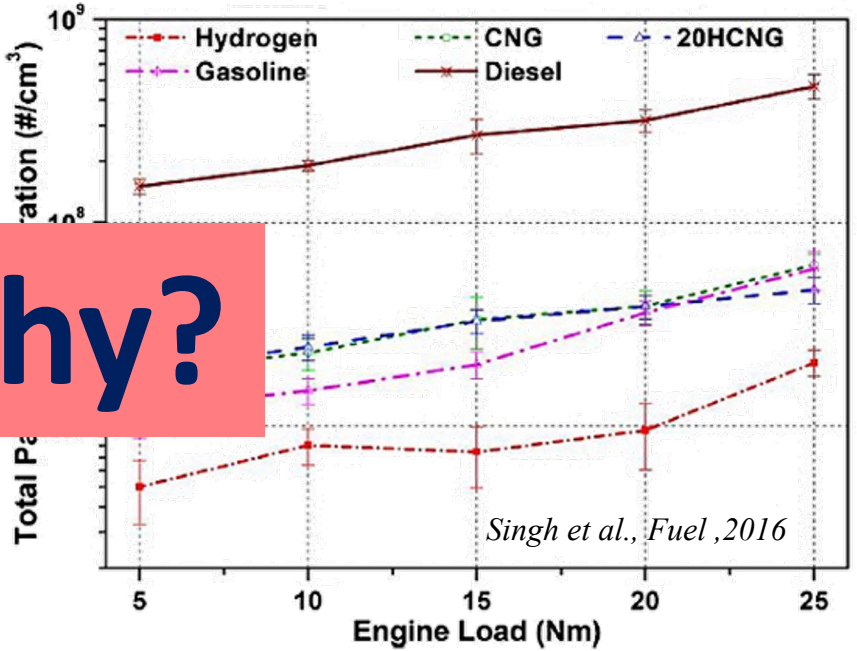
Previously unknown phenomenon

170% increase in particle emission

Thawko et al., Int. J Hydrogen Energy, 2019

Total particle concentration comparison





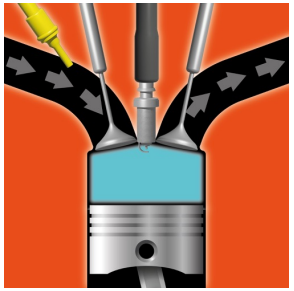
Why?

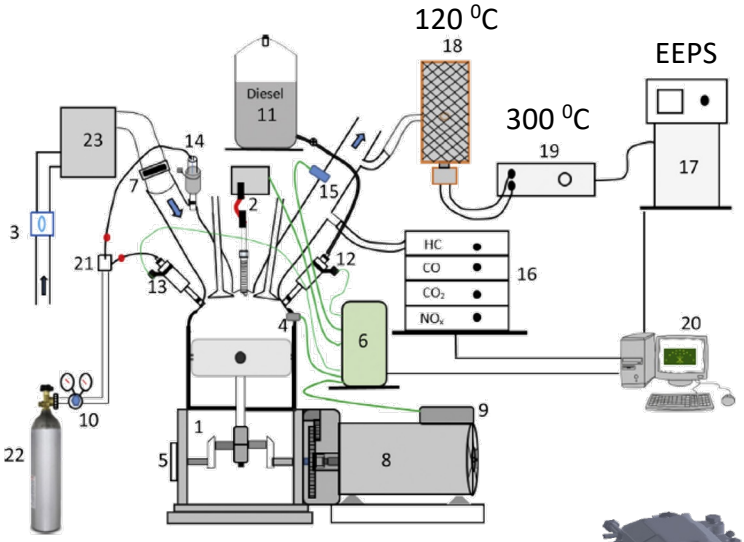
Previous studies showed significant PN reduction with hydrogen combustion

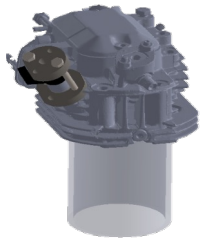
Experimental setup- Research engine

Single cylinder, Petter AD1 based	
Bore x Stroke, mm	80x73
Displacement, cm^3	367
Compression ratio	15-17.3
Power, kW @ speed, rpm	5.3 @ 3000
Fuel injection system	Direct
	Port

A comparison of direct and port reformate injection

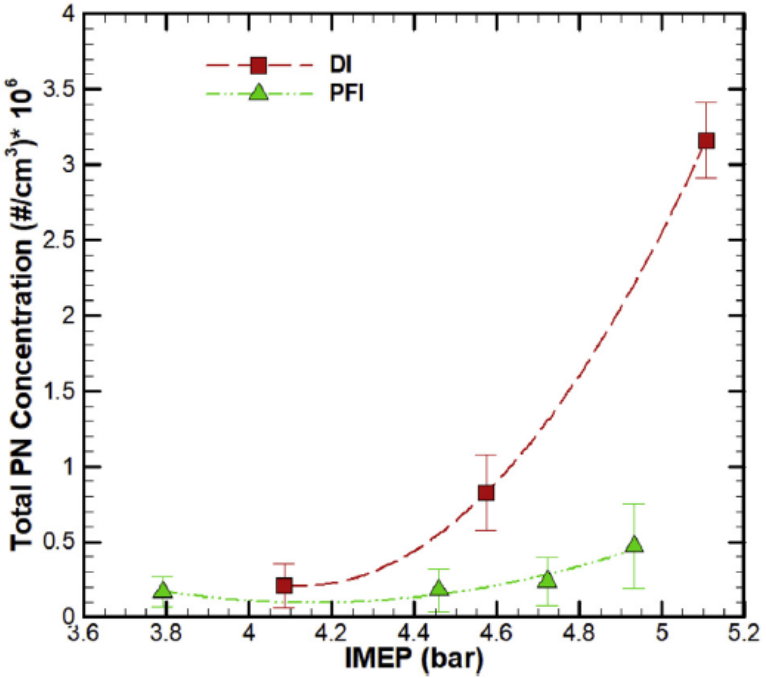






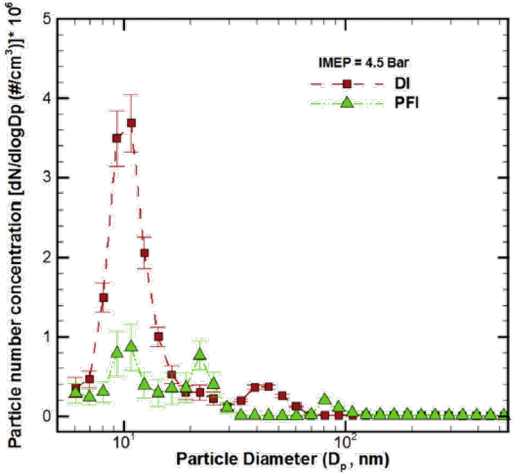
Particle formation- Direct vs Port Fuel Injection

Reformate fuel



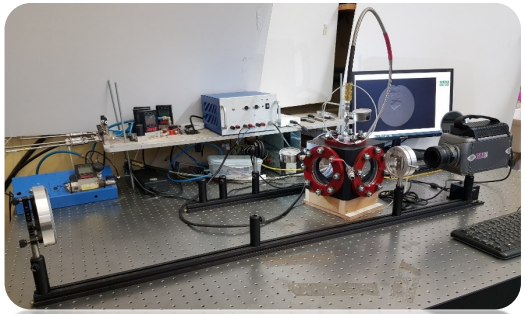
Thawko et al., Int. J Hydrogen Energy, 2019

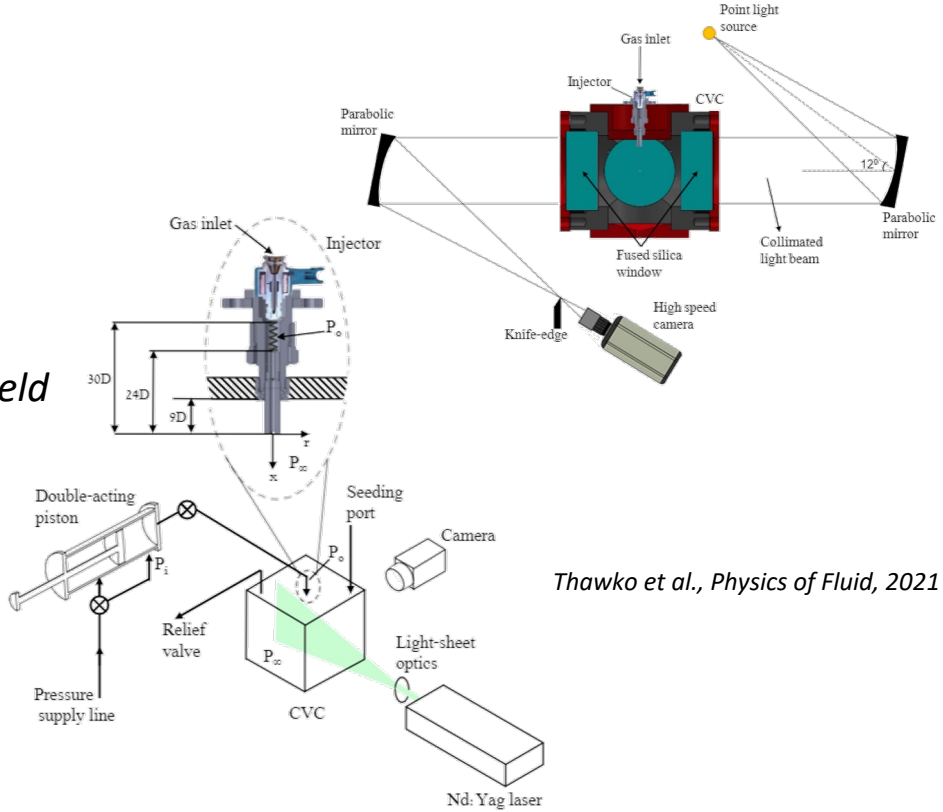
- Increased particles formation for direct injection
- Excessive lubricant involvement in the combustion



Underexpanded jet flow field

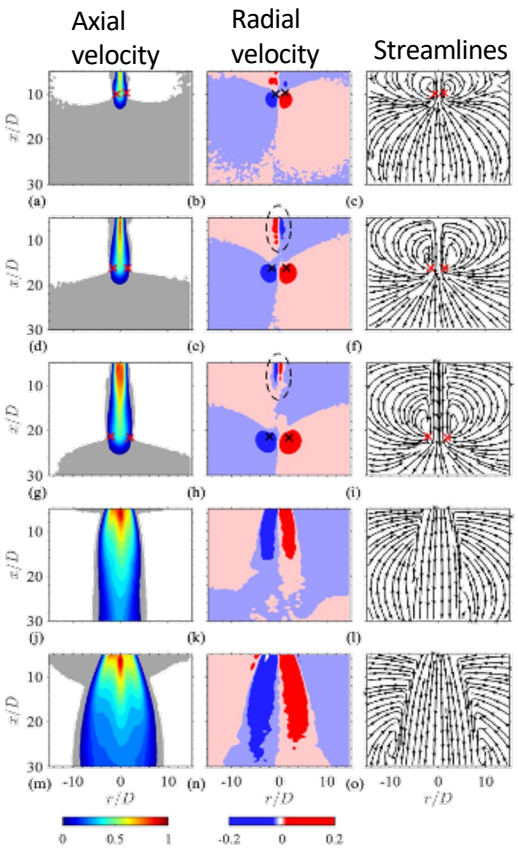
- *Fundamental investigation at ICE typical conditions*
- Goal:
  - *Study of the transient underexpanded jet*
  - *Detailed flow field characteristics*
- Method:
  - *Schlieren & PIV technique for the near- and far-field characterization, respectively*

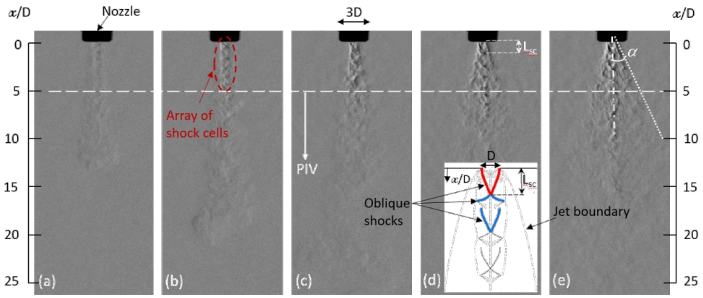




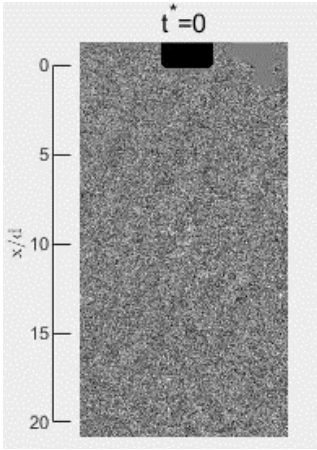
Thawko et al., Physics of Fluid, 2021

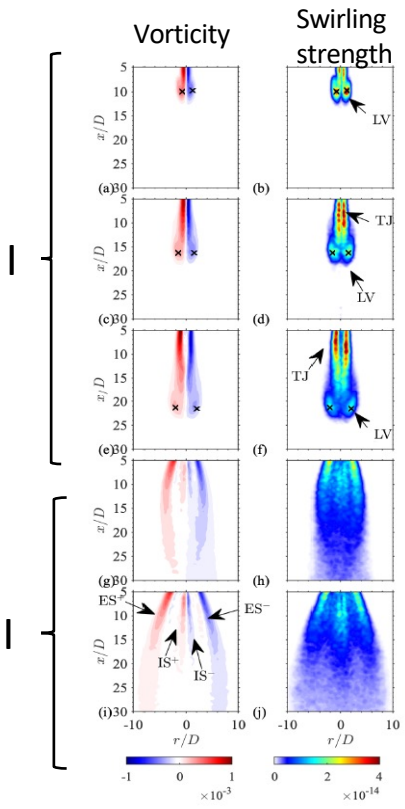
Flow field characterization- Free flow jet





- **Air entrainment encouraged by the transient underexpanded jet**





Thawko et al., Physics of Fluid, 2021

Flow field characterization- Impinging jet

- **Two rolled-up vortex regions with large-scale motion are formed in the wall jet region**
- **Th**
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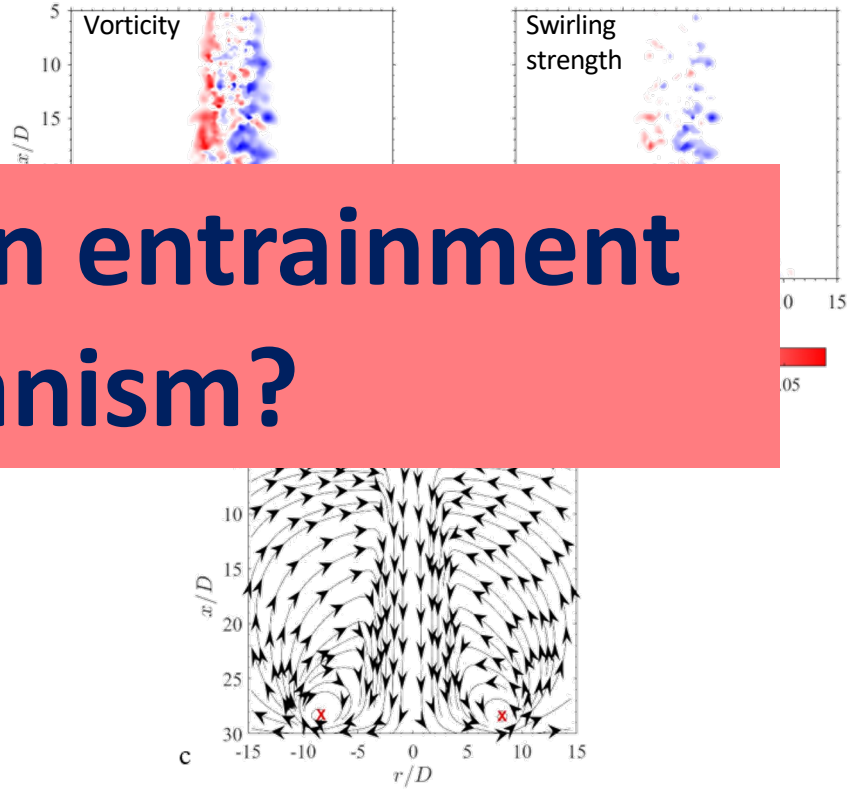
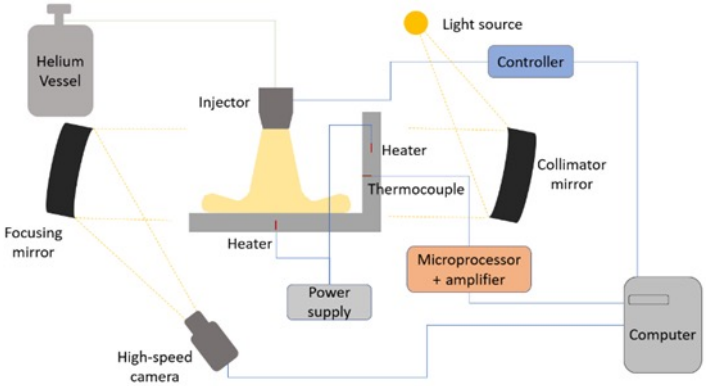


Is this the main entrainment mechanism?

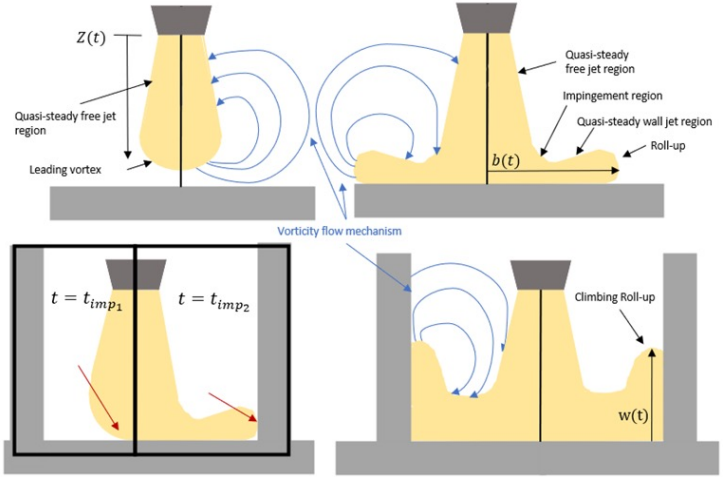
Interaction of a gaseous impinging jet with a heated lubricated surface

Several experiments were preformed via Shadowgraph optical imaging Z-type configuration

- **Perpendicular impinging jets were traced along the free, piston and liner jet regimes for further understanding of the entrainment mechanism**
- **The jets were injected onto heated piston and lubricated liner like surfaces to clarify the lubricant vapor entrainment phenomena**

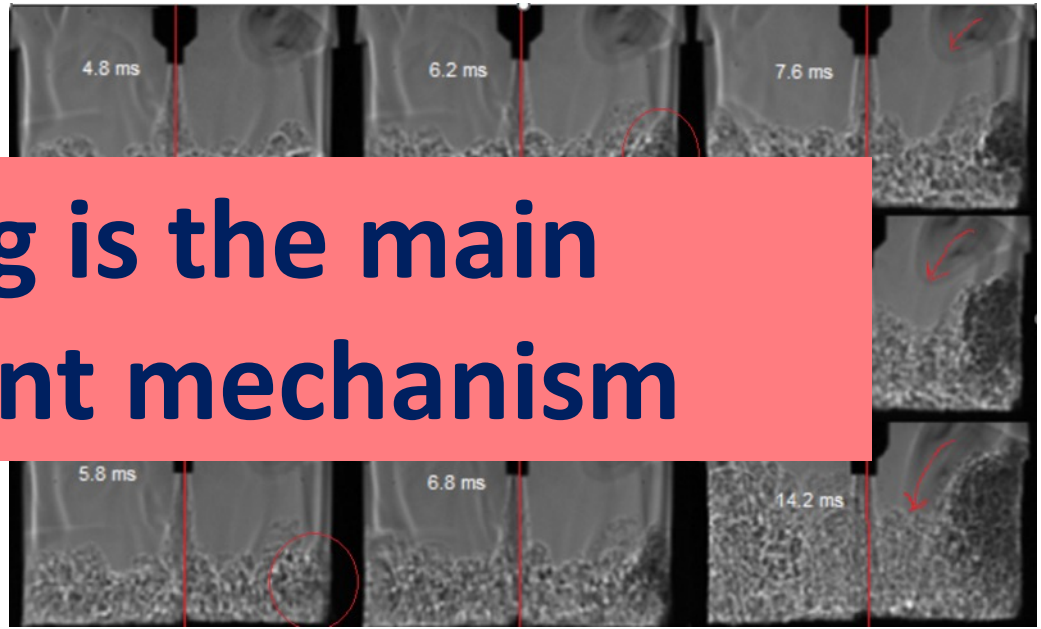


Holtzer & Tartakovsky, SAE Technical Paper 2023-01-0308, 2023



Main lubricant entrainment mechanism

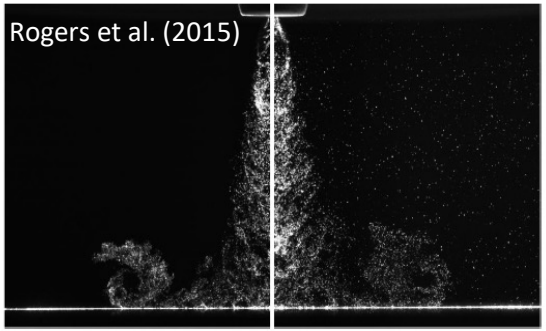
- **Recirculation –** entrainment

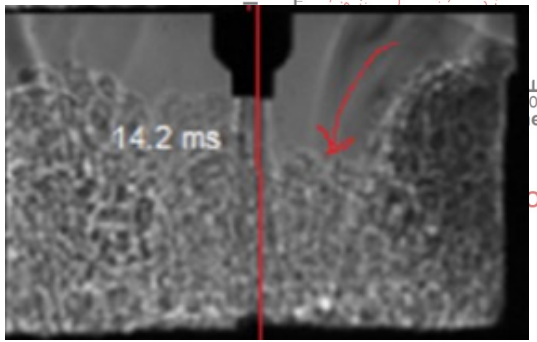


Sweeping is the main entrainment mechanism

Holtzer & Tartakovsky, SAE Technical Paper 2023-01-0308, 2023

Particle formation mechanism in non-premixed H_2 combustion





Hydrogen low quenching distance

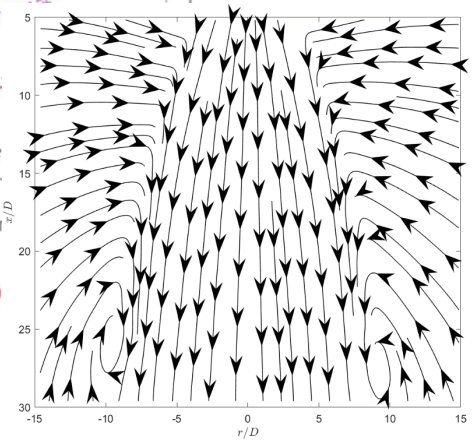
Excessive lubricant evaporation

Why?

Lubricant entrainment into cylinder bulk

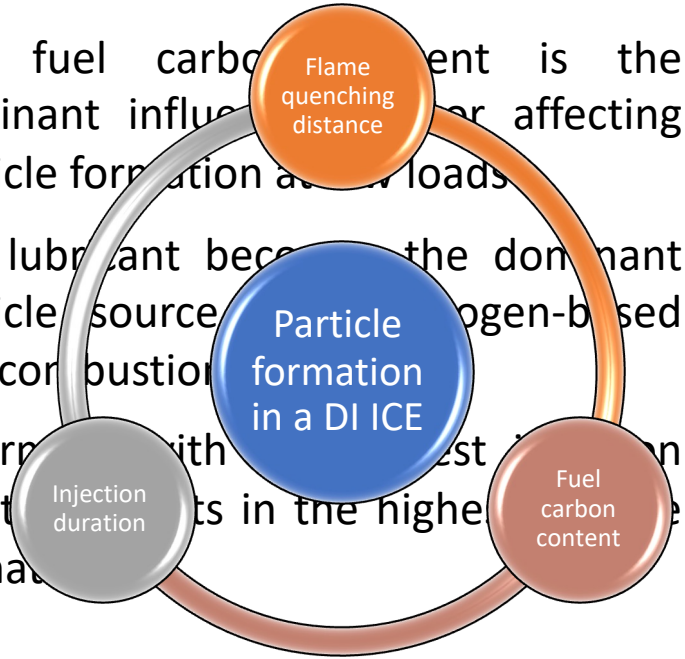
Particle formation

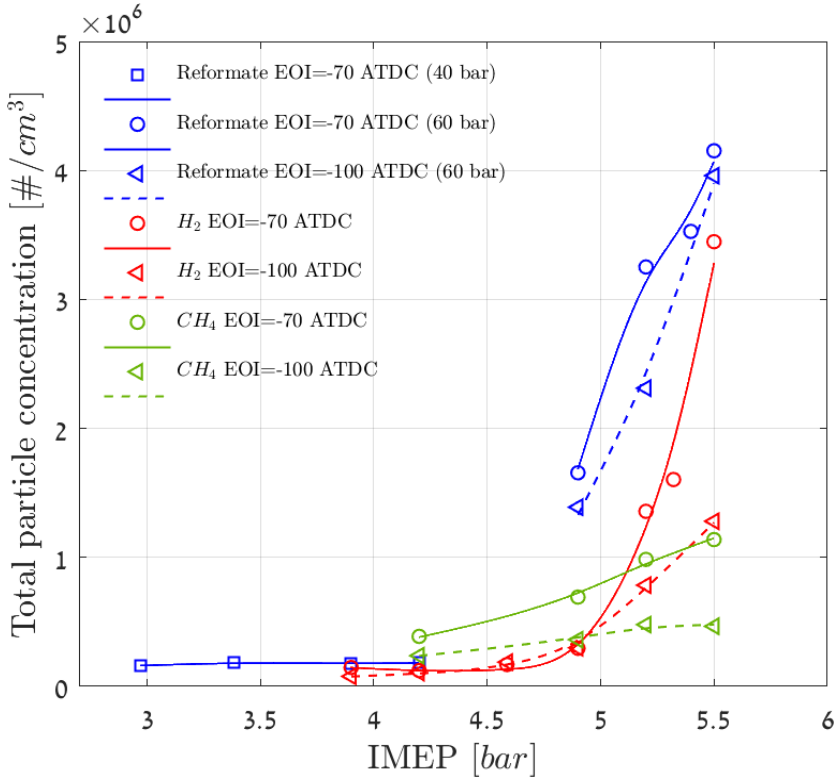
Both for DI&PFI



Non-premixed combustion of gaseous fuel - fuel type effect on particle emission

- The fuel carbo ent is the dominant influe r affecting particle for ation a w loads
- The lubr ant bec the don nant particle source ogen-b sed fuel cor bustio
- Reform ith est n durat ts in the highe e format





Thawko et al., Energy Conversion and Management, 2022

Summary

- Excessive particle formation was discovered with reformate/hydrogen compared to hydrocarbon fuels
- Reformate/hydrogen direct injection results in higher particle formation compared to port fuel injection
- Particle formation mechanism in non-remixed hydrogen combustion was described
- Sweeping is the main lubricant vapor entrainment mechanism into the combustion chamber bulk
- Longer injection duration results in a higher particle formation

Acknowledgments

Q & A

Thank you for your attention!

Prof. Leonid Tartakovsky

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