Particulate Formation in Hydrogen-Fed Internal Combustion Engines

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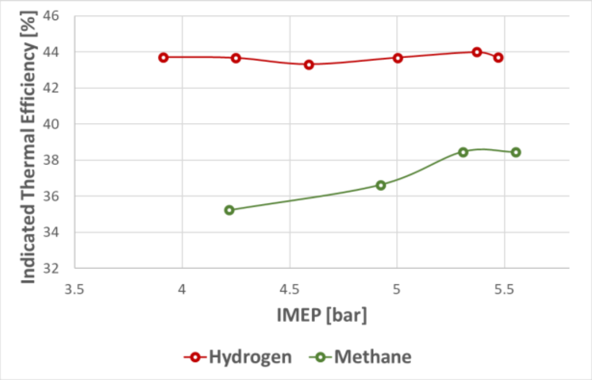
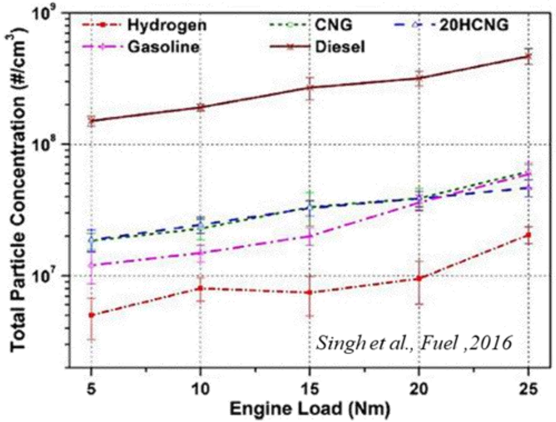
Hydrogen is a great sustainable fuel for IC engine

- ✓ Carbon-free
- ✓ Wide flammability limits
- ✓ High burning velocity (207 cm/s vs ~35 for gasoline)
- ✓ Contributes to better antiknock performance



<u>Wide-spread opinion</u>:

Carbon-free hydrogen combustion in IC engine should lead to performance improvement and emissions reduction

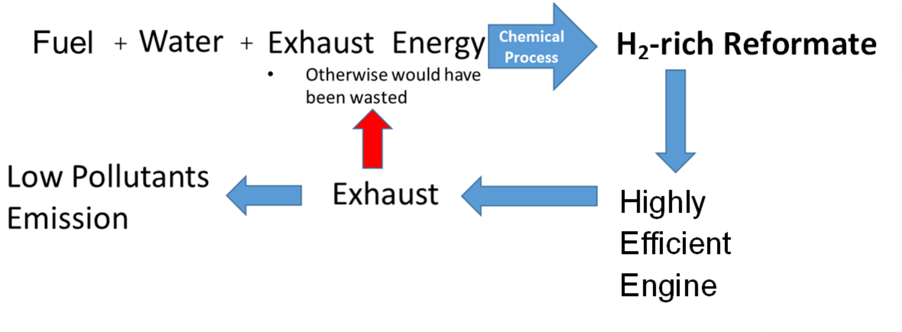


The challenges of hydrogen as an ICE fuel

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

To remind: M_{H2} = 2.016 g/mol,

Boiling T = -253C



Exhaust waste heat is used to produce hydrogen onboard

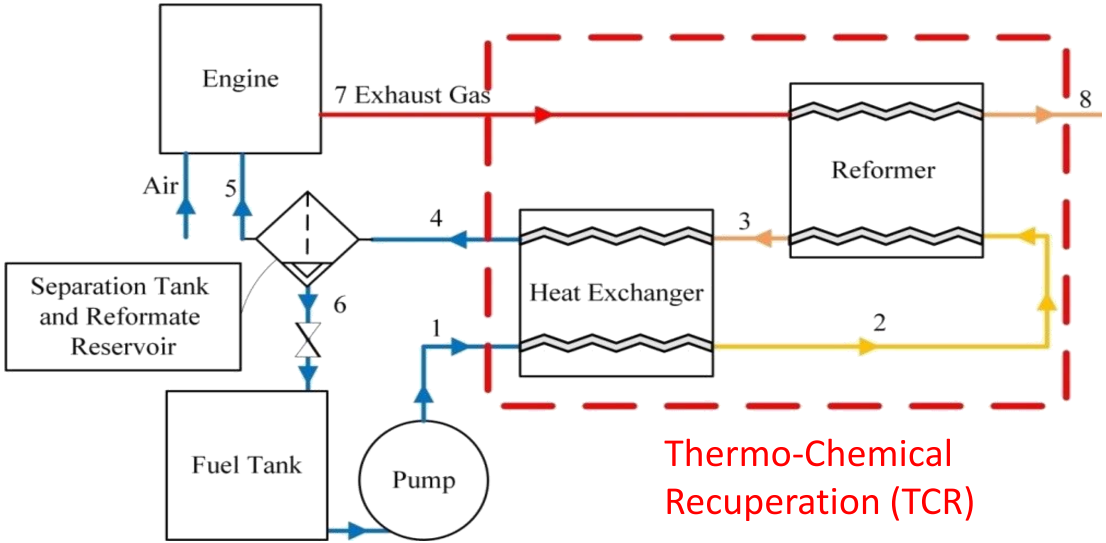
Can be overcome through onboard on-demand hydrogen production

Because port reformate injection leads to abnormal combustion and power loss, **we suggested employing the direct injection**

Onboard on-demand hydrogen production from a sustainable fuel

High-Pressure ThermoChemical Recuperation

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



Thermo-Chemical Recuperation (TCR)

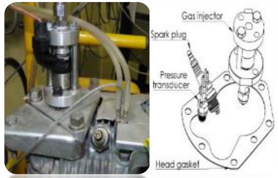
Methanol Steam Reforming (MSR)

$CH_3OH+H_2O \rightarrow 3H_2+CO_2$ ΔH≈50 kJ/mol

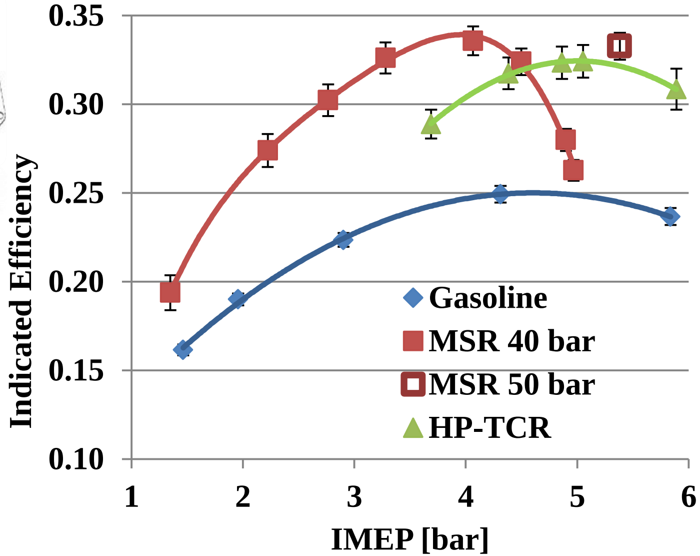
Low reforming temperatures- 250-300 C

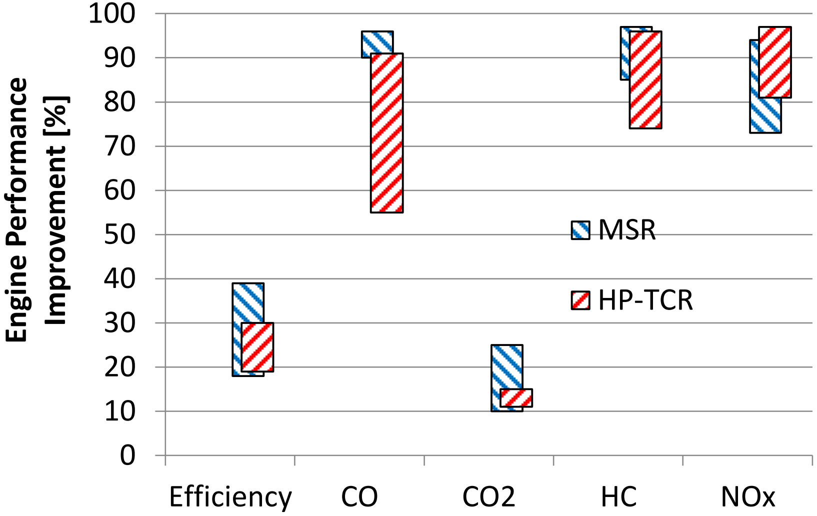
Tartakovsky L., Sheintuch M., Veinblat M., Thawko A., International Patent Application No. PCT/IB2020/056382, 2021

High-Pressure ThermoChemical Recuperation Performance



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

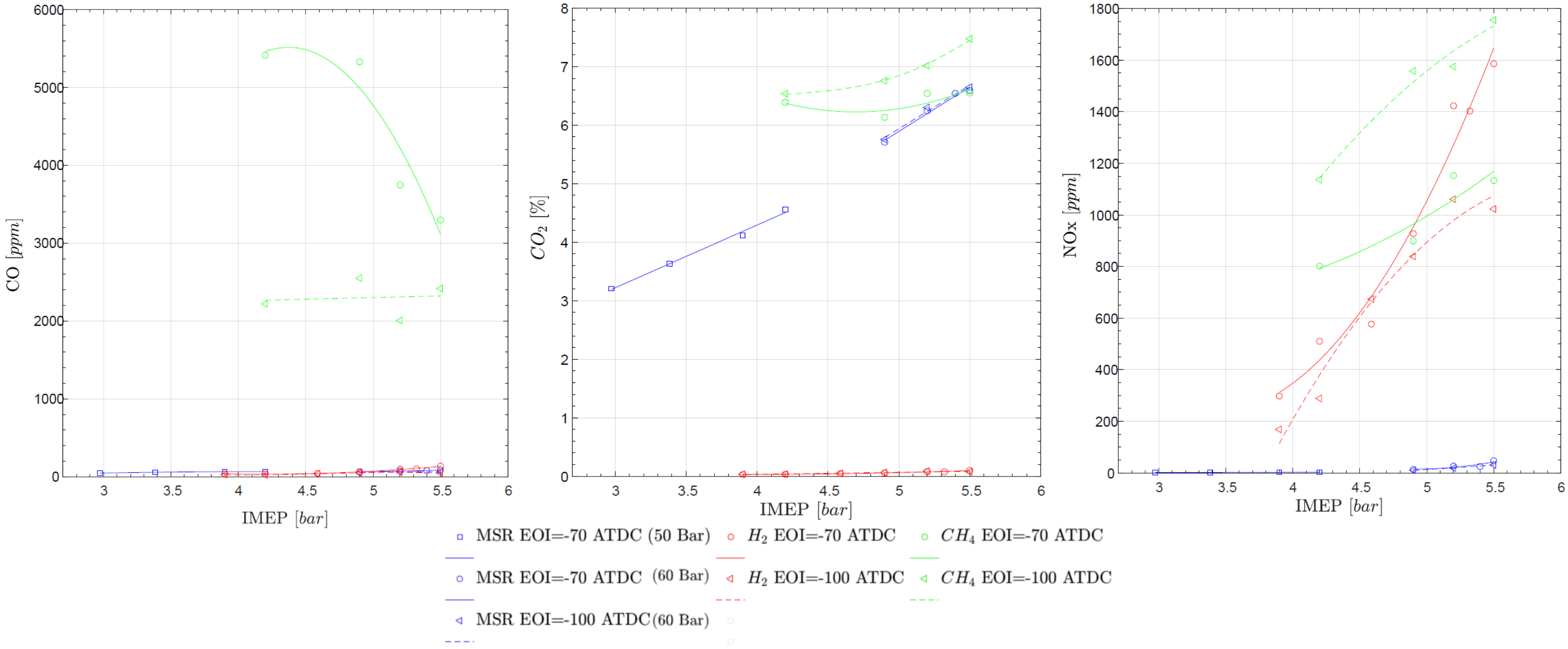




- ➢ **19%-30% relative increase in indicated efficiency**
- ➢ **A reduction in NO_x, CO and HC emissions by up to 97, 91 and 96, respectively**

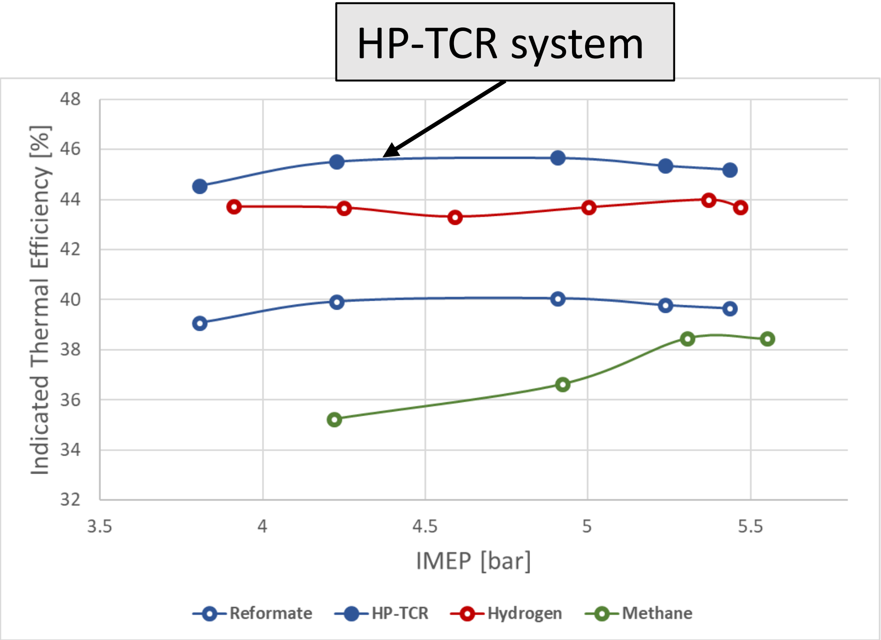
Fuel type effect on gaseous pollutant emission – DI engine

- CO is near-zero for MSR and hydrogen
- CO_2 for MSR - from the injected reformate
- NO_x is near-zero for MSR due to CO_2



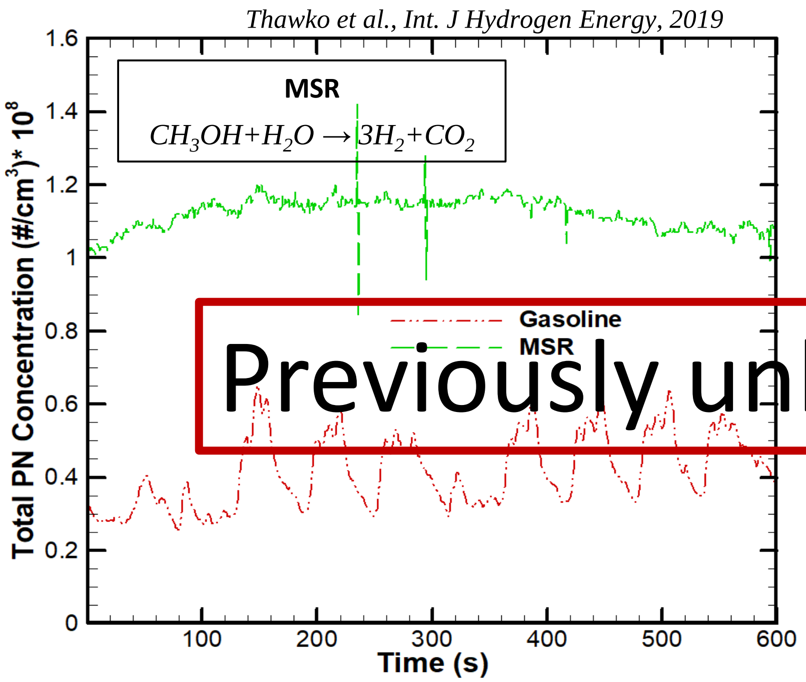
Fuel type effect on DI engine performance

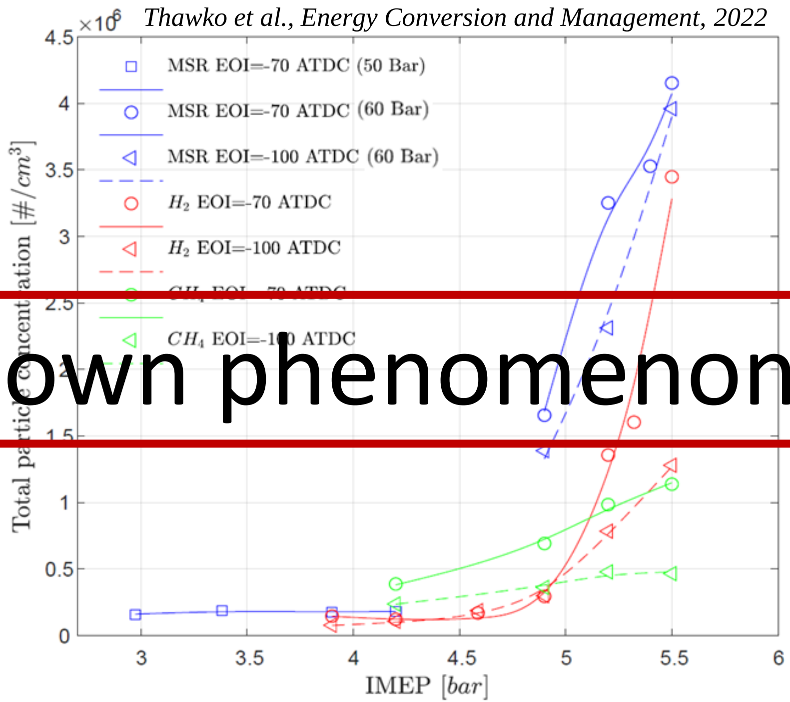
- HP-TCR system efficiency is higher than for the pure hydrogen
- Ultra-low NO_x emission for the reformate due to CO_2 presence
- Ultra-low CO emission for both the reformate and hydrogen
- Advanced EOI is favored because of better fuel-air mixing



Thawko et al., Energy Conversion and Management, 2022

Total particle concentration comparison





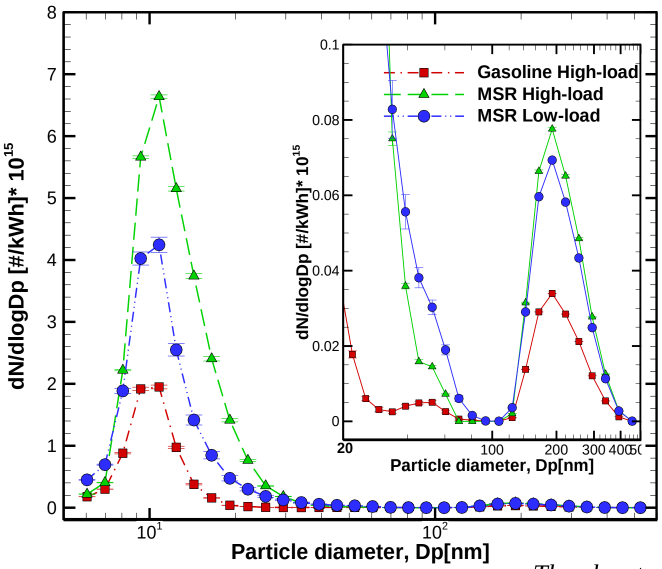
Previously unknown phenomenon

This result contradicts the previously published data and a straightforward intuition

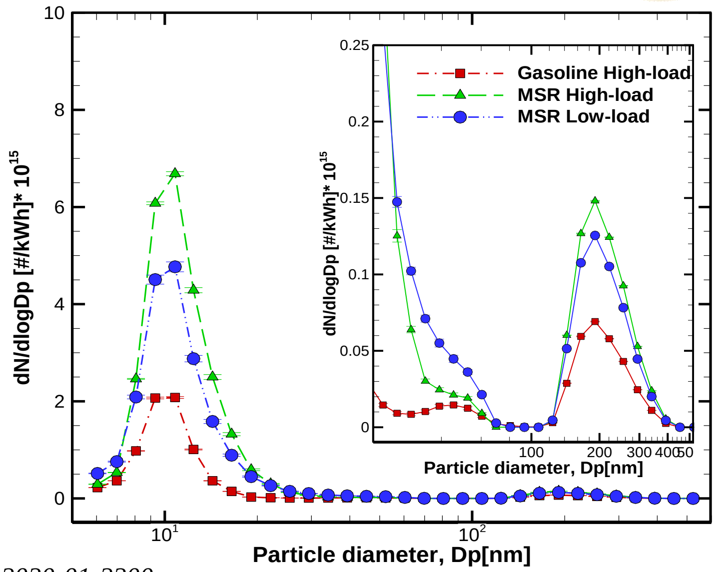
Particle size distribution – different oils

- Higher PN concentration for all particle size with the reformate
- PM were collected and characterized- lubricant additives were found

(a) Oil 1 (mineral)



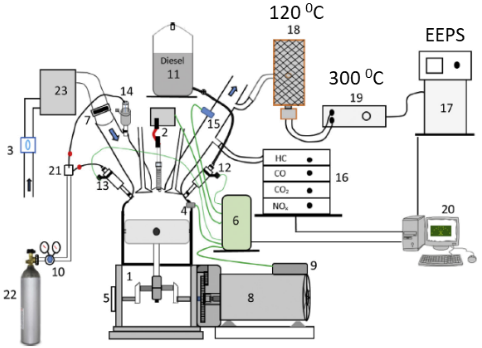
(b) Oil 2 (synthetic)



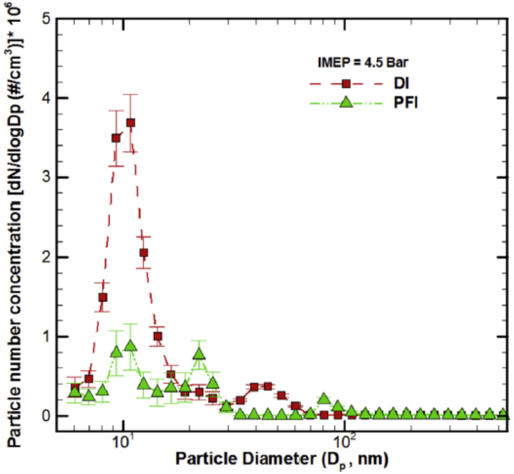
Thawko et al., SAE Technical paper 2020-01-2200

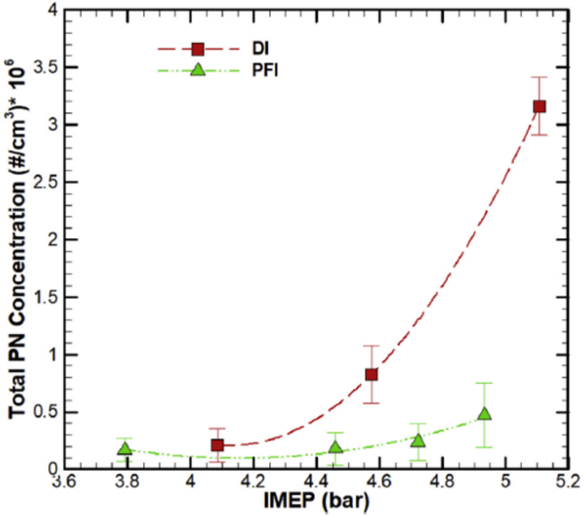
Particle formation- Direct vs Port Fuel Injection

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



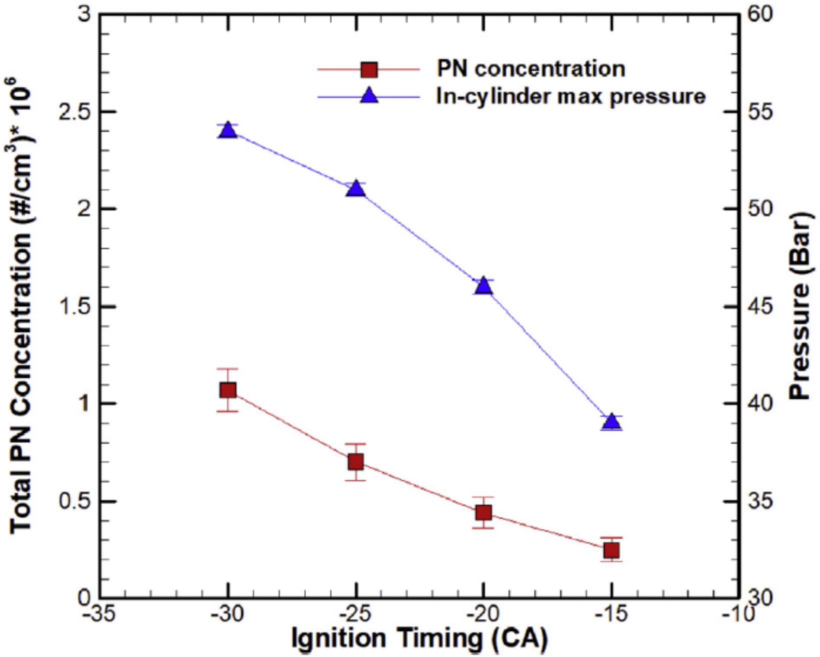
- Increased particles formation for direct injection
- Excessive lubricant involvement in the combustion





Particle formation - ignition timing effect

Reformate fuel

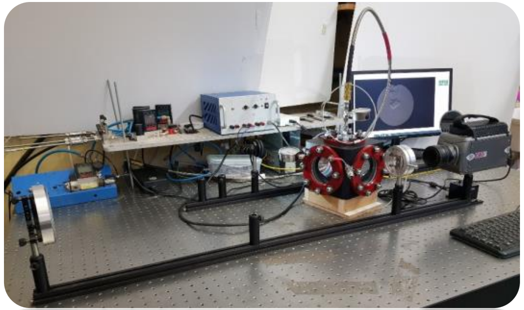


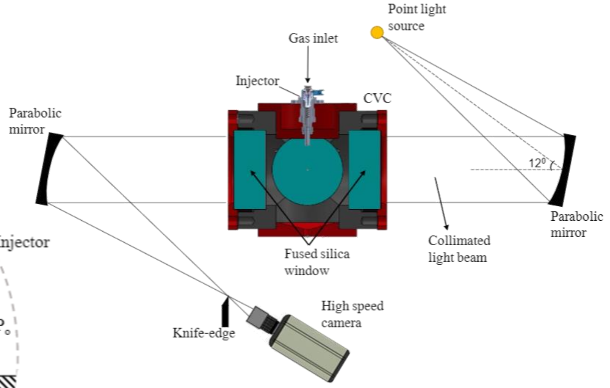
- ➢ Advanced ignition – increase in PN concentration
  - ➢ Higher In-cylinder pressure followed by lower flame quenching distance
  - ➢ More intensive lubricant evaporation
  - ➢ More Lubricated surface exposed to flame

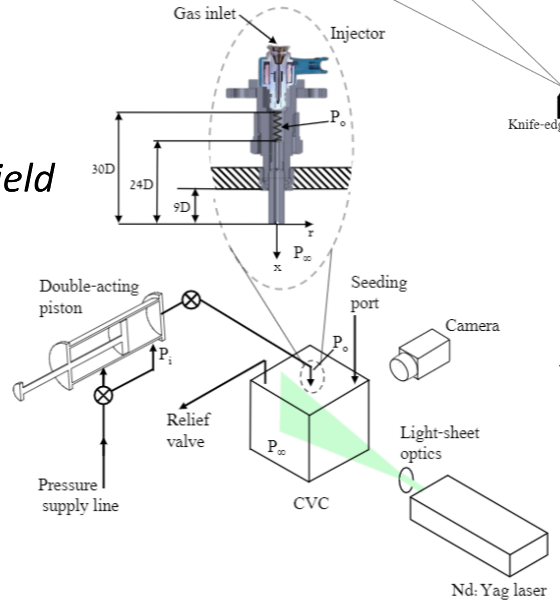
Thawko et al., Int. J Hydrogen Energy, 2019

Underexpanded gaseous jet flow field

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

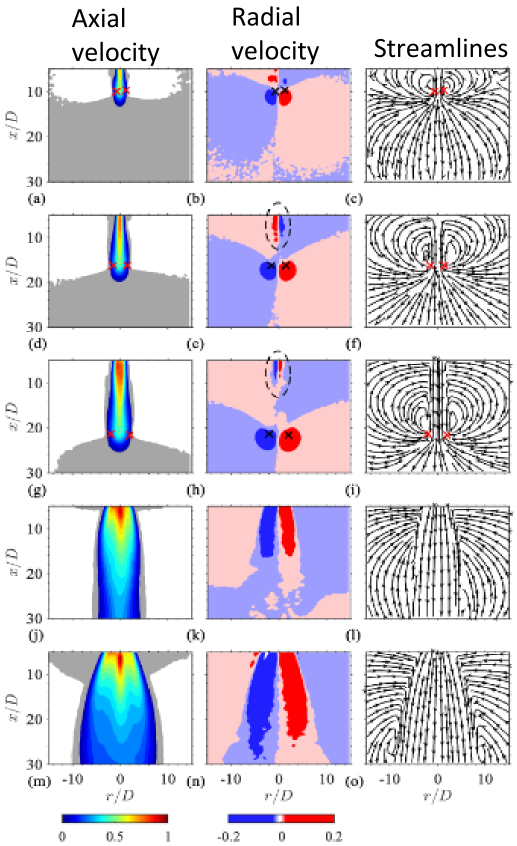


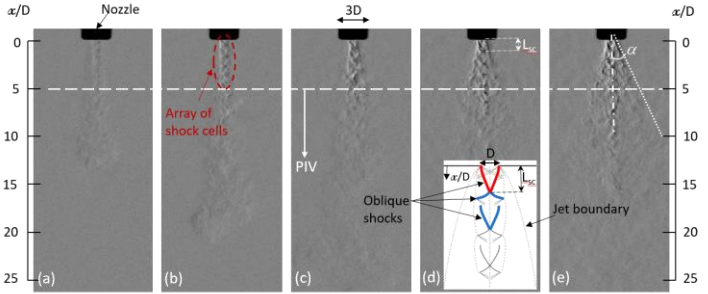




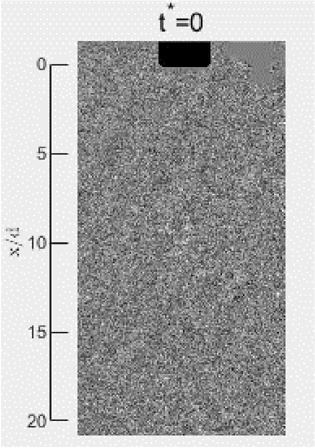
Thawko et al., Physics of Fluid, 2021

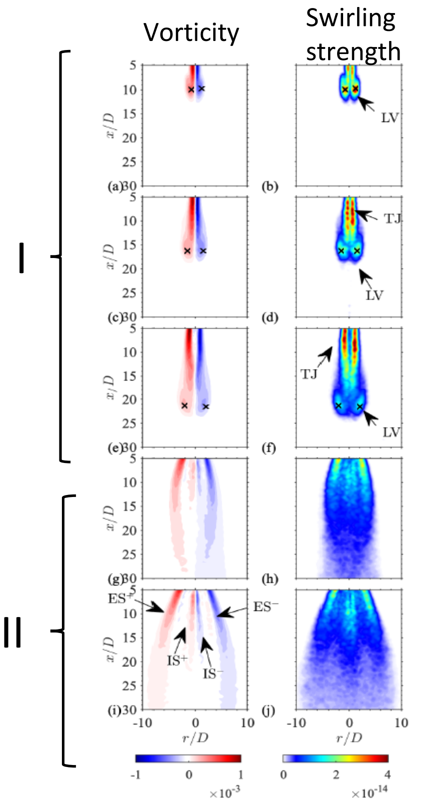
Flow field characterization- Free flow jet





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

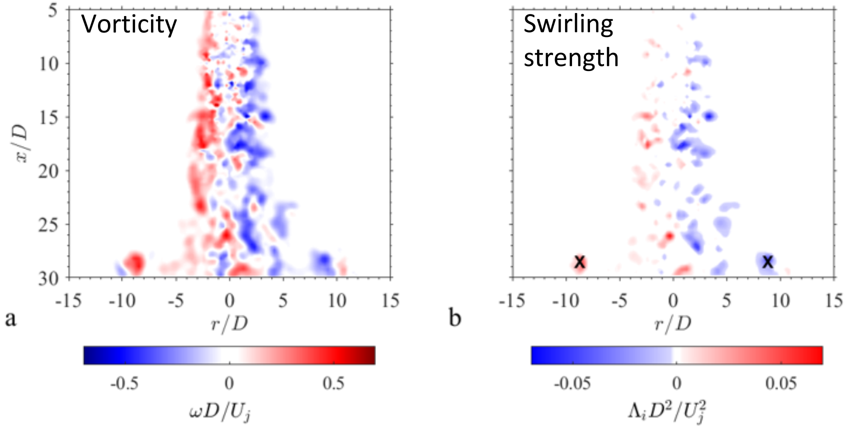




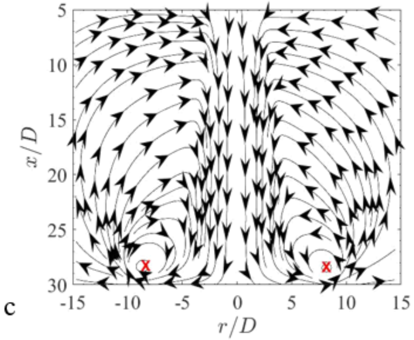
Thawko et al., Physics of Fluid, 2021

Flow field characterization- Impinging jet

- **Two rolled-up vortex regions with large-scale motion are formed in the wall jet region**
- **The lubricant vapor near cylinder walls entrained into the jet in the free-jet region and participates in the combustion**



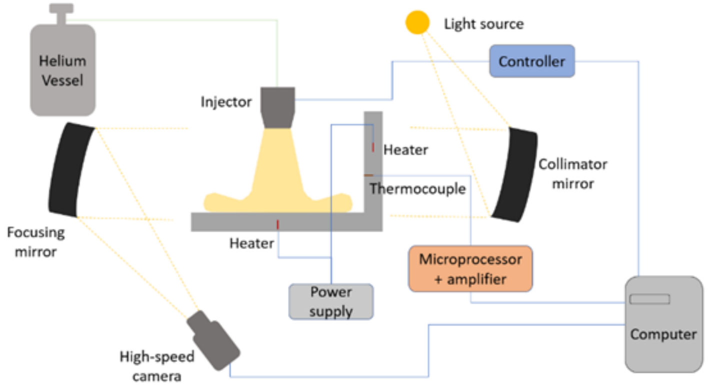
Is this the main entrainment mechanism?



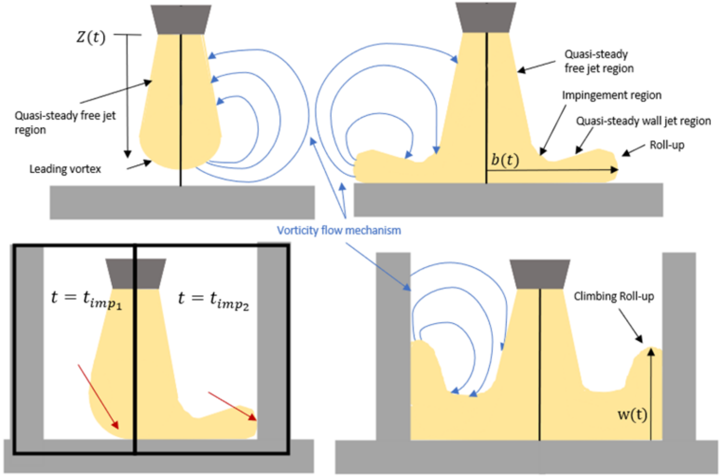
Interaction of a gaseous impinging jet with a heated lubricated surface

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**

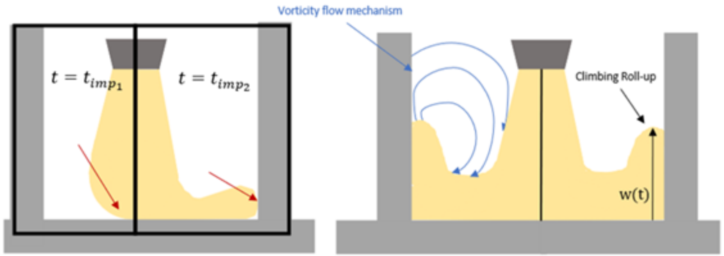


Holtzer & Tartakovsky, SAE Technical Paper 2023-01-0308, 2023

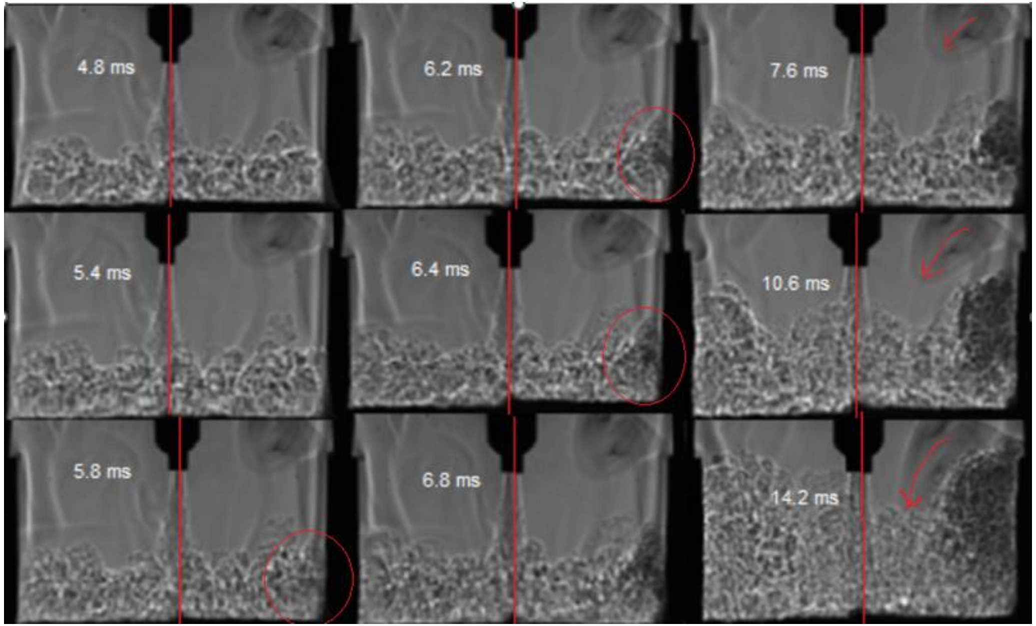


Main lubricant entrainment mechanism

- **Recirculation –** entrainment of the lubricant vapor in the free-jet region
- **Sweeping –** entrainment of the lubricant vapor along the liner by the climbing roll-up

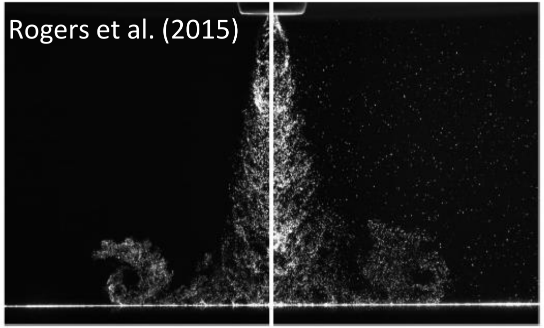


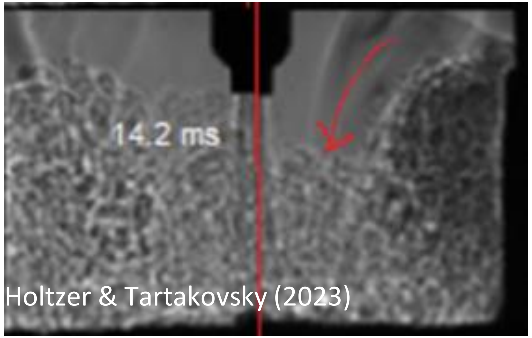
Holtzer & Tartakovsky, SAE Technical Paper 2023-01-0308, 2023

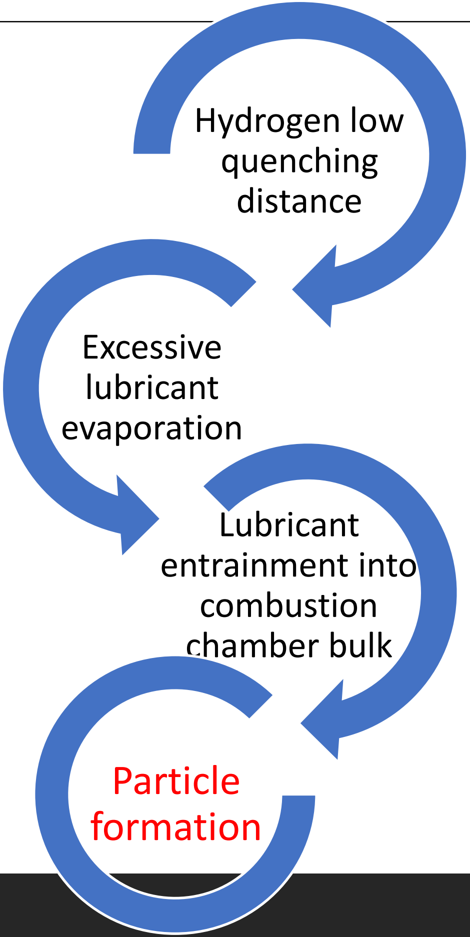


Sweeping is the main entrainment mechanism

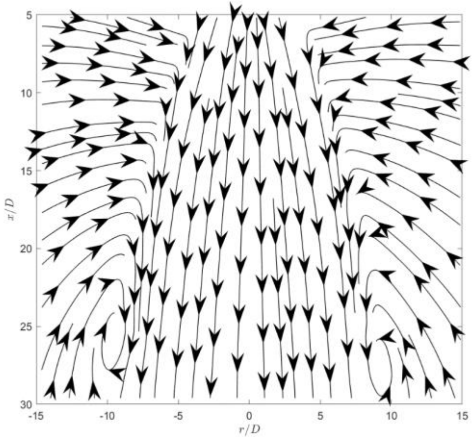
Particle formation mechanism in non-premixed H_2 combustion





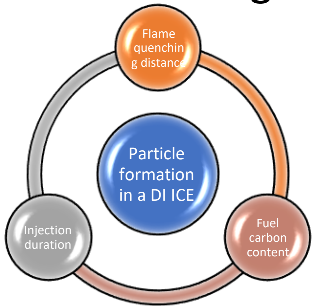


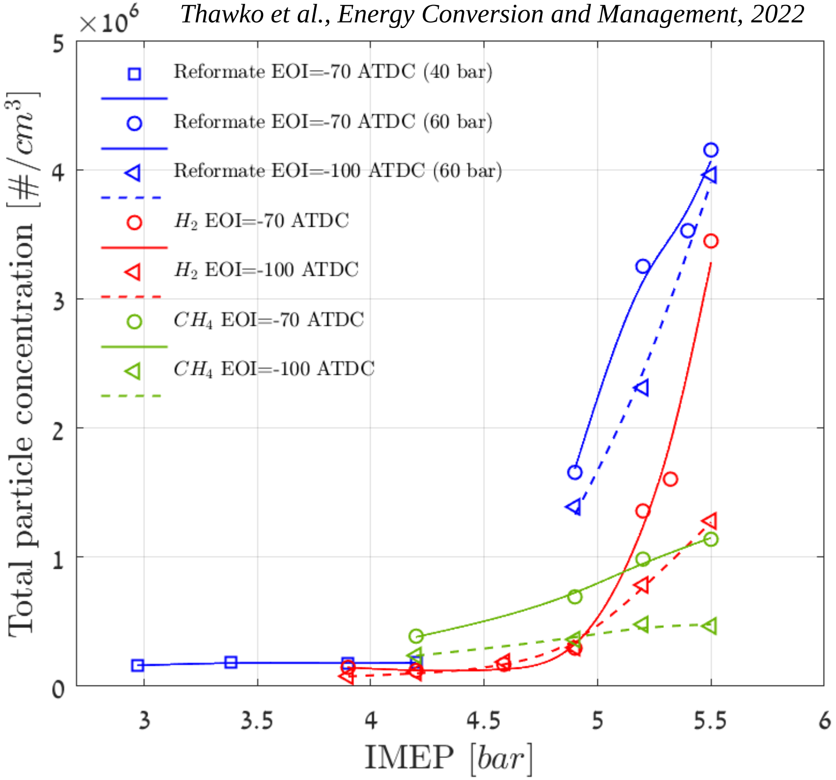
Both for DI&PFI



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

- The fuel carbon content is the dominant influencing factor affecting particle formation at low loads
- The lubricant becomes the dominant particle source with hydrogen-based fuel combustion
- Reformate with the highest injection duration results in the highest particle formation





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

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GTEP
Grand Technion Energy Program
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Q & A

Thank you for your attention!

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