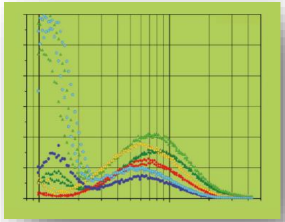
Technion Internal Combustion Engine Laboratory

GTEP Grand Technion Energy Program

TECHNION Israel Institute of Technology

Particle emission from direct injection internal combustion engine fed with various gaseous fuels

Andy Thawko, Michael Shapiro and Leonid Tartakovsky

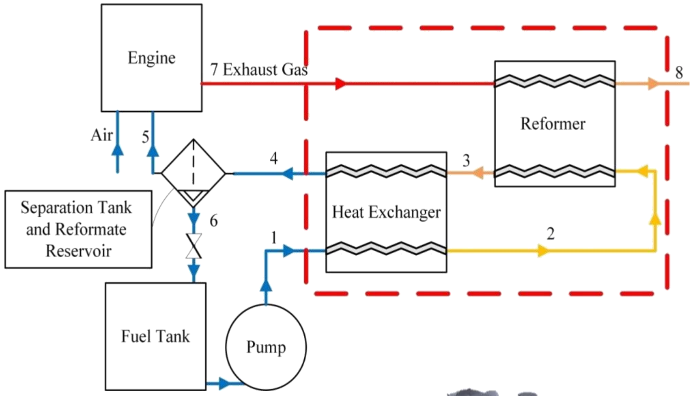


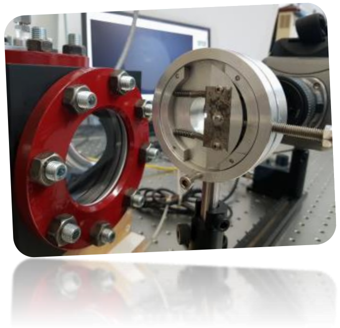
June 23rd, 2021

24th ETH Conference on Combustion Generated Nanoparticles

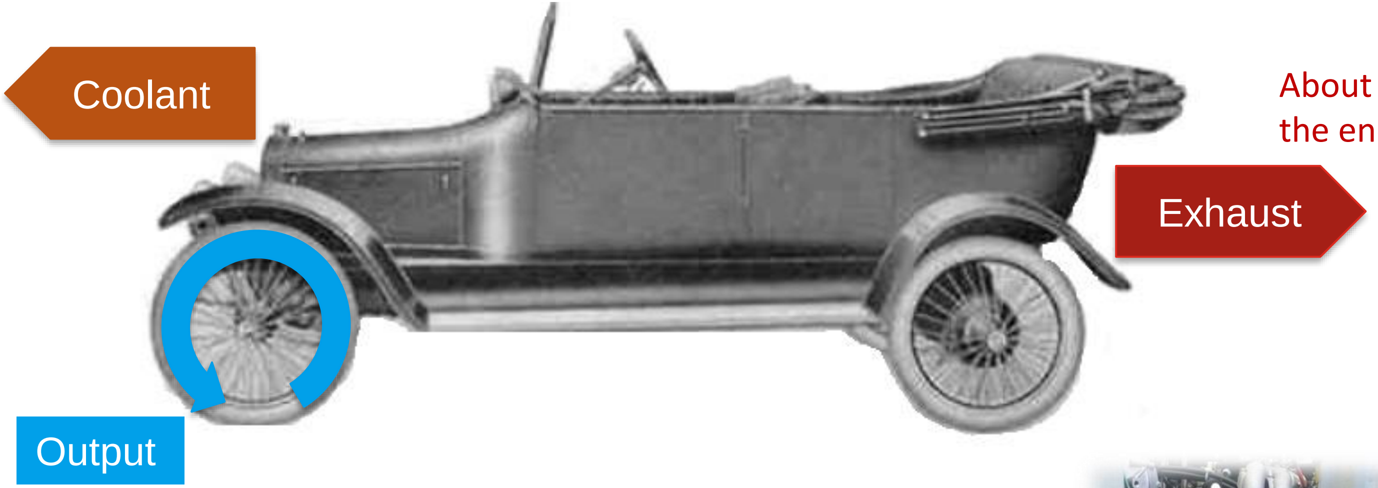
Outline

- Scientific background- Fuel Reforming
- Experimental setup- DI ICE fed with H_2, CH_4, and reformate
- Results:
  - Engine performance
  - pollutant emission
  - Particle emission
- Underexpanded jet characteristics
- Summary





Fuel energy distribution



About 1/3 of the energy

$$400\ ^{o}C < T_{Exhaust} < 900\ ^{o}C$$

Why to waste it…?!

The goal

Emission mitigation

Hydrogen combustion

On-board Fuel reforming

Efficiency improvement

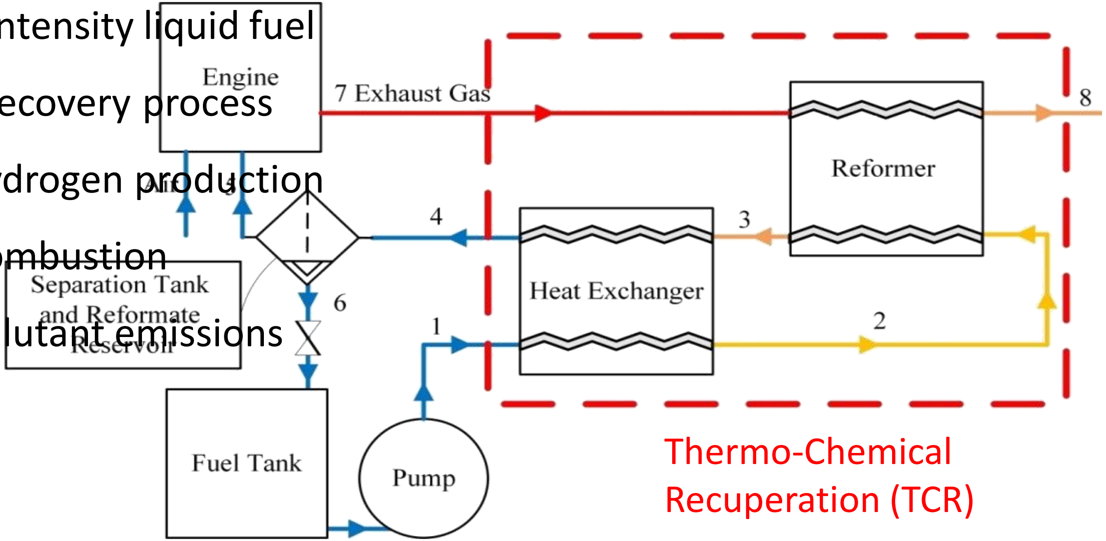
Waste heat recovery

Crude oil dependency reduction

Methanol - alternative (renewable) fuel

High-Pressure ThermoChemical Recuperation

- ✓ Primary alternative (renewable) and low-carbon intensity liquid fuel
- ✓ Waste heat recovery process
- ✓ On-board hydrogen production
- ✓ Hydrogen combustion
- ✓ Ultra-low pollutant emissions



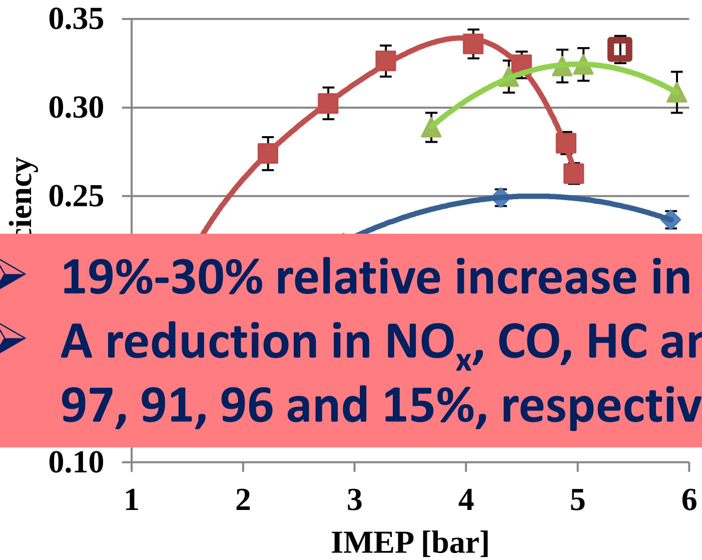
Thermo-Chemical Recuperation (TCR)

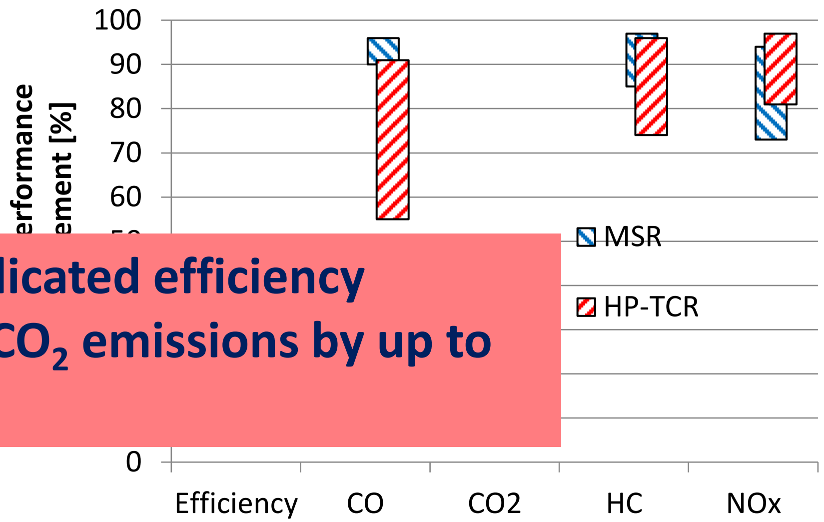
Methanol Steam Reforming (MSR)

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

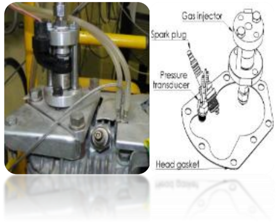
Tartakovsky L., Sheintuch M., Veinblat M., Thawko A., Patent pending, 2019

High-pressure ThermoChemical Recuperation





- ➢ **19%-30% relative increase in indicated efficiency**
- ➢ **A reduction in NO_x, CO, HC and CO_2 emissions by up to 97, 91, 96 and 15%, respectively**



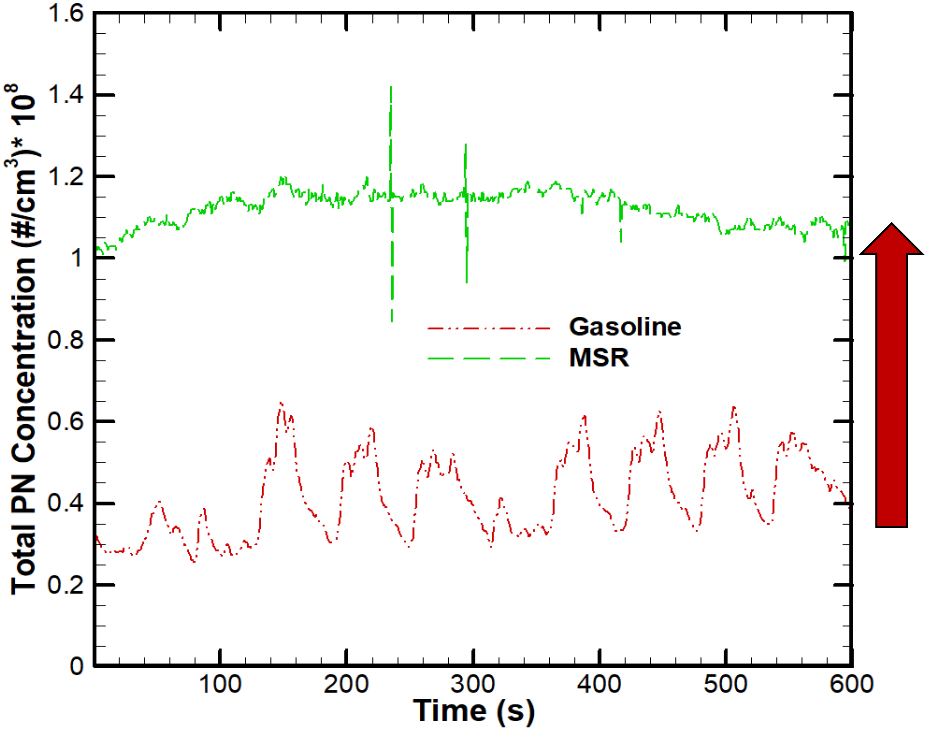
Single cylinder, spark ignition engine (Robin EY-20 based)		
Bore x Stroke, mm		67x52
Displacement, cm^3		183
Compression ratio		6.3
Power, kW @ speed, rpm		2.2 @ 3000
Fuel supply system	Gasoline	Carburetor
	Hydrogen-Rich Reformate	Direct injection

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

Total particle concentration comparison

MSR

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



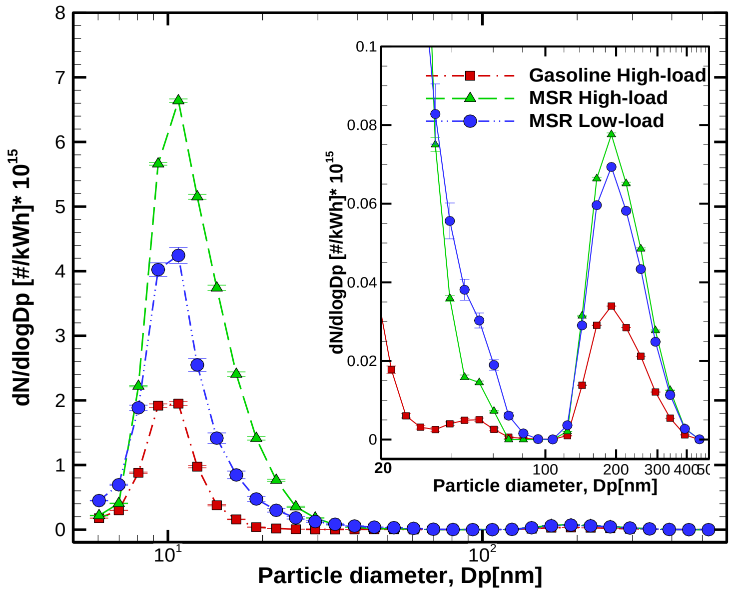
170% increase in particle emission

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

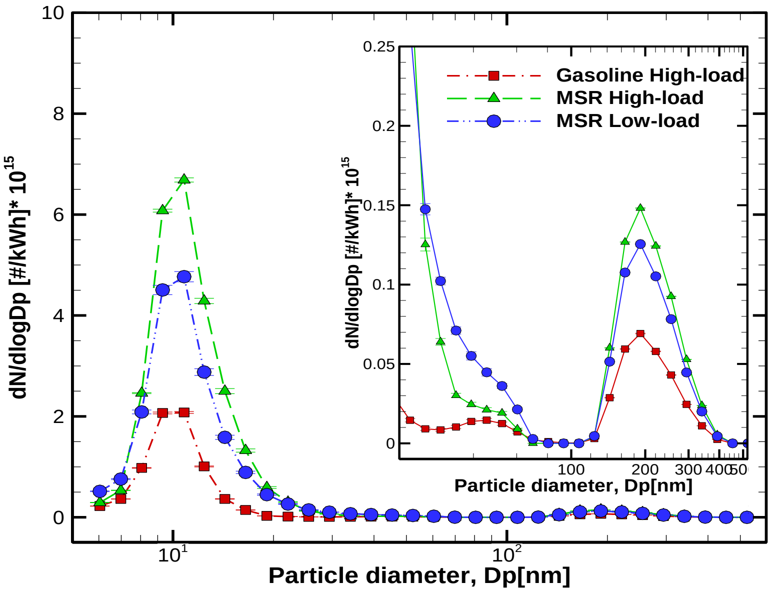
Particle size distribution – different oils

- Higher specific PN concentration for all particle size with the reformate

(a) Oil 1 (mineral)

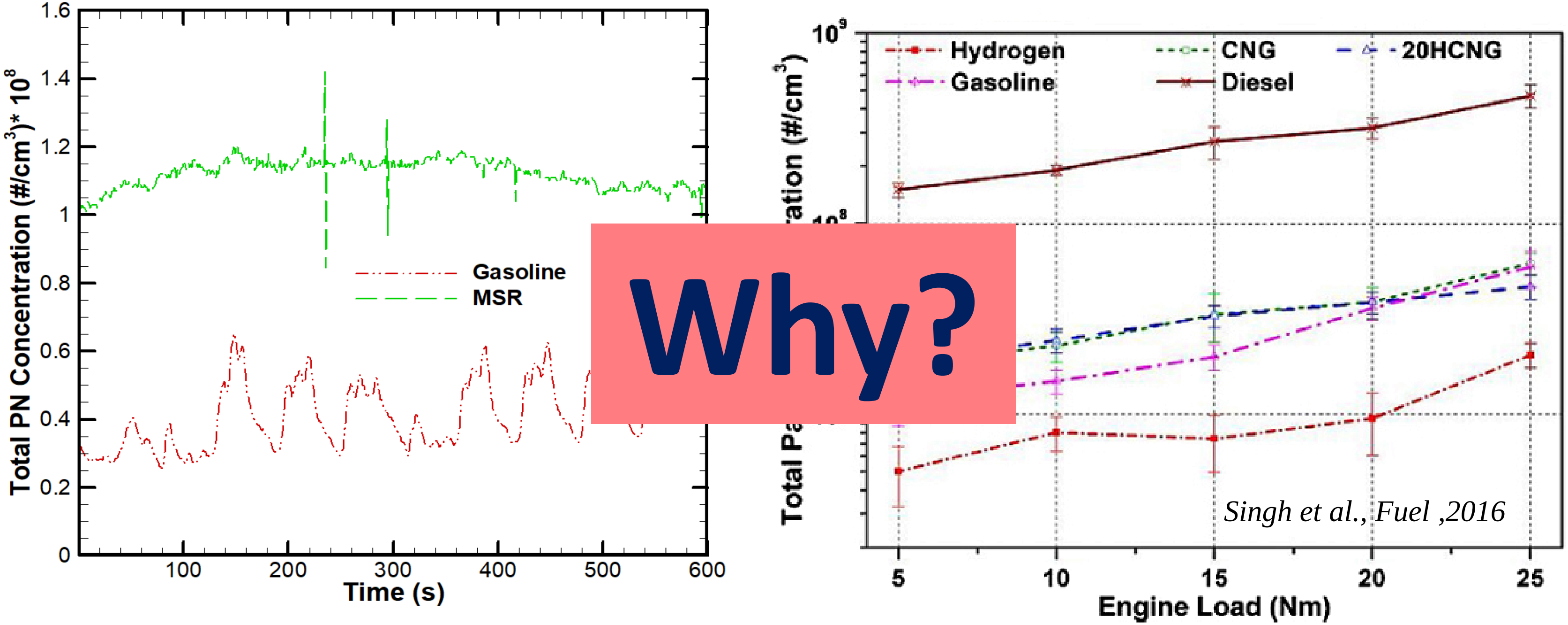


(b) Oil 2 (synthetic)



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

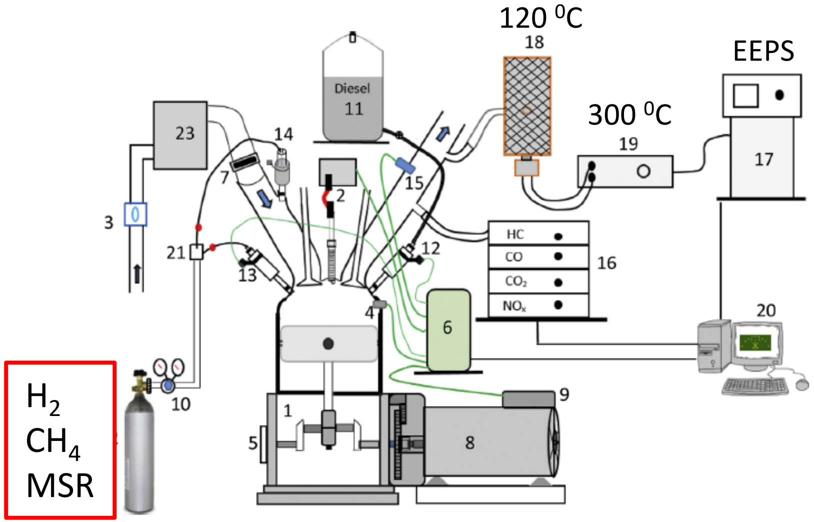
Total particle concentration comparison

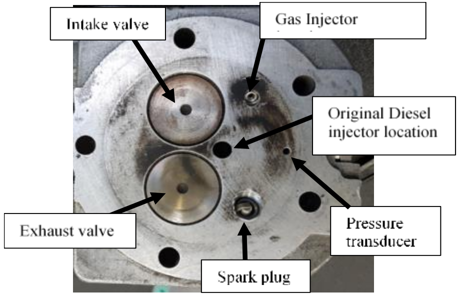


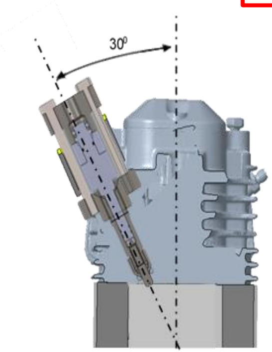
Previous studies showed significant PN reduction with hydrogen combustion

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

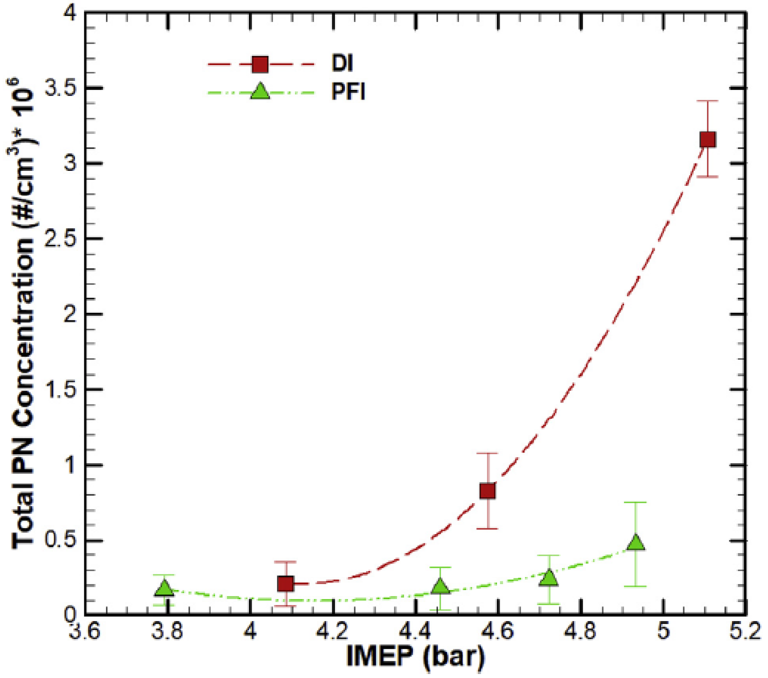






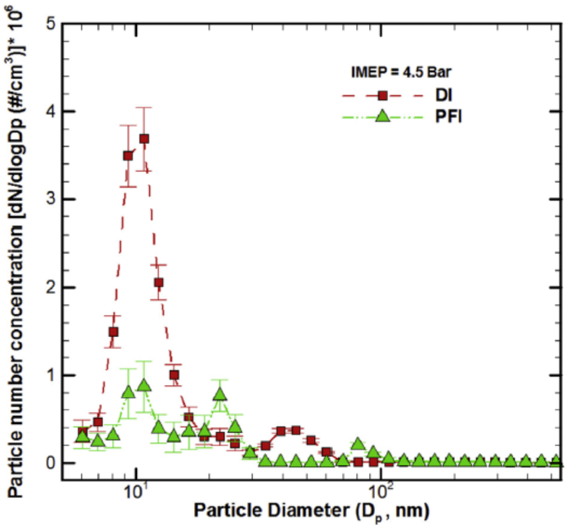
Particle formation- Direct vs Port Fuel Injection

Reformate fuel

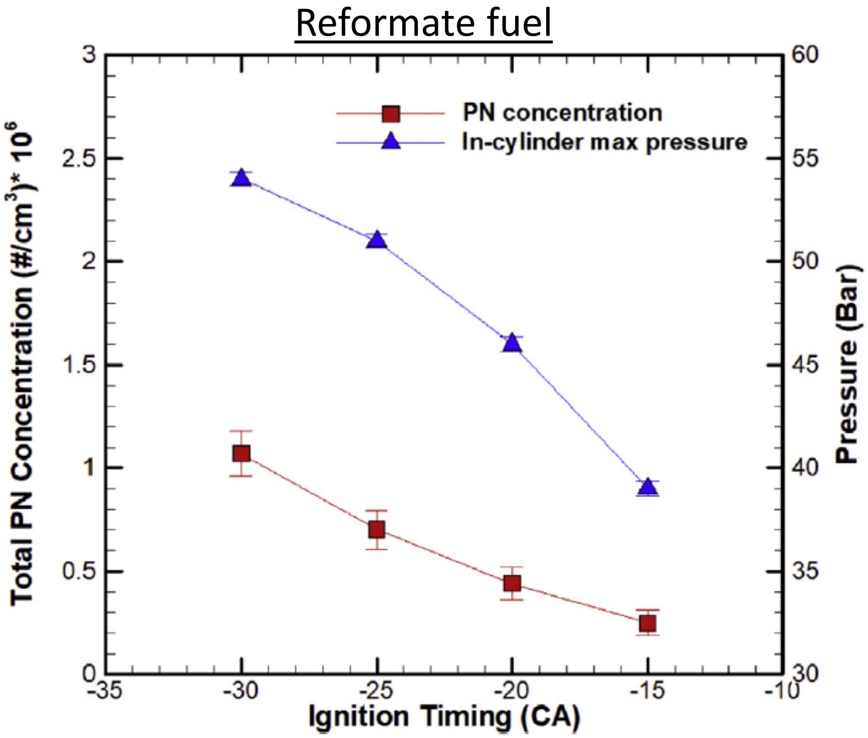


Thawko et al., Int. J Hydrogen Energy, 2019

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



Particle formation - ignition timing effect

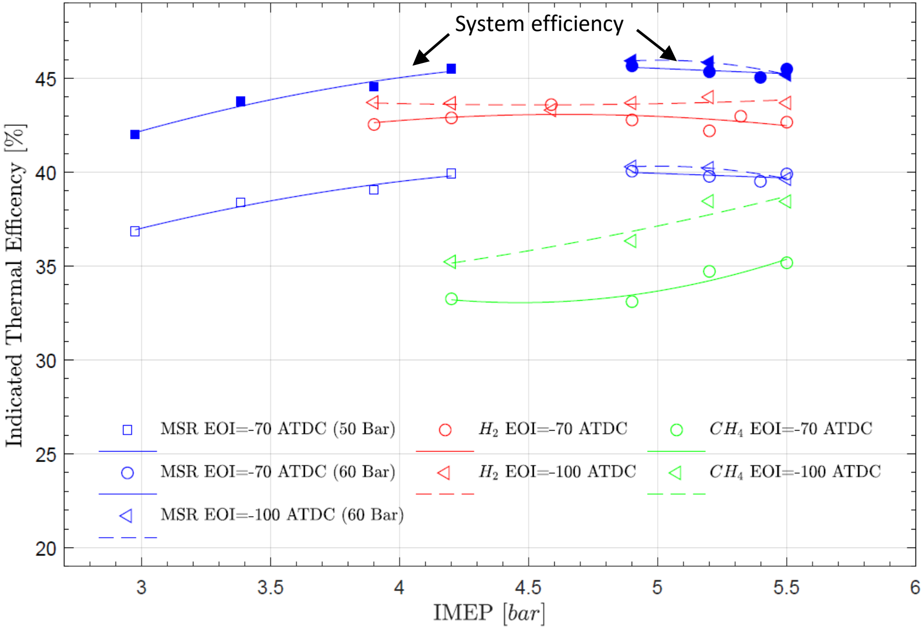


- Advanced ignition – increase in PN concentration
  - Higher In-cylinder pressure followed by lower flame quenching distance
  - More Lubricated surface exposed to flame

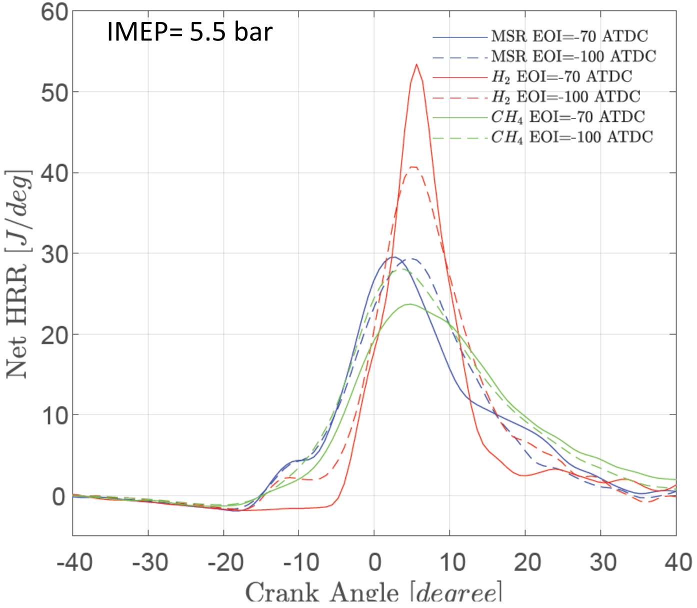
Thawko et al., Int. J Hydrogen Energy, 2019

Gaseous fuel DI- fuel type effect on engine performance

- Engine CR=15.5, WOT
- HP-TCR **system** efficiency is higher than hydrogen fuel
- Advanced EOI is favored because of better Fuel-air mixing

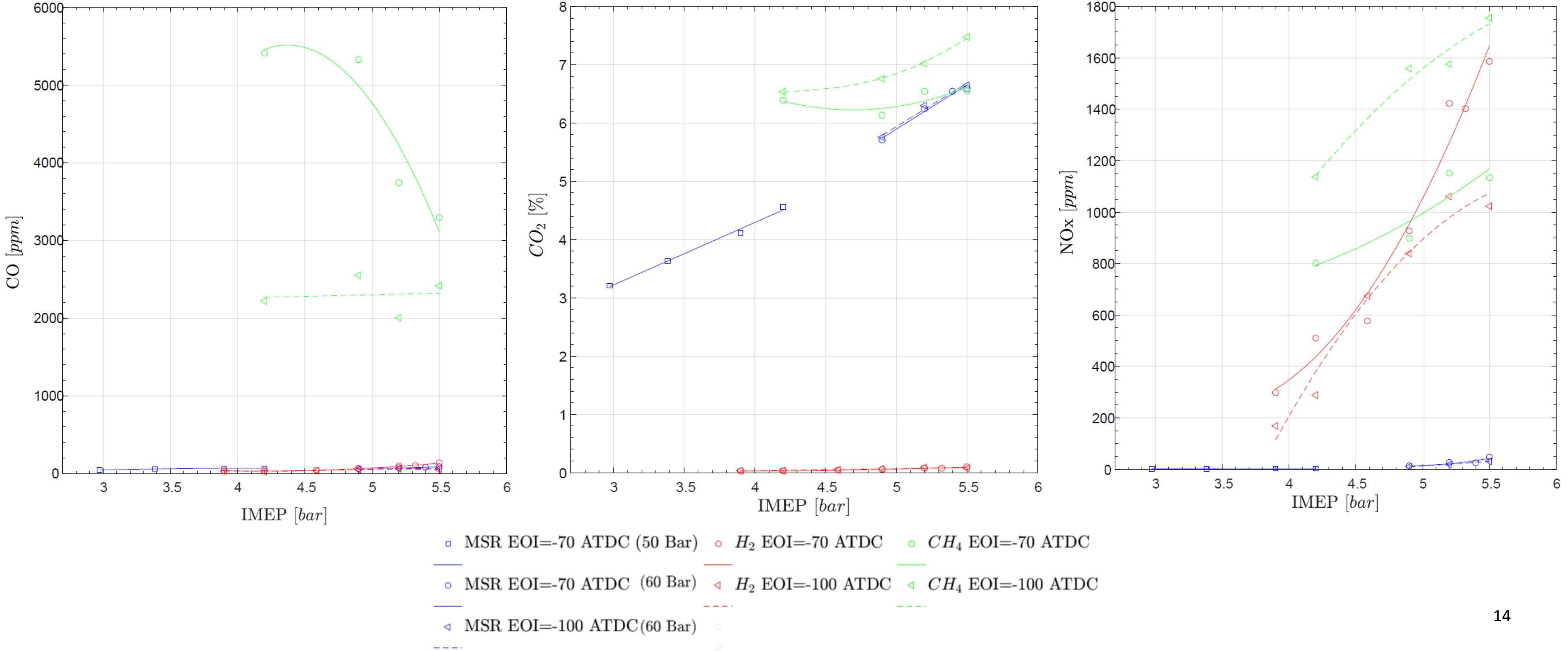


- HRR is affected by the EOI timing for hydrogen and methane
- The MSR has a long injection duration, thus no effect on HRR

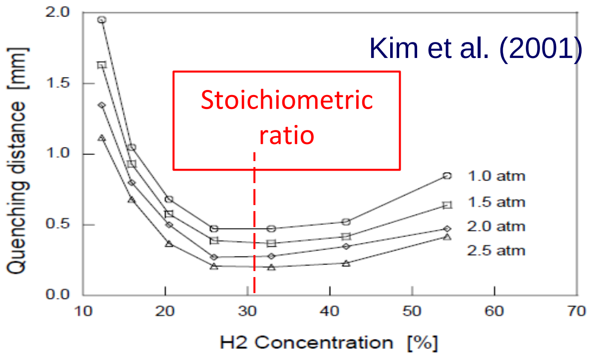


Gaseous fuel DI- fuel type effect on pollutant emission

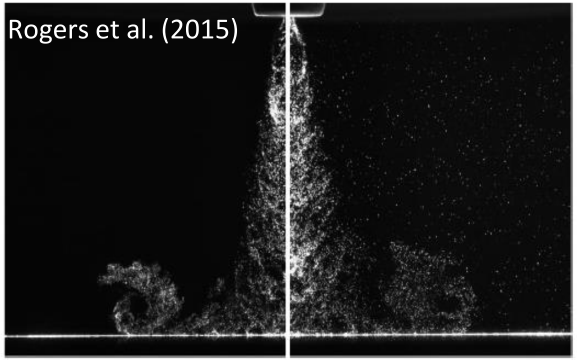
- CO pollutant is near-zero emission for MSR and hydrogen fuel
- CO_2 emission for MSR fuel is from the injected reformate composition
- NOx pollutant is near-zero emission for MSR due to CO2 presence

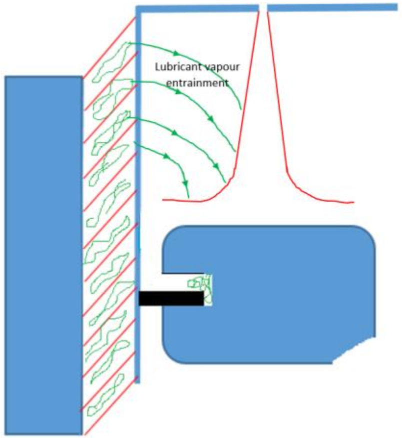


Particle formation in DI-ICE fed with hydrogen-rich reformate- Possible mechanisms



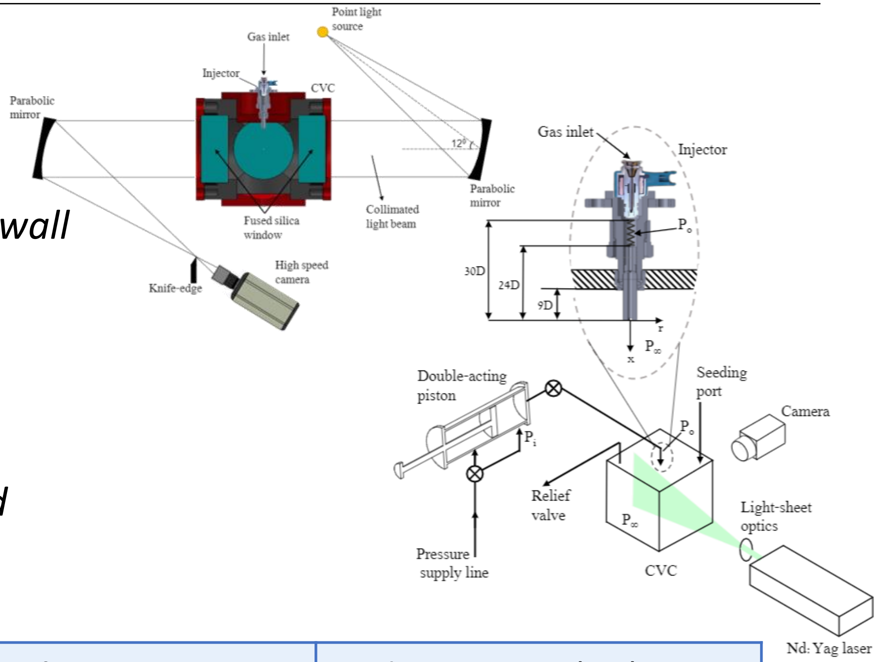
- Hydrogen low quenching distance
- Jet-wall impingement
- Lubricant vapor entrainment into the gaseous jet

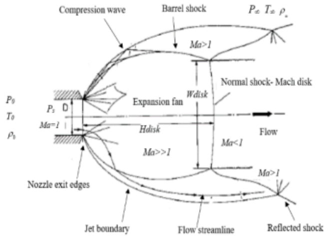




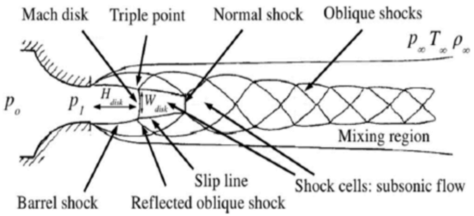
Underexpanded jet flow field- single nozzle exit injector

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





Crist S. et al., AIAA J., 1966

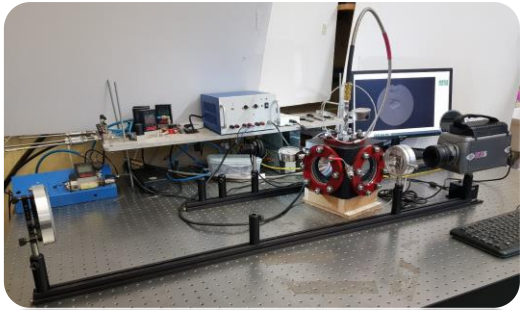


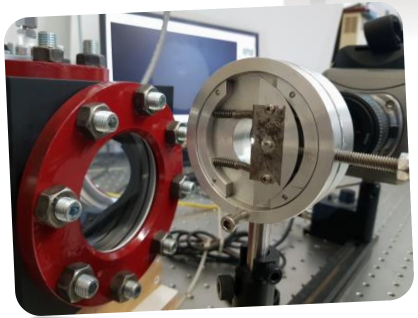
Snedeker RS. et al., J. Fluid Mechanics, 1971

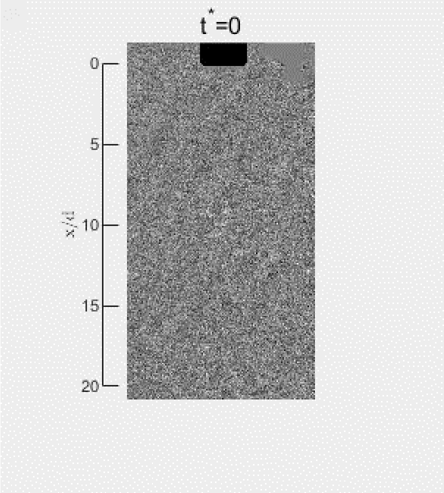
Classification	Nozzle pressure ratio (NPR)
Subsonic jet	$1 < P_0/P_\infty < 1.893$
Moderately underexpanded jet	$2.08 < P_0/P_\infty < 3.8$
Highly underexpanded jet	$3.84 < P_0/P_\infty$

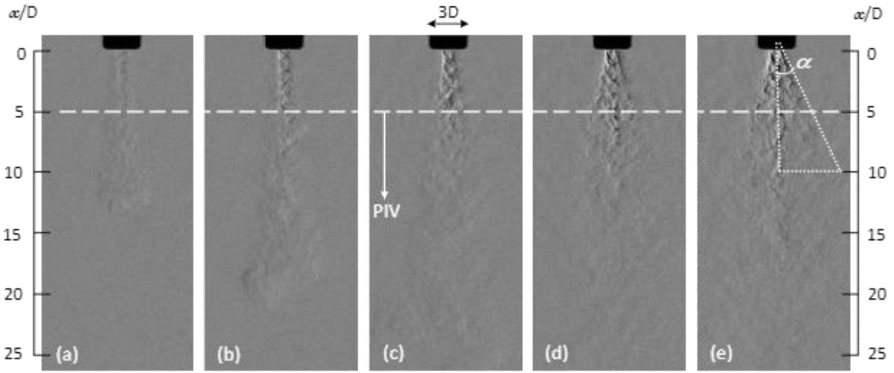
Near-field structure- Jet type characterization

- Jet type transition from subsonic to underexpanded jet



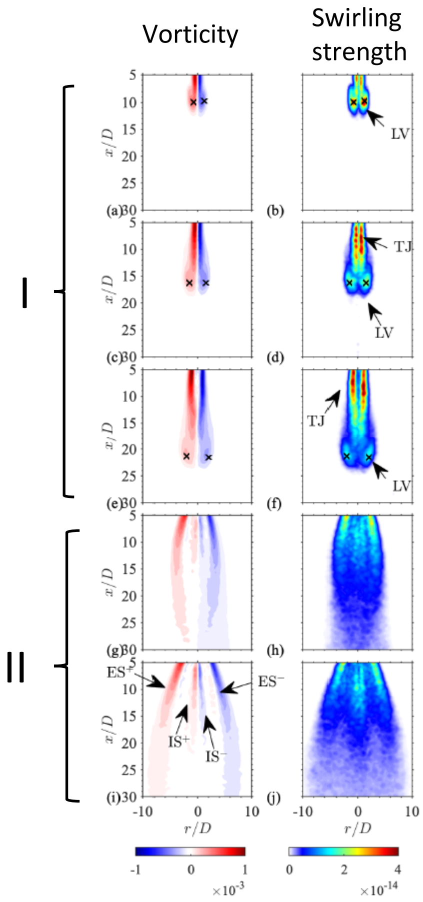




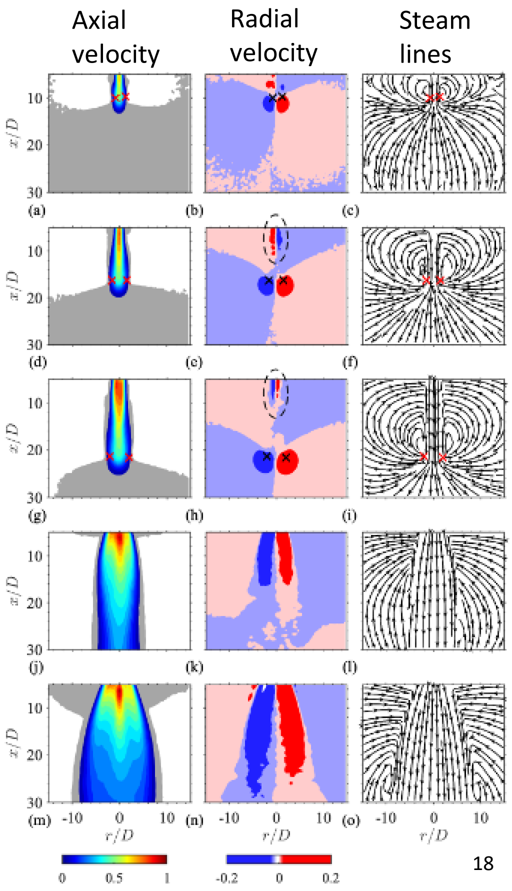


Thawko et al., physics of fluid, 2021 (under review)

Far-field characterization- mean temporal evolution



- Two stage jet development
- Inner shear layer appears during stage II
- NPR rise result in a change of radial velocity direction at jet centerline
- **Excessive air entrainment encouraged by the leading vortex**



Thawko et al., physics of fluid, 2021 (under review)

Summary

- DI-ICE with High-Pressure Thermo-Chemical Recuperation was developed enabling:
  - **Efficiency improvement** (up to 30%) compared to gasoline counterpart
  - **Gaseous pollutant emission reduction** (up to 97%, 91% and 96% for NOx, CO and HC, respectively)
- **Excessive particle formation** with gaseous **DI method**
- The mechanism of Lubricant vapor entrainment into the jet was demonstrated
- Future research- improving the fuel-air mixing of direct injection method

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הועדה לתכנון ולתקצוב

Grazie mille!

Merci beaucoup!

非常感谢您!

どうもありがとう！

Большое спасибо!

شكرا لكم!

תודה רבה!

Тхьэуегъэпсэу!

Vielen Dank!

Muchas gracias!

대단히 감사합니다!

बहुत बहुत धन्यवाद !

Puno vam hvala!

Σας ευχαριστώ πολύ!

Dziękuję Ci!

Thank you for your attention!

Andy Thawko

Technion – Israel Institute of Technology

Grand Technion Energy Program

Email: Andythawho@technion.ac.il