Technion Internal Combustion Engine Laboratory

Grand Technion Energy Program

TECHNION Israel Institute of Technology

Particle Emissions of Direct Injection IC Engine Fed with a Hydrogen-rich Gaseous Fuel

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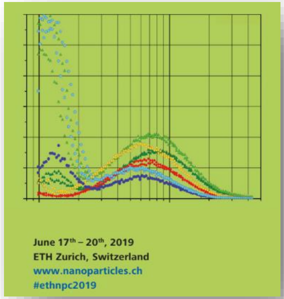
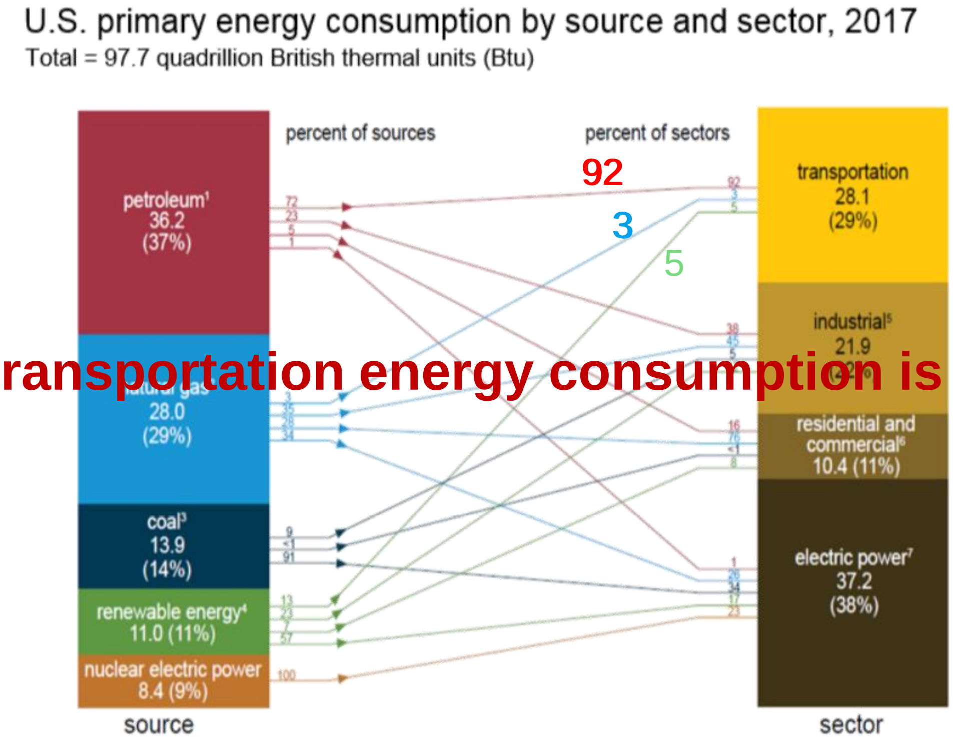


Outline

- Scientific background- Fuel Reforming
- Experimental Setup
- Performance of ICE with Thermo-Chemical Recuperation
- Particle Emission
- Summary

Petroleum consumption for transportation



92% of the transportation energy consumption is from crude oil

Source: U.S Energy Information Administration (April 2018)

European emission legislation

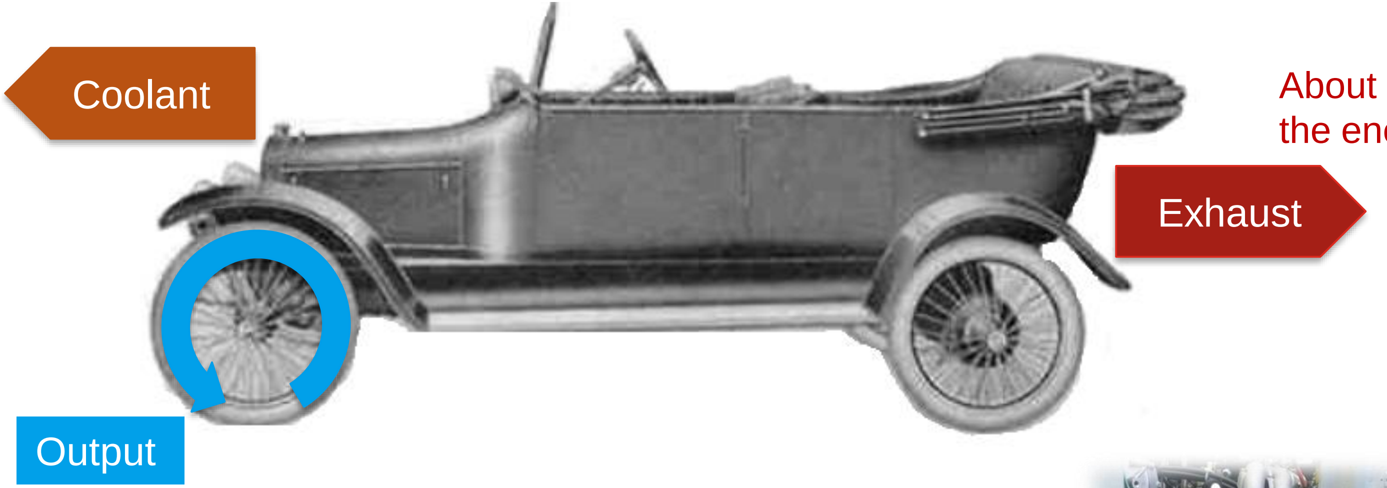
Diesel Passenger Cars:

Emissions	Unit	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5a	Euro 6b/c
NOx	mg/km	-	-	500	250	180	80
HC+NOx	mg/km	970	700	560	300	230	170
CO	mg/km	2720	1000	640	500	500	500
PM	mg/km	140	80	50	25	5.0	4.5
PN	#/km	-	-	-	-	-	$6 \cdot 10^{11}$

Gasoline Passenger Cars:

Emissions	Unit	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5a	Euro 6b/c
THC	mg/km	-	-	200	100	100	100
NOx	mg/km	-	-	150	80	60	60
HC+NOx	mg/km	970	500	-	-	-	-
CO	mg/km	2720	2200	2300	1000	1000	1000
PM	mg/km	-	-	-	-	5.00	4.50
PN	#/km	-	-	-	-	-	$6 \cdot 10^{11}$

Fuel energy distribution

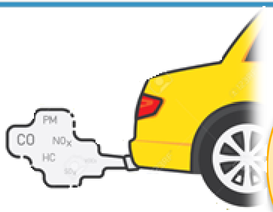


About 1/3 of the energy

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

Why to waste it…?!

The goal



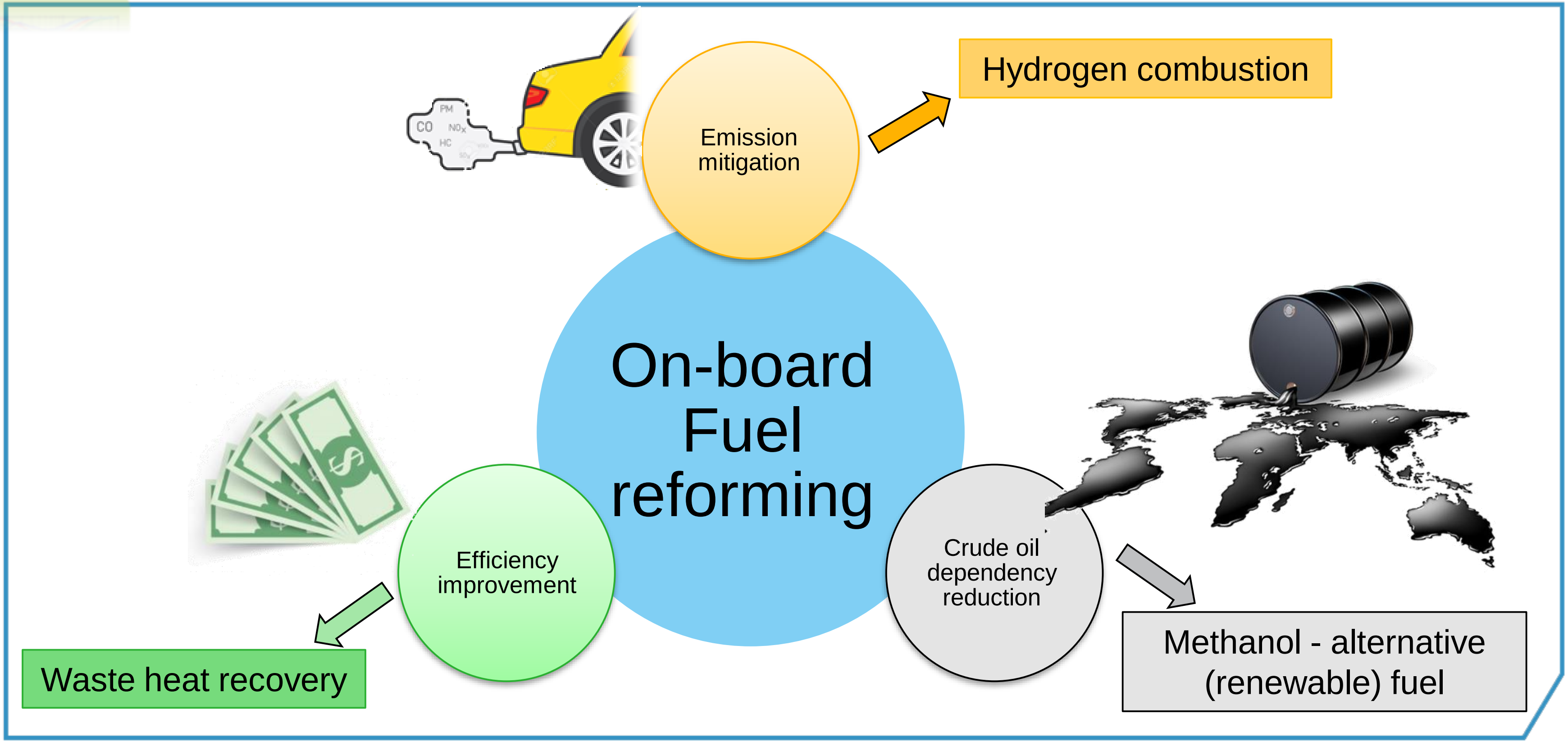
Emission mitigation

Feasible solution

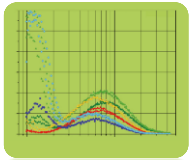
Efficiency improvement

Crude oil dependency reduction

Our goal

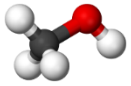


PM
CO
NOx
HC
Emission mitigation
Hydrogen combustion
On-board Fuel reforming
Efficiency improvement
Waste heat recovery
Crude oil dependency reduction
Methanol - alternative (renewable) fuel



Primary fuel selection

METHANOL



LIQUID METHANOL:

- Promising primary liquid fuel
  - Low carbon-intensity
  - Potentially renewable
  - Can be produced from natural gas or coal
    - Alternative for oil as a short term solution
- Can be produced from captured CO_2 – PtX fuel (electrofuel)
- No significant infrastructure change needed
- **Low reforming temperatures**

GASEOUS REFORMING PRODUCTS:

- Hydrogen-rich gaseous fuel: (75%)H_2+(25%)CO_2
- Better fuel properties
  - LHV increase
  - Higher antiknock quality
  - High laminar flame speed
  - Wide flammability limits
- Zero-impact pollutant emissions
- No problems of onboard hydrogen storage

$$\text{Methanol Steam Reforming (MSR):}\quad CH_3OH_{(g)} + H_2O_{(g)} \rightarrow CO_2 + 3H_2 \quad \Delta H = 50\,\text{kJ/mol}$$

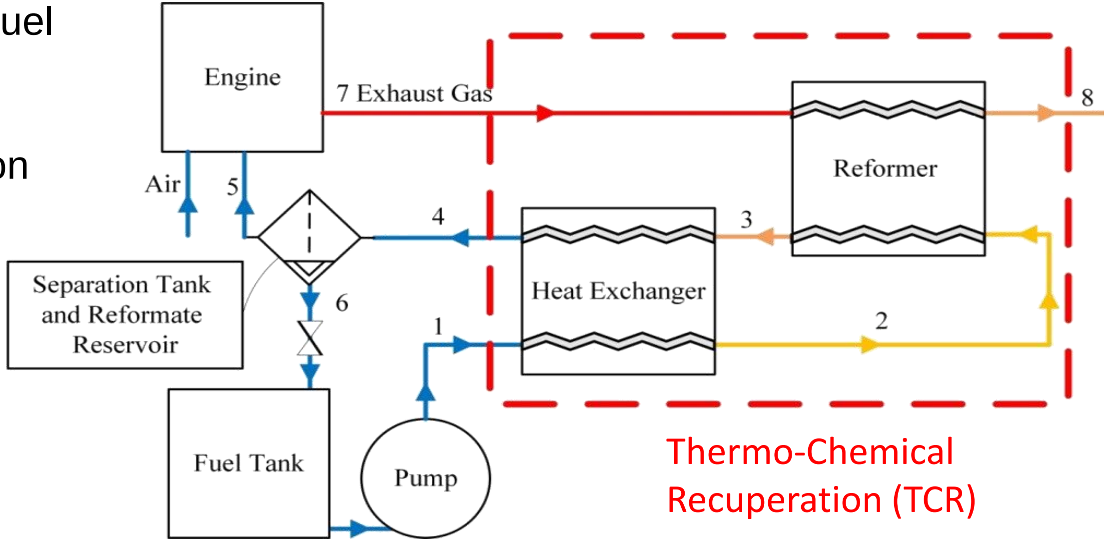
High-Pressure Thermo-Chemical Recuperation

✓Primary alternative (renewable) and low-carbon intensity liquid fuel

✓Waste heat recovery process

✓ On-board hydrogen production

✓Ultra-low pollutant emissions



Thermo-Chemical Recuperation (TCR)

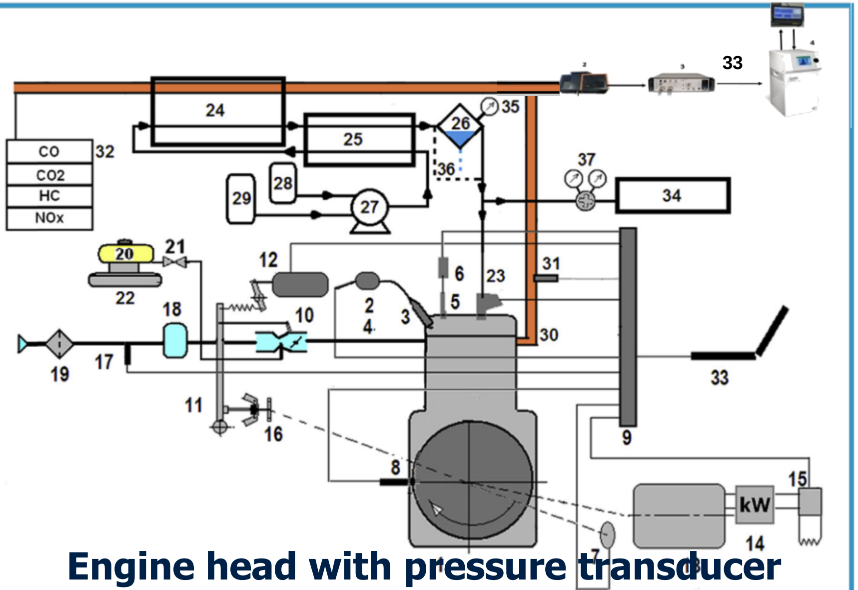
Methanol Steam Reforming (MSR)

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

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

Experimental Setup

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



Engine head with pressure transducer spark plug and injector

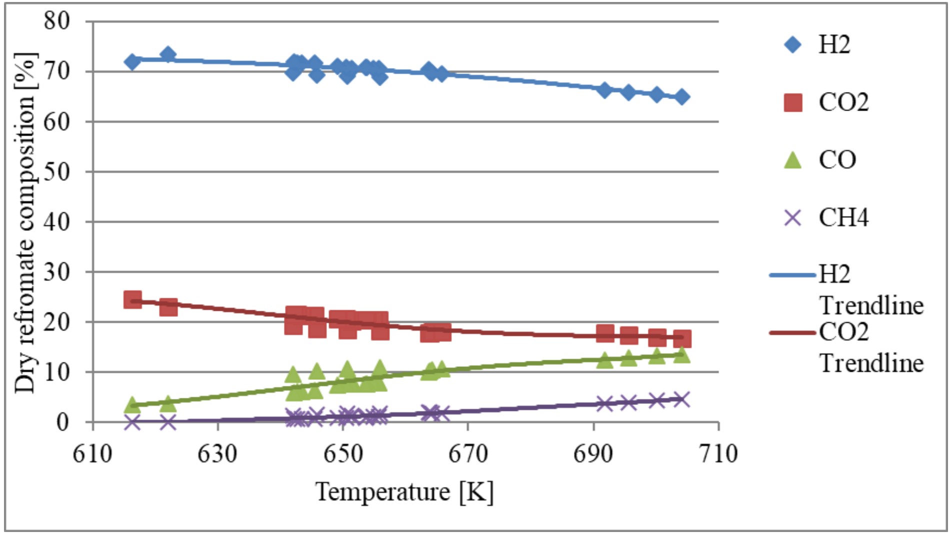
5 - In-cylinder pressure sensor
6 - Reformate direct injector
7 – Encoder

9 – Engine control system
24 – Reformer
33 – EEPS system

Measured reformate composition

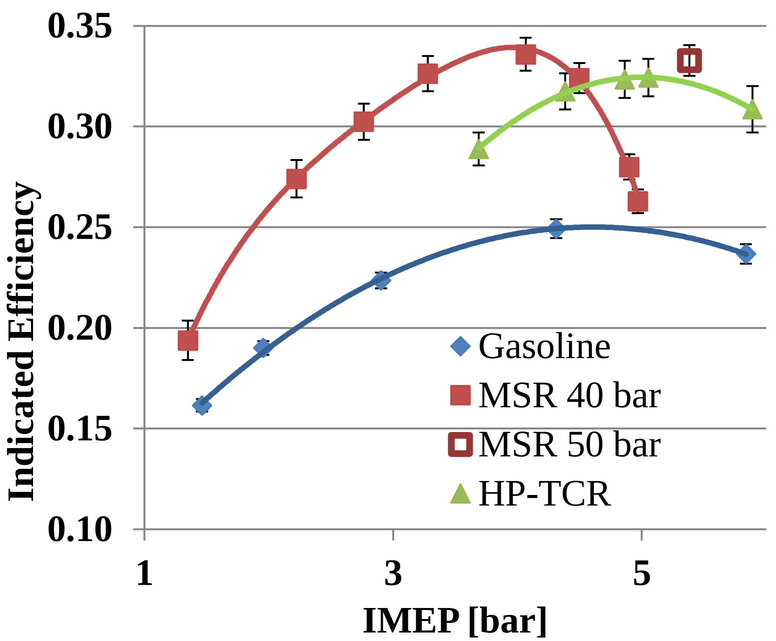
Methanol Steam Reforming (MSR)

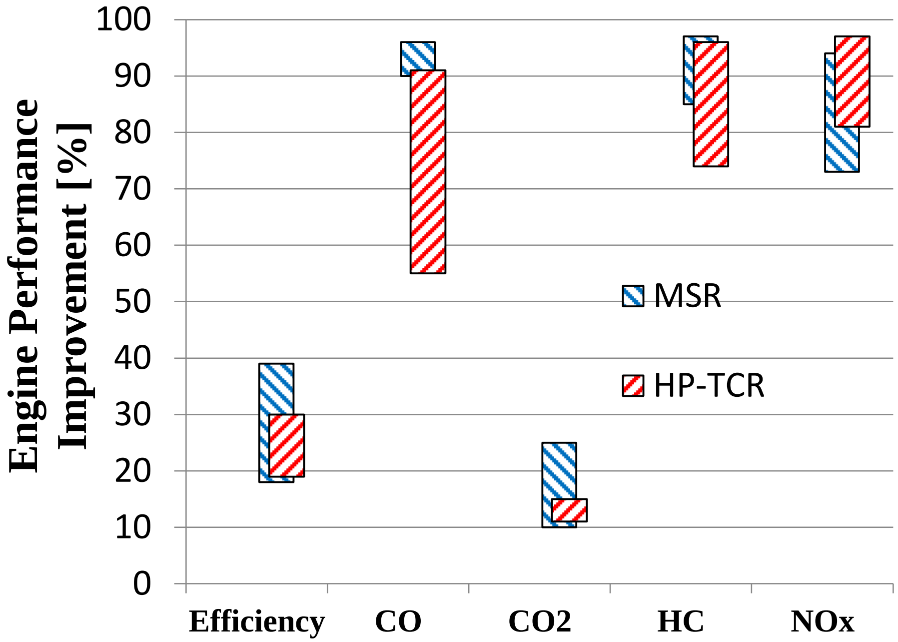
$CH_3OH+H_2O \rightarrow 3H_2+CO_2$ $\Delta H \approx 50$ kJ/mol



Poran, Thawko, Eyal, Tartakovsky, Int. J Hydrogen Energy, 2018

Thermo-Chemical Recuperation system Performance



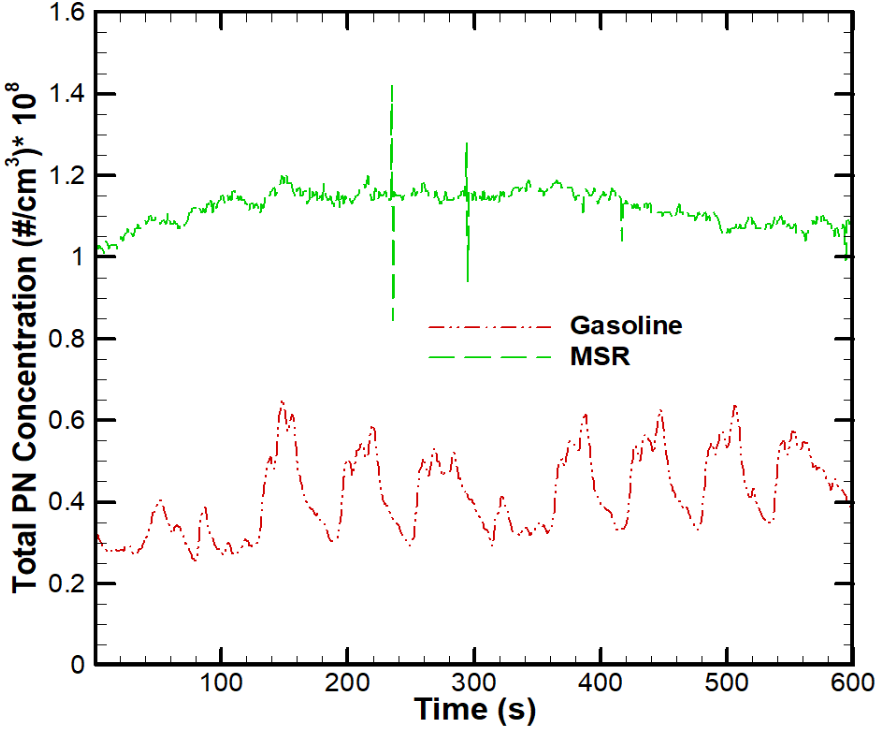


Poran, Thawko, Eyal, Tartakovsky, Int. J Hydrogen Energy, 2018

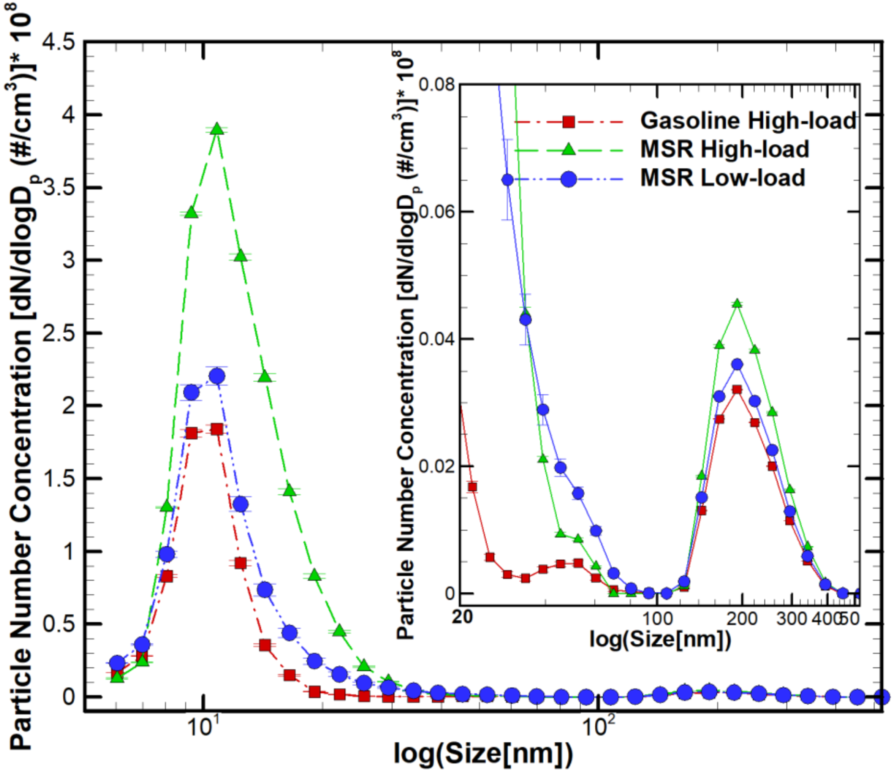
Total particle concentration comparison

MSR

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



Particle size and number distribution- Effect of Fuel

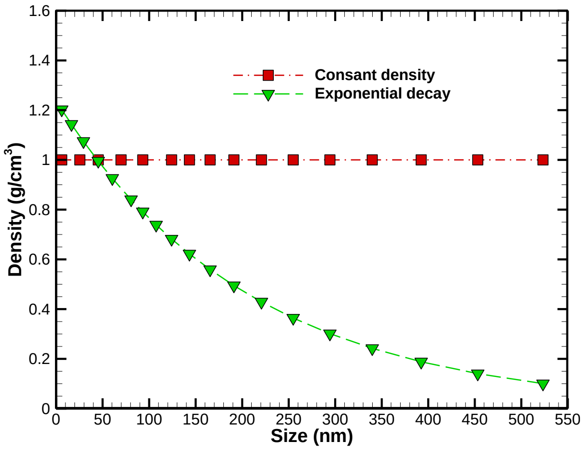


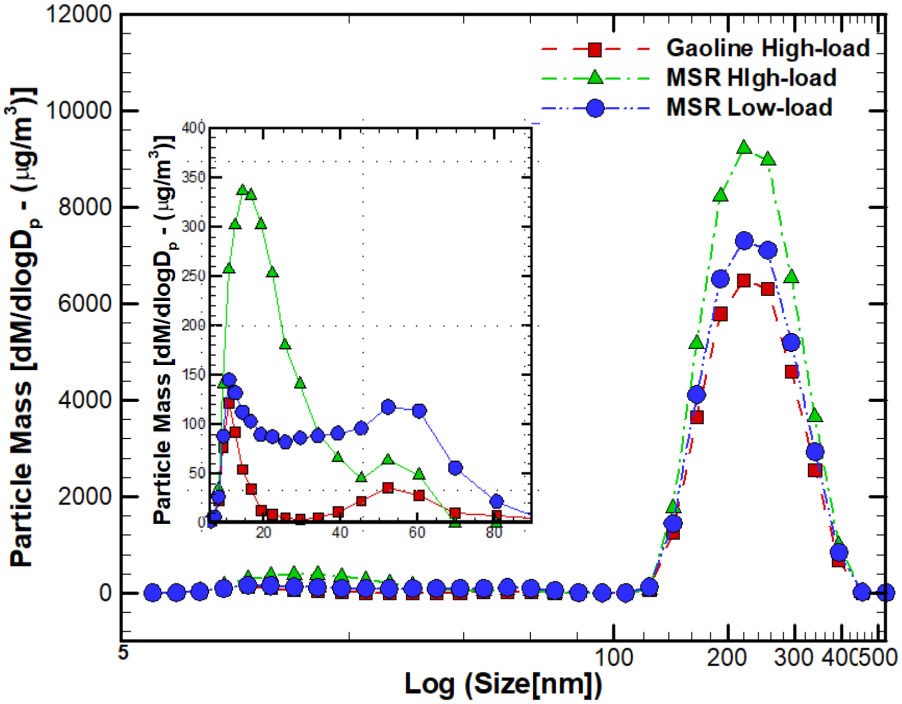
Particle size and mass distribution- Effect of Fuel

Based on Maricq's et al. density distribution

$$\rho_{eff} = 1.2378 \times \frac{4}{3} e^{-0.0048 D_p}$$

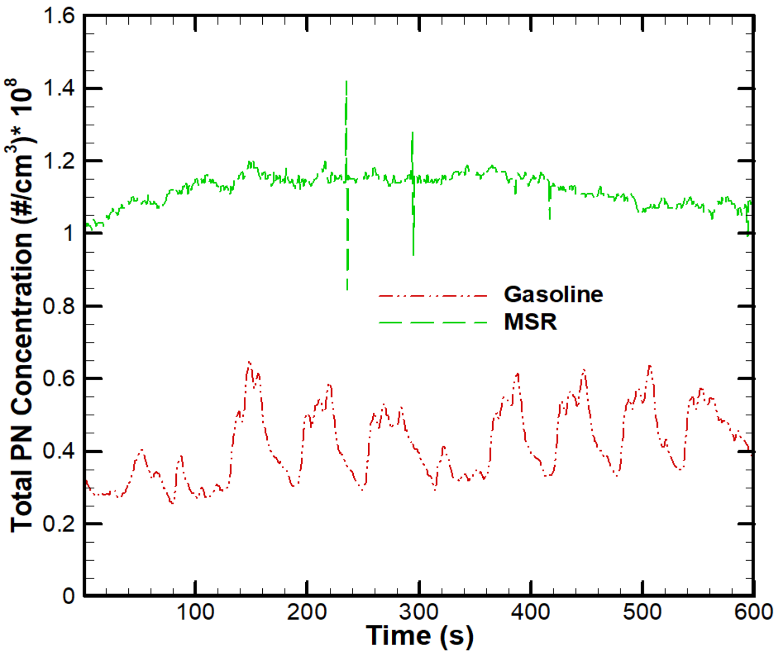
$$m_p = \rho_{eff} \frac{4}{3} \pi (\frac{D_p}{2})^3$$

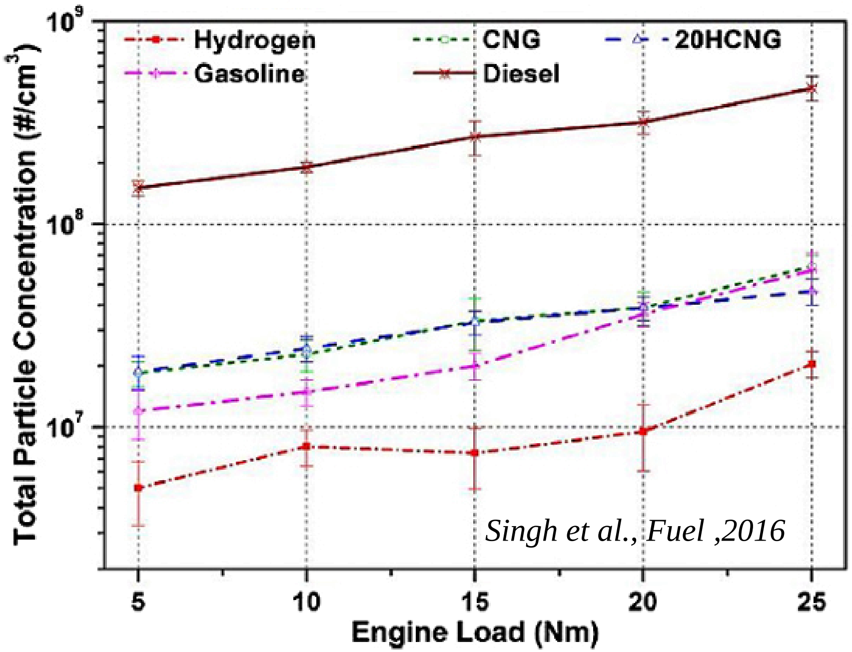




Maricq et al., Aerosol Science and Technology, 2006

Total particle concentration comparison



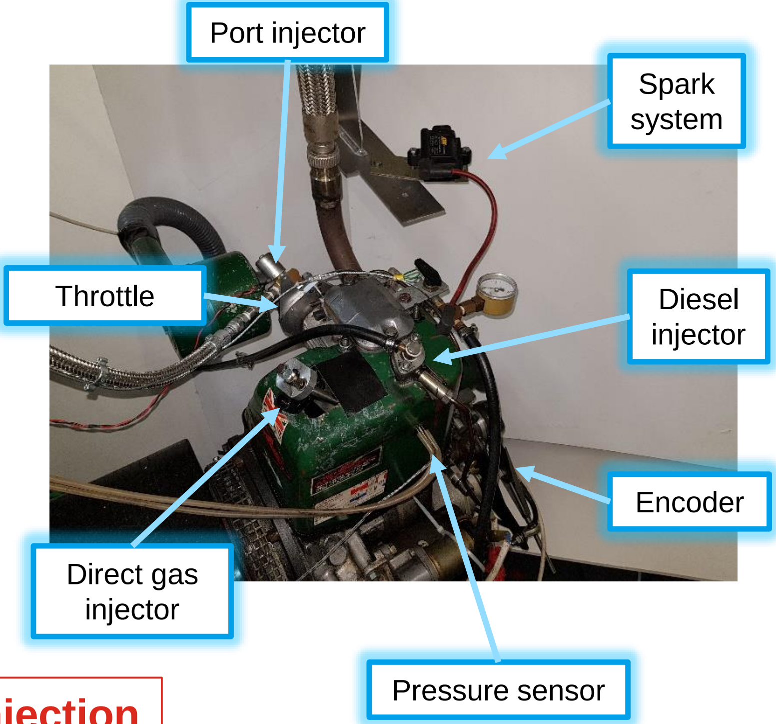


Previous studies showed significant PN reduction with hydrogen combustion

High compression ratio ICE

Experimental setup

Single cylinder, Petter AD1 based		
Bore x Stroke, mm		80x73
Displacement, cm^3		367
Compression ratio		16
Power, kW @ speed, rpm		5.3 @ 3000
Fuel injection system	**Diesel**	Direct
	Hydrogen-Rich Reformate	direct
		port

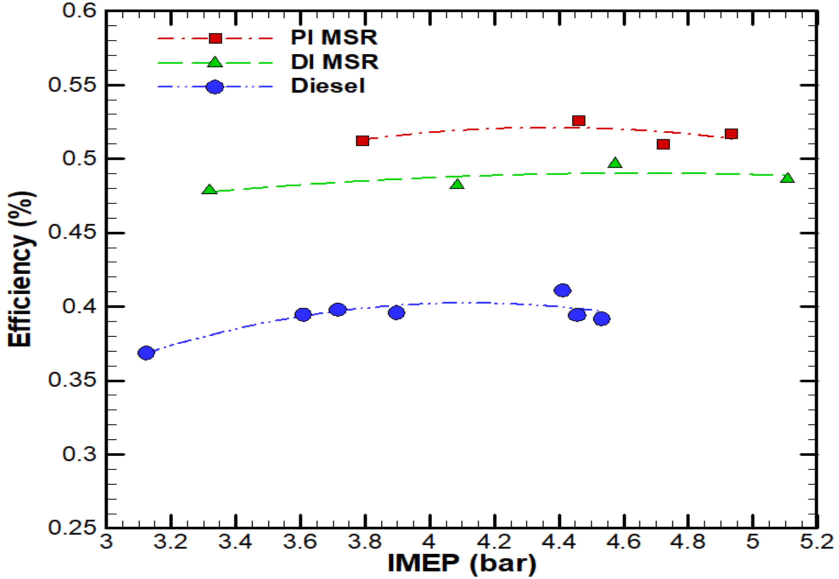


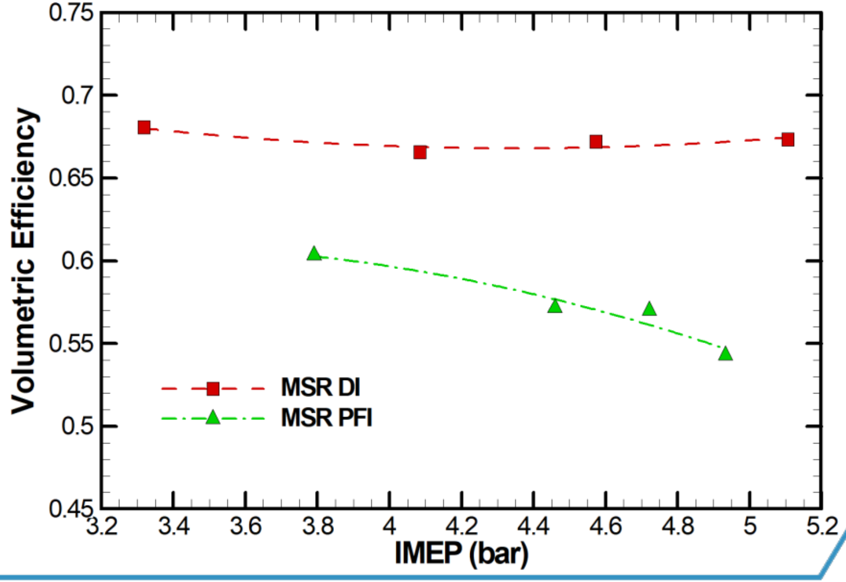
A comparison of direct and port reformate injection

Fuel injection strategy - Efficiency

- *Wide open throttle in all cases*
- *13-19% improvement for MSR DI*
- *23-26% improvement for MSR PI*

- PI limitations:
  - Maximal power loss
  - Low volumetric efficiency
  - Abnormal combustion- backfire, pre-ignition



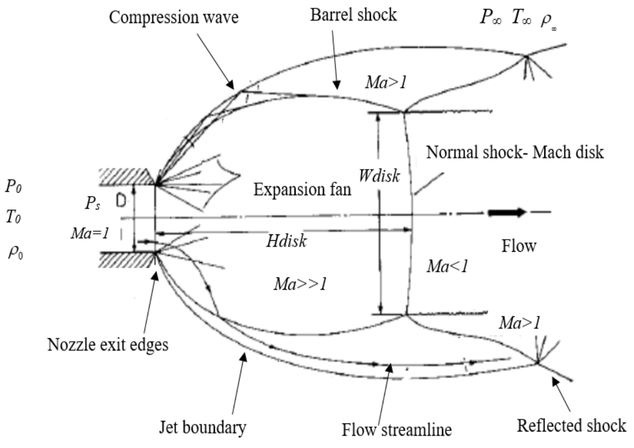


High pressure hydrogen-rich reformate injection

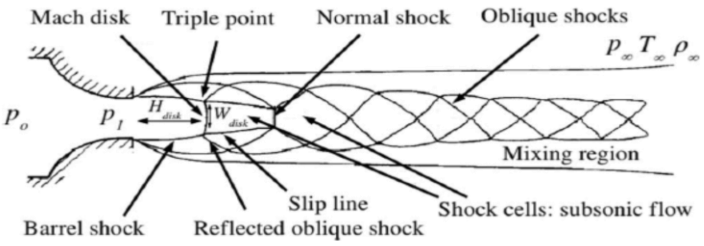
- *Underexpanded gaseous jet*
- *Possible mechanisms for particle formation*

Underexpanded jet in gaseous fuel DI

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	$3.84 < P_0/P_\infty$

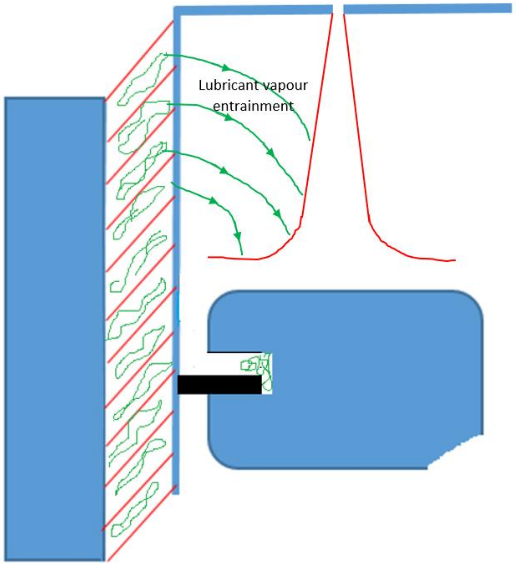


Crist S. et al., AIAA J., 1966

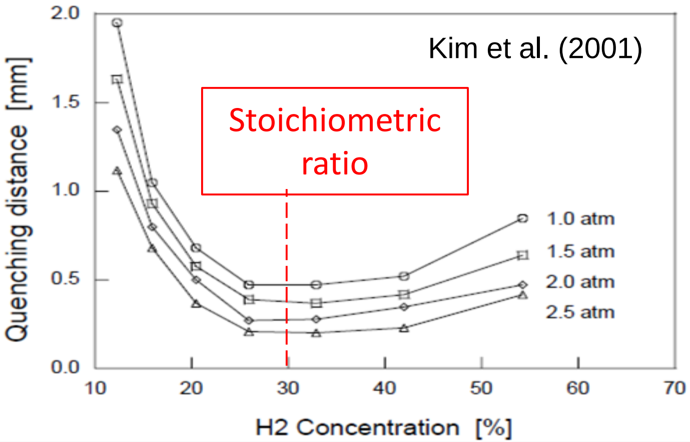


Snedeker RS. et al., J. Fluid Mechanics, 1971

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



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



Summary

- **DI-ICE with High-Pressure Thermo-Chemical Recuperation was developed enabling:**
  - Efficiency improvement (up to 39%)
  - Gaseous pollutant emission reduction (up to 94%, 96% and 97% for NOx, CO and HC, respectively)
- **Direct injection of reformate leads to higher particle formation compared to gasoline**
- **Future research will focus on identification of particle formation mechanism, and development of methods to mitigate particle emission**

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Thank you for your attention!

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