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

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18 June 2019

23rd ETH Conference on Combustion Generated Nanoparticles
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:

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

### Gasoline Passenger Cars:

<table>
<thead>
<tr>
<th>Emissions</th>
<th>Unit</th>
<th>Euro 1</th>
<th>Euro 2</th>
<th>Euro 3</th>
<th>Euro 4</th>
<th>Euro 5a</th>
<th>Euro 6b/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>THC</td>
<td>mg/km</td>
<td>-</td>
<td>-</td>
<td>200</td>
<td>100</td>
<td>100</td>
<td>100</td>
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<tr>
<td>NOx</td>
<td></td>
<td>-</td>
<td>-</td>
<td>150</td>
<td>80</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>HC+NOx</td>
<td></td>
<td>970</td>
<td>500</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CO</td>
<td></td>
<td>2720</td>
<td>2200</td>
<td>2300</td>
<td>1000</td>
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<tr>
<td>PM</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.0</td>
<td>4.50</td>
</tr>
<tr>
<td>PN</td>
<td>#/km</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6 \times 10^{11}</td>
</tr>
</tbody>
</table>
Fuel energy distribution

Coolant

Exhaust

Output

About 1/3 of the energy

400 °C < T_{Exhaust} < 900 °C

Why to waste it...?!
The goal

Feasible solution

- Emission mitigation
- Efficiency improvement
- Crude oil dependency reduction
Our goal

On-board Fuel reforming

Emission mitigation

Efficiency improvement

Crude oil dependency reduction

Hydrogen combustion

Waste heat recovery

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 CO₂ – PtX fuel (electrofuel)
- No significant infrastructure change needed
- Low reforming temperatures

**GASEOUS REFORMING PRODUCTS:**
- Hydrogen-rich gaseous fuel: (75%)H₂+(25%)CO₂
- 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

MethanolSteam Reforming (MSR): \( CH_3OH_{(g)} + H_2O_{(g)} \rightarrow CO_2 + 3H_2 \quad \Delta H = 50 \text{ kJ/mol} \)
Thermo-Chemical Recuperation (TCR)

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

Methanol Steam Reforming (MSR)

\[ CH_3OH + H_2O \rightarrow 3H_2 + CO_2 \quad \Delta H \approx 50 \text{ kJ/mol} \]

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

Single cylinder, spark ignition engine (Robin EY-20 based)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore x Stroke, mm</td>
<td>67x52</td>
</tr>
<tr>
<td>Displacement, cm³</td>
<td>183</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>6.3</td>
</tr>
<tr>
<td>Power, kW @ speed, rpm</td>
<td>2.2 @ 3000</td>
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<tr>
<td>Fuel supply system</td>
<td></td>
</tr>
<tr>
<td>Gasoline</td>
<td>Carburetor</td>
</tr>
<tr>
<td>Hydrogen-Rich Reformate</td>
<td>Direct injection</td>
</tr>
</tbody>
</table>

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)

\[ CH_3OH + H_2O \rightarrow 3H_2 + CO_2 \quad \Delta H \approx 50 \text{ kJ/mol} \]

Poran, Thawko, Eyal, Tartakovskyy, Int. J Hydrogen Energy, 2018
**Thermo-Chemical Recuperation system Performance**

Total particle concentration comparison

\[ \text{MSR} \]
\[ CH_3OH + H_2O \rightarrow 3H_2 + CO_2 \]
Particle size and number distribution - Effect of Fuel
Particle size and mass distribution - Effect of Fuel

Based on Maricq’s et al. density distribution

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

\[
m_p = \rho_{eff} \frac{4}{3} \pi \left(\frac{D_p}{2}\right)^3
\]

Maricq et al., Aerosol Science and Technology, 2006
Total particle concentration comparison

Previous studies showed significant PN reduction with hydrogen combustion

Singh et al., Fuel, 2016
High compression ratio ICE
## Experimental setup

### Single cylinder, Petter AD1 based

<table>
<thead>
<tr>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore x Stroke, mm</td>
<td>80x73</td>
</tr>
<tr>
<td>Displacement, cm³</td>
<td>367</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>16</td>
</tr>
<tr>
<td>Power, kW @ speed, rpm</td>
<td>5.3 @ 3000</td>
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<tr>
<td>Fuel injection system</td>
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</tr>
<tr>
<td>Diesel</td>
<td></td>
</tr>
<tr>
<td>Hydrogen-Rich Reformate</td>
<td></td>
</tr>
<tr>
<td>Direct</td>
<td></td>
</tr>
<tr>
<td>Direct</td>
<td></td>
</tr>
<tr>
<td>Port</td>
<td></td>
</tr>
</tbody>
</table>

### 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

<table>
<thead>
<tr>
<th>Classification</th>
<th>Nozzle pressure ratio (NPR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsonic jet</td>
<td>$1 &lt; \frac{P_0}{P_\infty} &lt; 1.893$</td>
</tr>
<tr>
<td>Moderately underexpanded jet</td>
<td>$2.08 &lt; \frac{P_0}{P_\infty} &lt; 3.8$</td>
</tr>
<tr>
<td>Highly underexpanded jet</td>
<td>$3.84 &lt; \frac{P_0}{P_\infty}$</td>
</tr>
</tbody>
</table>

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

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*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

Kim et al. (2001)
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

Summary
The financial support of:

- Israel Science Foundation (ISF)
- Israel Ministry of Environmental Protection
- Israel Ministry of Energy
- Nancy and Stephen Grand Technion Energy Program (GTEP)
- The Council for Higher Education (CHE)- Planning and Budgeting Committee (PBC)

is highly appreciated
Thank you for your attention!

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