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Low-NOx, low-smoke combustion

• Promoting mixing of fuel and air before ignition to reduce smoke
• Low-temperature combustion to reduce NOx – lean mixtures + EGR, heat release after TDC….
• HCCI is one end of this spectrum – no “in-cycle” control over heat release. Engine control very difficult also only low load.
• Practical implementation in diesel engines – Toyota UNIBUS system (early fuel injection/HCCI), Nissan MK (late injection + EGR) “premixed enough” combustion.
• Combination of the two – multiple injections
• Enhancing mixing – high injection pressures, more swirl …

These systems are usually run on diesel fuels (CN > 30, RON < 60) which are very prone to auto-ignition.
Importance of high Engine Ignition Delay (EID)

- We can define EID = CA50 – SOI (Start of injection). CA50 is the crank angle at which 50% of total heat release occurs.
- EID can be taken as measure of “mixedness”.
- The larger the EID, the more premixed the fuel and air at the time of heat release. This reduces smoke and also NOx if the global mixture strength is sufficiently lean.
- Lots of EGR has to be used to increase EID with conventional diesel fuels.
- In general with diesel fuels to get low NOx and low smoke at high IMEP is very difficult.

Can we make use of the auto-ignition resistance of fuels to increase EID and improve performance?
Previous work with diesel fuels of different auto-ignition quality

- Different diesel fuels tested with different injection strategies in SAE 2005-01-2127

- At fixed operating conditions in Nissan MK combustion, injection timing sweeps

- Higher EID and lower NOx for lower Cetane (more resistant to auto-ignition) fuels at the same CA50

- But these tests were done at low Comp. Ratio (CR) of 11.4 and low loads 3.1-4.2 bar IMEP.

Rest of the results from SAE 2006-01-3385 and 2007-01-006

Pin = 1.5 bar abs, 1200 RPM, 25% EGR, \( \lambda = 4 \), Tin = 40 C
Experiments

- 2L single cylinder engine. CR = 14
- 1200 RPM, Tin = 40º C, EGR using exhaust from stoichiometric SI engine (3-way catalyst), characterised by CO2 content of intake air – e.g 25 % EGR ~ 3.8 % CO2.
- 8 hole nozzle, 1300 bar injection pressure
- Measured CA50, NOx, Smoke, HC, CO etc

<table>
<thead>
<tr>
<th>Fuel</th>
<th>CN</th>
<th>Density g/cc</th>
<th>IBP ºC</th>
<th>T10 ºC</th>
<th>T50 ºC</th>
<th>T90 ºC</th>
<th>FBP ºC</th>
<th>Aromatics % vol</th>
<th>LHV** MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swedish MK1</td>
<td>54</td>
<td>0.81</td>
<td>195</td>
<td>208</td>
<td>240</td>
<td>273</td>
<td>297</td>
<td>~ 3</td>
<td>43.8</td>
</tr>
<tr>
<td>Diesel 1</td>
<td>39</td>
<td>0.81</td>
<td>167</td>
<td>179</td>
<td>196</td>
<td>220</td>
<td>246</td>
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<td>43.5</td>
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<td>Diesel 2</td>
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<td>0.83</td>
<td>167</td>
<td>179</td>
<td>198</td>
<td>222</td>
<td>246</td>
<td>50</td>
<td>43.3</td>
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<tr>
<td>Gasoline</td>
<td>~15*</td>
<td>0.726</td>
<td>32</td>
<td>50</td>
<td>102</td>
<td>144</td>
<td>176</td>
<td>29</td>
<td>43.2</td>
</tr>
</tbody>
</table>

Three Diesel fuels and one 95 RON gasoline.

** Lower Heating Value
Experimental Detail

Phase I – Comparison between fuels. All four fuels tested with Pin = 1.5 bar abs. at two conditions –a) 0.6 g/s fuel without any EGR ($\lambda \sim 3.8$) and b) 0.8 g/s with 10% EGR* ($\lambda \sim 2.6$). Gasoline also tested at 0.8 g/s without EGR ($\lambda \sim 3$) and diesels at 0.8 g/s with 25% EGR** ($\lambda \sim 2$).

Phase II – Further tests with gasoline with higher inlet pressure, higher fuelling rates and higher EGR to see if higher IMEPs could be reached with low NOx and low smoke.

Phase III – Double Injection

* 21% ** 35%
Phase I results – Comparison between Fuels

- Engine will not run on gasoline with very early SOI in HCCI mode

Expected results –
- CA50 decreases with CN

0.6 g/s, No EGR, Pin = 1.5 bar abs, Tin = 40 C, 1200 RPM
Phase I results – Engine Ignition delay

- Significantly higher ignition delay for gasoline
- Difference between 39 CN and 54 CN less than when CR was 11.4

0.6 g/s, No EGR, Pin = 1.5 bar abs, Tin = 40 C, 1200 RPM
Comparison between gasoline and diesel (Swedish MK1) heat release patterns

0.6 g/s, No EGR, Pin =1.5 bar abs, Tin = 40 C, 1200 RPM

Low smoke (< 1% AVL opacity) because of high oxygen for both fuels concentration but higher NOx with diesel.
Phase I results - NOx

0.6 g/s, No EGR, Pin = 1.5 bar abs, Tin = 40 C, 1200 RPM

NOx decreases with ignition delay
Phase I results – NOx and IMEP

Very much lower NOx for the same IMEP for gasoline because of higher EID.
Increasing injection rate will increase IMEP but also smoke for the diesel fuel and NOx for all fuels. NOx can be reduced by EGR.

IN THE REST OF THE PRESENTATION SWEDISH MK1 DIESEL WILL BE COMPARED WITH GASOLINE with Pin = 2 bar abs, EGR ~ 25% stoich
Smoke increases with injection rate

Swedish MK1 diesel fuel, Pin = 2 bar abs, EGR ~ 25% stoich
Single Injection starting at TDC

Smoke vs IMEP, SOI at TDC
Heat release rate and needle lift for low and high smoke cases
Smoke decreases as injection is retarded for diesel but very low for gasoline

Pin = 2 bar abs, 1.2 g/s fuel, EGR ~ 25% stoich (38%)
Single Injection
Low smoke for gasoline because of higher EID

Smoke vs ignition delay

Pin = 2 bar abs, 1.2 g/s fuel, EGR ~ 25% stoich (38%)
Gasoline fuel rate can be increased up to a point

Pin = 2 bar abs, different injection rates and SOI and EGR

NOx increases with IMEP (fuel rate) but can be controlled with EGR. ISFC decreases with IMEP
HC and CO decrease as fuel rate is increased.

Gasoline

Pin = 2 bar abs, different injection rates and SOI and EGR
High IMEP point with gasoline, single injection

Pressure, heat release rate and needle lift curves for gasoline with 14.86 bar IMEP (0.1 bar std), 1.8% smoke and ISNOx, ISFC, ISCO and ISHC of 1.21 g/kWh, 178 g/kWh, 3 g/kWh and 3.6 g/kWh respectively. Needle lift, arbitrary scale.

More overlap between heat release and injection event for high smoke case
Double Injection Strategies Used

- Total injection of 1.2 g/s. Pilot injection at fixed injection rate and SOI of 150 CAD before TDC (when the valves close), sweep of SOI of main injection near TDC of fixed injection rate - at two different fractions of the total fuel mass in the pilot for gasoline.

- For the diesel fuel, for a total injection rate of 1.2 g/s, the main injection was fixed at 0.84 g/s at TDC and the SOI of the pilot was varied.

- Main injection was fixed at 1.19 g/s with SOI at 11 CAD before TDC in most cases, and the pilot injection quantity, with SOI fixed at 150 CAD before TDC, was varied for gasoline. The two limits are too early combustion and high smoke.
Comparison between diesel and gasoline

Total fuel rate 1.2 g/s, 70% in main injection. Lowest possible smoke with diesel was 7.

**Swedish MK1 diesel.** Main injection SOI at – 6 CAD. Mean IMEP 11.84 (std 0.115 bar) bar. AVL smoke opacity 8.7%. In g/kWh, ISFC= 183, ISNOx = 0.3, ISHC = 11.3, ISCO = 10

**Gasoline.** Main injection SOI at – 9 CAD. Mean IMEP 12.86 (std 0.108 bar) bar. AVL smoke opacity 0.9%. In g/kWh, ISFC= 174, ISNOx = 0.39, ISHC = 6.8, ISCO = 9
Comparison between diesel and gasoline - pressure

Total fuel rate 1.2 g/s, 70% in main injection. Lowest possible smoke with diesel was 7.8%.
Smoke – total fuel rate 1.2 g/s different injection strategies

Lowest smoke possible is lower with single injection for diesel. This is because early injection causes heat release during compression stroke – reduces ignition delay for main injection.

• Smoke level much lower for gasoline at high IMEP
Fuel consumption – total fuel rate 1.2 g/s
different injection strategies

- With diesel fuel, double injection increases ISFC compared to single injection
- With gasoline, double injection does not increase ISFC
- ISFC decreases as IMEP increases
Smoke at high IMEP with gasoline

- With gasoline, double injection helps reduce smoke at high load
- Even with double injection smoke increases eventually at high load
Double injection allows MHRR to be reduced and delayed without increasing cyclic variation and at lower emissions.

All experiments at bar abs. inlet pressure, 40 C intake temp. ~35% EGR based on actual exhaust.

<table>
<thead>
<tr>
<th>Injection</th>
<th>Fuel Rate Mean g/s</th>
<th>CO2 Intake %</th>
<th>IMEP* Mean bar</th>
<th>IMEP* std bar</th>
<th>AVL smoke % opacity</th>
<th>ISNOx g/kWh</th>
<th>ISFC g/kWh</th>
<th>ISHC g/kWh</th>
<th>ISCO g/kWh</th>
<th>MHRR* J/deg</th>
<th>Angle of MHRR* CAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single**</td>
<td>1.436</td>
<td>4.05</td>
<td>14.86</td>
<td>0.115</td>
<td>1.81</td>
<td>1.21</td>
<td>178</td>
<td>3.6</td>
<td>3.4</td>
<td>1446</td>
<td>10.8</td>
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<tr>
<td>Double***</td>
<td>1.46</td>
<td>4.14</td>
<td>15.07</td>
<td>0.138</td>
<td>0.28</td>
<td>0.59</td>
<td>179</td>
<td>3.0</td>
<td>5.8</td>
<td>817</td>
<td>18.2</td>
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<tr>
<td>Double***</td>
<td>1.549</td>
<td>4.16</td>
<td>15.95</td>
<td>0.112</td>
<td>0.33</td>
<td>0.58</td>
<td>179</td>
<td>2.9</td>
<td>6.8</td>
<td>1393</td>
<td>14.1</td>
</tr>
</tbody>
</table>

* Mean from 100 cycles
** SOI @ -16 CAD from SAE 2006-01-3385
*** 1.19 g/s @ -11 CAD and rest at -150 CAD
Conclusions (1)

- The engine can be run on gasoline in partially pre-mixed mode even when it cannot be run in HCCI mode.
- Much higher ignition delay for gasoline compared to diesel at a given set of operating conditions and hence lower smoke (and lower NOx).
- Double injection helps reduce maximum heat release rate while maintaining IMEP, low emissions and fuel consumption for gasoline.
- Much higher IMEP possible with gasoline compared to diesel for low smoke and NOx.
- IMEP = 15.95 bar, smoke < 0.07 FSN, ISNOx, ISCO, ISHC and ISFC of ~ 0.6, 6.8, 2.9, 179 g/kWh. This was with 23% pilot, 2 bar abs. Pin and 35% EGR (actual).
- Highest IMEP possible with diesel fuel for this low smoke < 6.5 bar.
- Further improvements should be possible with optimisation of injection and mixture preparation (multiple injections, more injector holes....)
Conclusions (2)

• Further work is needed to understand the effect of higher speeds and the lowest loads that can be run in partially premixed mode on gasoline

• In general, if smoke and NOx are to be reduced by promoting premixed combustion, the fuel needs to be as much like gasoline as possible

• In practice, the extent to which this is possible depends on other critical requirements – low noise, cold starting, low load operation … - being met

• What currently matters is the diesel fuel quality required by future diesel engines.

• If the strategy to reduce smoke and NOx in such engines is to promote premixed combustion, increasing fuel cetane number will not help – it might actually make control of smoke more difficult. Higher volatility for the fuel might be beneficial.