Improvement of Natural Gas-Diesel Dual-Fuel PCCI Combustion by Controlling Mixture Formation at Low Load Conditions

Prof. Choongsik Bae

Korea Advanced Institute of Science and Technology
Department of Mechanical Engineering
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Research background & Objective

Engine & Fuel properties

Results

Conclusion
Emission regulation and after-treatment cost

- CO₂ emissions regulations
- Stringent emission regulations (PM, NOₓ & PN)
- Increasing cost for meeting the regulations
  - High rate of after-treatment device (SCR, DPF) cost

→ Need for in-cylinder combustion technology (HCCI, PCCI, GCI, Dual-Fuel)  

Natural Gas (NG) as fuel for ICEs

- **Price-competitiveness**
  - Production of unconventional NG resources
- **Low CO₂ emissions**
  - Low-carbon fuel

Source: Outlook for Natural Gas, IEA, 2017

Source: Annual Energy Outlook, EIA, 2017
● **Volvo FH LNG model**
  - 13L in-line 6-cylinder engine
  - EURO VI compliant heavy-duty truck
  - LNG + Diesel dual-fuel
  - Injection system: Westport HPDI injector
  - LNG substitution: 90~95%
  - CO$_2$ emissions reduction of 20% compared to conventional diesel engine

Source: [http://www.westport.com/is/core-technologies/combustion/hpdi](http://www.westport.com/is/core-technologies/combustion/hpdi)
Opportunities & Challenges in advanced combustion technologies

Opportunities

- **Low NO$_x$ & PM emissions**
  - premixed low combustion temperature

- **High thermal efficiency**
  - rapid volumetric combustion
  - lower heat transfer loss

Challenges

- **Combustion phasing control**
  - auto-ignition controlled by chemical kinetics

- **Limited operation range**
  - Light load: misfire or low combustion efficiency due to insufficient thermal energy
  - High load: high MPRR due to rapid volumetric combustion

- **High HC & CO emissions**
  - Low combustion temperature

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Volvo Powertrain France, *THIESEL*, 2008

HCCI: homogeneous charge compression ignition
PCCI: premixed charge compression ignition
LTC: low temperature combustion
NO$_x$: nitrogen oxides
PM: particulate matter
MPRR: maximum pressure rise rate
HC: hydrocarbon
CO: carbon monoxide
Single-fuel PCCI = $\Phi$ stratification

-20 CAD aTDC

-30 CAD aTDC

-40 CAD aTDC

Diesel Inj. timing + EGR

PCCI

$\Phi$ Stratification
Dual-fuel PCCI = $\Phi +$ reactivity stratification

**DF-PCCI?**

**In-cylinder fuel blending** with at least **two fuels of different reactivity**

- **Low reactivity fuel** is introduced early and premixed with air.
- **High reactivity fuel** is injected into the premixed charge before ignition.

![Diagram of combustion process]

### Early injection of low reactivity fuel
- Gasoline
- Ethanol
- Natural gas

### Late injection of high reactivity fuel
- Diesel
- Biodiesel
- DME...

**Diesel Inj. timing + EGR + Blending ratio**

**PCCI**

$\Phi$ Stratification

**DF-PCCI**

$\Phi +$ reactivity stratification

- **Control of combustion phasing**
- **Expansion of operating range**
Advantages of Natural Gas

- Reactivity difference: natural gas & diesel > gasoline & diesel
  → Improvement of combustion phasing control
  → Expansion of high load limit because of lower peak MPRR & longer combustion duration
- Low-carbon fuel → Reduction in CO₂ emissions
- Abundant reserves → Cost-effectiveness

Source: University of Wisconsin-Madison, SAE 2012-01-0379
Natural gas as fuel for DF-PCCI combustion

Disadvantages of Natural Gas
- Reactivity difference: natural gas & diesel > gasoline & diesel
- Challenges at light load: (low combustion efficiency, high HC and CO emissions)

Barriers to Commercialization!

<table>
<thead>
<tr>
<th>Results</th>
<th>4 bar</th>
<th>9 bar</th>
<th>11 bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soot [g/ikW-hr]</td>
<td>0.004</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>NOx [g/ikW-hr]</td>
<td>0.24</td>
<td>0.25</td>
<td>0.08</td>
</tr>
<tr>
<td>CO [g/ikW-hr]</td>
<td>10.8</td>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>UHC [g/ikW-hr]</td>
<td>10.5</td>
<td>0.5</td>
<td>2.2</td>
</tr>
<tr>
<td>$\eta_{\text{gross}}$ [%]</td>
<td>45.1%</td>
<td>50.4%</td>
<td>50.6%</td>
</tr>
<tr>
<td>PPRR [bar/deg]</td>
<td>2.7</td>
<td>5.1</td>
<td>8.1</td>
</tr>
<tr>
<td>Ring. Intens. [MW/m$^2$]</td>
<td>0.2</td>
<td>1.5</td>
<td>2.8</td>
</tr>
</tbody>
</table>
## Research Objective

<table>
<thead>
<tr>
<th>Without EGR</th>
<th>0.30 MPa</th>
<th>0.45 MPa</th>
<th>0.60 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel SOI [CAD aTDC]</td>
<td>-35</td>
<td>-40</td>
<td>-55</td>
</tr>
<tr>
<td>NG substitution [%]</td>
<td>54</td>
<td>70</td>
<td>76</td>
</tr>
<tr>
<td>NO\textsubscript{X} [g/kWh]</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>PM [g/kWh]</td>
<td>0.002</td>
<td>0.003</td>
<td>0.004</td>
</tr>
<tr>
<td>THC [g/kWh]</td>
<td><strong>11.3</strong></td>
<td>8.4</td>
<td>6.3</td>
</tr>
<tr>
<td>CO [g/kWh]</td>
<td><strong>31.9</strong></td>
<td>7.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Combustion efficiency [%]</td>
<td><strong>91.5</strong></td>
<td>94.8</td>
<td>96.1</td>
</tr>
<tr>
<td>Thermal efficiency [%]</td>
<td><strong>37.0</strong></td>
<td>41.7</td>
<td>44.0</td>
</tr>
<tr>
<td>MPRR [MPa/CAD]</td>
<td>3.3</td>
<td>4.0</td>
<td>4.2</td>
</tr>
</tbody>
</table>
## Barriers
- Low combustion efficiency, high HC & CO emissions at low loads

## Cause
- Low reactivity of natural gas & very lean fuel-air mixture at low loads

## Strategy
- **Higher diesel portion** in fuel-air mixture formation
  - Reactivity of the mixture ↑ & equivalence ratio ↑
  - But the combustion phasing can be advanced.
- **Introduction of cooled-EGR** for combustion phasing control

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### Diagrams

**Graph 1:**
- NG Substitution Ratio [%] vs Diesel SOI [CAD aTDC]
- CA50 [CAD aTDC]
- Misfire Zone

**Graph 2:**
- EGR Rate [%] vs Diesel SOI [CAD aTDC]
- CA50 [CAD aTDC]
- Misfire Zone
Contents

Research background & Objective
Engine & Fuel properties
Results
Conclusion
Experimental Setup

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine type</td>
<td>Single-cylinder, compression-ignition</td>
</tr>
<tr>
<td>Displacement [L]</td>
<td>0.981</td>
</tr>
<tr>
<td>Bore [mm]</td>
<td>100</td>
</tr>
<tr>
<td>Stroke [mm]</td>
<td>125</td>
</tr>
<tr>
<td>Compression ratio [-]</td>
<td>17.4</td>
</tr>
<tr>
<td>Valves per cylinder</td>
<td>4 (2 intake &amp; 2 exhaust)</td>
</tr>
<tr>
<td>Fuel injection system</td>
<td>Common-rail DI system</td>
</tr>
<tr>
<td>EGR system</td>
<td>Cooled-EGR</td>
</tr>
</tbody>
</table>

The diagram shows the experimental setup with various components such as an Air Mass Flow Meter, DC Dynamometer, Intake Surge Tank, Exhaust Surge Tank, Engine, and various measuring devices and systems.
## Fuel Properties & Limitations of tests

<table>
<thead>
<tr>
<th>Natural gas</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (CH(_4)) [%]</td>
<td>91.31</td>
</tr>
<tr>
<td>Ethane (C(_2)H(_6)) [%]</td>
<td>5.34</td>
</tr>
<tr>
<td>Propane (C(_3)H(_8)) [%]</td>
<td>2.17</td>
</tr>
<tr>
<td>Butane (C(_4)H(_10)) [%]</td>
<td>0.92</td>
</tr>
<tr>
<td>Reactive H/C ratio [-]</td>
<td>3.78</td>
</tr>
<tr>
<td>Motor octane number (MON) [-]</td>
<td>124</td>
</tr>
<tr>
<td>Methane number (MN) [-]</td>
<td>81.7</td>
</tr>
<tr>
<td>Lower heating value (LHV) [MJ/kg]</td>
<td>46.5</td>
</tr>
<tr>
<td>Gas density [kg/m(^3)]</td>
<td>0.829</td>
</tr>
</tbody>
</table>

### Diesel

<table>
<thead>
<tr>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 293 K [kg/m(^3)]</td>
</tr>
<tr>
<td>Cetane number [-]</td>
</tr>
<tr>
<td>Lower heating value (LHV) [MJ/kg]</td>
</tr>
<tr>
<td>T10 (K)</td>
</tr>
<tr>
<td>T50 (K)</td>
</tr>
<tr>
<td>T90 (K)</td>
</tr>
</tbody>
</table>

### Limitations

<table>
<thead>
<tr>
<th>Emissions [g/kWh]</th>
<th>&lt; 0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO(_X) emissions [g/kWh]</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>PM emissions [g/kWh]</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>COV of IMEP [%]</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>MPRR [MPa/CAD]</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>
Inj. timing & NG substitution swing at 0.30 MPa IMEP

- **Pilot-diesel DF combustion**
  - CA50 was retarded by retarding diesel SOI.

- **DF-PCCI combustion**
  - CA50 was retarded by advancing diesel SOI and increasing NG substitution ratio.
Combustion phasing control in DF-PCCI combustion

- **DF-PCCI combustion**
  - CA50 was retarded by advancing diesel SOI and increasing NG substitution ratio.
  - **Advanced injection timing** → locally leaner & less reactive fuel-air mixture → retardation of CA50
  - **Increased NG substitution** (= less diesel mass injected)
    → locally leaner & less reactive fuel-air mixture → retardation of CA50
CA50 was introduced as the combustion indicator for DF-PCCI.

To reduce the NO\textsubscript{X} emissions under EURO VI limitation, advanced injection timing & increased NG substitution should be applied.

NG substitution → Locally leaner & Less reactive fuel-air mixture → NG mass trapped in crevice → Combustion temperature ↓ → NO\textsubscript{X} & PM ↓ → $\eta_{\text{combustion}}$ ↓ → THC & CO ↑
DF-PCCI combustion without EGR

- Diesel SOI = -35 CAD aTDC
- However, the advanced injection timing & increased NG substitution can increase HC & CO emissions.

- Advanced injection timing
- NG substitution ↑
- Locally leaner & Less reactive fuel-air mixture
- NG mass trapped in crevice ↑
- Combustion temperature ↓
- NOx & PM ↓
- $\eta_{combustion}$ ↓
- THC & CO ↑
DF-PCCI combustion with EGR

- Advanced injection timing
- NG substitution ↑
  - Locally leaner & Less reactive fuel-air mixture
  - NG mass trapped in crevice ↑
  - Combustion temperature ↓
  - NOx & PM ↓
  - THC & CO ↑

- Retarded injection timing
- Diesel portion ↑
  - Locally rich & More reactive fuel-air mixture
  - NG mass trapped in crevice ↓
  - Advanced CA50 NOx ↑
  - Retarded CA50 NOx ↓

To reduce THC & CO at low loads

Cooled-EGR
DF-PCCI combustion with EGR – Combustion parameters

- EGR rate ↑
  - Portion of High reactivity fuel (diesel) ↑ (= NG trapped in crevice ↓)
  → Local Equivalence ratio & Reactivity of fuel-air mixture ↑
  → Peak heat release rate ↑ & Combustion duration ↓
  → Approaching Constant-volume combustion cycle
  → Indicated thermal efficiency ↑
DF-PCCI combustion with EGR

- EGR rate ↑ & Diesel portion ↑
- Approaching constant-volume cycle
- NG mass trapped in crevice ↓
- Indicated thermal efficiency ↑
- THC ↓ NOX & PM ↓
Introduction of EGR

- Increase in combustion efficiency & thermal efficiency
- Reduction in HC & CO emissions with NOX & PM emissions under EURO VI
- The effect is significant at the lower load operations (0.30 MPa IMEP)
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Research background & Objective
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Results
Conclusion
Single-Fuel (Diesel) PCCI vs Dual-Fuel PCCI

- **Indicated thermal efficiency**
  - **0.30 MPa IMEP:** SF-PCCI > DF-PCCI
  - **0.45 MPa IMEP:** SF-PCCI < DF-PCCI
Thank you for your kind attention

Choongsik Bae, Professor
SAE Fellow
Engine Laboratory, Department of Mechanical Engineering
KAIST (Korea Advanced Institute of Science and Technology)
csbae@kaist.ac.kr
+82. 42. 350. 3063
http://engine.kaist.ac.kr