From Gasoline to Ethanol Direct Injection Engines

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Development trend: Turbocharged GDI engine

Why TC GDI has become today’s development focus:

- high potential advantages in exploiting TC and GDI technologies
  - to meet customer expectations
  - to comply with legal requirements.
- we have learned to exploit such advantages with development techniques tailored to turbocharged gasoline direct injection combustion systems.
Meeting drivers’ expectations:
Performance development:
TC GDI shows continuous improvements

Gasoline DI is meeting customer expectations and complies with legal requirements

Meeting legal requirements:
Emissions development: the particle number (mostly soot) example for TC GDI

GDI TC: with the correct package of development techniques, „soot free“ combustion is achievable

How would Ethanol DI change such diagrams?
Gasoline – Ethanol comparison:

Ethanol has promising as well as challenging features

1. How will such fuel features influence engine operation?
2. What does it need to exploit fuel advantages?
3. What is required to overcome the risks?

### Fuel features

<table>
<thead>
<tr>
<th>Chemical Formula</th>
<th>Gasoline</th>
<th>Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-)</td>
<td>( C_7H_{16} )</td>
<td>( C_2H_6O )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Molecular Weight</th>
<th>Gasoline</th>
<th>Ethanol</th>
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</thead>
<tbody>
<tr>
<td>(-)</td>
<td>99</td>
<td>46</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Carbon Content</th>
<th>Gasoline</th>
<th>Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>(%m)</td>
<td>84.9</td>
<td>52.2</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Hydrogen Content</th>
<th>Gasoline</th>
<th>Ethanol</th>
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</thead>
<tbody>
<tr>
<td>(%m)</td>
<td>15.1</td>
<td>13.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Density Liquid at 20° (kg/l)</th>
<th>Gasoline</th>
<th>Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kg/l)</td>
<td>0.740</td>
<td>0.790</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Oxygen Content</th>
<th>Gasoline</th>
<th>Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>(%m)</td>
<td>0</td>
<td>34.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lower Heating Value (MJ/kg)</th>
<th>Gasoline</th>
<th>Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>(MJ/kg)</td>
<td>42.6</td>
<td>26.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heat of Evaporation (kJ/MJ)</th>
<th>Gasoline</th>
<th>Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kJ/MJ)</td>
<td>≈ 8.0</td>
<td>33.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Octane Rating RON</th>
<th>Gasoline</th>
<th>Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-)</td>
<td>95</td>
<td>&gt;100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tem evaporation (°C)</th>
<th>Gasoline</th>
<th>Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>(°C)</td>
<td>25 - 210</td>
<td>78</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vapor pressure (hPa)</th>
<th>Gasoline</th>
<th>Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>(hPa)</td>
<td>60 - 95</td>
<td>17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ignition temperature (°C)</th>
<th>Gasoline</th>
<th>Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>(°C)</td>
<td>400</td>
<td>425</td>
</tr>
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### The Ethanol impact on combustion

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<tr>
<th>Heating Value</th>
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<tr>
<td>inject 1.5 liter Ethanol for 1 liter Gasoline</td>
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<th>Evaporation</th>
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<td>ethanol has much higher risk at cold start</td>
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<th>Octane number - RON</th>
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<tr>
<td>is a most attractive Ethanol feature</td>
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Ethanol is most attractive in high load operation

- Charge cooling
- Octane number

The risks

1. Handling 50% higher fuel flow needs specific attention in fuel injection development:
   - to meet the oil dilution risk
   - to tune spray – wall impingement events

2. Exploiting the RON advantage bears risks of high combustion chamber temperatures
   - spark plug, valve and piston durability
   - pre-ignition and irregular combustion
   - run-away knock

GDI high load operation: the need for fuel enrichment is a desaster for BSFC
Ethanol is most attractive in high load operation

thermodynamic efficiency of a modern Ethanol engine (here on E85) is in good company with best Diesel engines

How to develop an Ethanol DI combustion system?
### How to develop an Ethanol DI combustion system?

**Fuel features are the guide**

What are specific development actions?

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- More fuel injected ➡ more oil dilution
- Fuel evaporation ➡ is a big cold start issue
- High RON ➡ advanced spark timing yields lower exhaust gas temperature, but raises in-cylinder temperature
Oil dilution, GDI examples

...is an issue in every GDI engine, is a much larger issue when using Ethanol

The risk

- oil dilution with secondary lubrication risks
- loss local lubrication
- piston ring damage

Handling 50% higher fuel flow with Ethanol injection
see film for wall wetting effects
Oil dilution - improvement, GDI examples

50 70 deg CA ASOI

fuel spray and vapor in optical engine

spray footprint on glass liner

…is a much larger issue when using Ethanol

The recipe for improvement:

injection system:
select injector and injection parameters

intake ports – airflow:
use in-cylinder flow as an air curtain to protect liner surface
Combustion system development techniques for DI SI engines

This presentation: the tools we use in combustion system development

1. Use an optical engine to study mixture formation, ignition and combustion
   • at engine start
   • in catalyst heating mode
   • at low end torque

2. Use fiber optic sensor techniques to study high load combustion
   • knock
   • pre-ignition and irregular combustion
   • transient operation

3. Use thermal radiation techniques to study
   • spark plug temperature profiles
   • valve temperatures
Cold start: Injection is key to success

What we want to happen:
- inject small droplets
- they should float in air
- and evaporate in late compression cycle before ignition

How to operate an injector to accomplish such task?

What we can do: we select -
- fuel rail pressure
- injection timing,
- duration and
- multiple injections

The cold start risk

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Our chances:
- Compressed hot air is only heat source to evaporate Ethanol droplets
- Every droplet on cold combustion chamber wall is lost for ignition / combustion

Graphic shows pressure and temperature traces at compression ratio = 13. Ethanol evaporation starts later in cycles and needs more heat to evaporate.
Seeing the fuel sprays is understanding the chances for best parameter selection

Cold Start in Transparent Engine at 20°C

What we can do
• inject for minimum wall impingement
• use late injection to exploit compression heat and stratification

What we want to happen
• inject small droplets
• they should float in air
• and evaporate in late compression cycle before ignition

mixture formation
Engine start tests with Gasoline and E85

Cold start:

Direct injection offers features to make happen what we want to happen.

This needs efforts
• in enhancing injector spray formation capabilities
• understanding the fuel injection „windows of opportunity“

1. the Ethanol disadvantage
2. improvement with double injection
3. My expectations: we exploit development chances with modern injectors
Low end torque for high dynamic response

Self ignition and irregular combustion events need special development efforts

- we use the optical engine to clarify and improve mixture formation topics at boosted full load injection
- we use fiber optic flame sensors in the normal multicylinder TC engine to minimize risk of irregular combustion

What is “irregular combustion”?

mixture formation and combustion issues at low end torque: LSPI and knock

- fuel evaporation and homogenization at moderate airmotion – risk for oil dilution and wall film formation

LSPI – low speed pre-ignition: low speed = long chemical induction time and high load = high wall temperature yield a
  - large time-temperature integral to drive chemical reactions

LSPI chemical species risk from fuel, lube oil, deposits
LSPI - as any other irregular ignition event: if we know where it occurs, we may understand why it occurs.

Pre-ignition: occurs spontaneously in one out of many cycles

Diagnostics task: find the location of such spontaneous ignition events

Analysis task: find the root cause of pre-ignition

Development task: find ways to avoid / minimize risk of pre-ignition

Igniting a mixture: the parameters of influence:
A, B, n: chemical features
p, T: engine operation: boost, load

\[ t_{\text{SOC}} \sim \text{time to establish thermochemical chain reaction} \ldots \text{is driving LSPI} \]

\[ t_{\text{IVC}} \text{intake valve closure time} \]

\[ \tau : \text{ignition delay time} \]
Combustion system development techniques for DI SI engines

LSPI is member of a large family of irregular combustion events

Focus 2: Irregular combustion

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   - valve temperatures
A fiber optic spark plug sensor for PI location diagnostics

Low end torque – pre-ignition diagnostics with pressure and flame sensors

The spontaneous occurrence of PI events needs continuous signal recording and signal storage with trigger-on-event logics.

This brings us to the more general topic of irregular ignition/combustion events

A and B: flame and pressure signal of pre-ignition cycle.
C: locations of repeated PI events

ptnss 2011
Pre-ignition:
if we know where it occurs, we may understand why it occurs

Ethanol Octane number allows spark timing to provide maximum torque with stoichiometric mixture even at high speed / high load operation.

This gives higher thermodynamic efficiency at the risk of higher combustion chamber temperature.

**The high speed pre-ignition risk**

**HSPI: high speed pre-ignition**

Igniting a mixture: the parameters of influence
A, B, n: chemical features
p, T: engine operation: boost, load...is driving high speed PI
t_{SOC} ~ time to establish thermochemical chain reaction
t_{IVC} intake valve closure time
τ : ignition delay time

**Arrhenius**:\[
\tau = A \cdot p^{-n} \cdot e^{B / T}
\]

**Livengood, Wu**:\[
\frac{1}{t_{IVC}} \int_{t_{IVC}}^{t_{SOC}} \frac{1}{\tau(s)} ds = 1
\]
Pre-ignition: if we know where it occurs, we may understand why it occurs.

The high speed pre-ignition risk

Example shows one pre-ignition cycle with flame signal recorded with 40-channel VisioKnock spark plug sensor.

- Sensor channel identifies sector at which pre-ignition occurs.
- Collecting repeated PI events shows that PI always occurs within sector comprising exhaust valves.
- Recommended action: improve valve seat cooling, select cooled exhaust valves.
A runaway knock example in a GDI engine at a “thermal stress test”

The knock - runaway knock risk

Ethanol Octane number allows spark timing to provide maximum torque with stoichiometric mixture even at high speed / high load operation.

This gives high thermodynamic efficiency at the cost of high combustion chamber temperature.

The consequence in case of „spark knock“:
- knock introduces high heat flux through combustion chamber surface, this raises local surface temperature
- subsequent cycles may run into pre-ignition mode
- Stopping pre-ignition needs fuel cut

Result for this operating point:
- engine needs >10 strong knock cycles to go into glow ignition

Result for engine testing:
- use SA (knock) versus time for thermal stress test
- use test bed watchdog to reduce testing risk
- use (partial) fuel cut to protect engine
- use thermal radiation signal to detect thermal runaway risk
Pre-ignition:
if we know where it occurs, we may understand why it occurs

The chemical species risk

In addition to fuel – air mixture there is oil, oil vapor, EGR, and deposits inside the combustion chamber.

- chemical kinetics of such species can introduce PI
- glowing deposits and free moving hot deposit flakes can survive one exhaust stroke and ignite fresh charge before spark ignition

Igniting a mixture: the parameters of influence

A, B, n: chemical features...is driving chemical species PI
p, T: engine operation: boost, load
t_{SOC} \sim \text{time to establish thermochemical chain reaction}
t_{IVC} \text{intake valve closure time}
\tau : \text{ignition delay time}
Combustion system development techniques for DI SI engines

This presentation

Focus 3: in-cylinder temperatures

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   • transient operation

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   • spark plug temperature profiles
   • valve temperatures
Combustion system development techniques for DI SI engines

Endoscope access into combustion chamber, IR sensitive camera

thermal image of hot combustion chamber surfaces

calibrated temperature field

„Single shot“ thermal imaging

Example shows gasoline engine thermal images. Temperatures in Ethanol engines are even more critical with risk of thermal pre-ignition or thermal damage of components.

Thermal imaging with endoscope, IR camera and temperature calibration techniques provides variants analysis in normal engine operation.
Combustion system development techniques for DI SI engines

access to valves with fiber optic spark plug sensors

Continuous, cycle and crank angle resolved thermal radiation measurement

example shows valve temperature response to knocking combustion cycles in GDI engine

Thermal risk analysis at load transients needs continuous signal recording:
- Fiber optic spark plug sensors access thermal radiation, IR sensitive photo diodes (PD) record radiation signals.
- Signal calibration is achieved with specific calibration device
Summary

1. Fuel features guide and dictate Ethanol engine development efforts

2. Direct injection together with turbocharging appears to best handle fuel obstacles and exploit fuel benefits

3. GDI development methods are well applicable to Ethanol engines across the entire load, speed and temperature range of a modern engine
From Gasoline to Ethanol Direct Injection Engines

References


Hirsch Alois, Kapus Paul, Philipp Harald, Winklhofer Ernst: „IRREGULAR IGNITION EVENTS IN TC GDI ENGINES: PHENOMENOLOGY, ANALYSIS AND ENGINE DEVELOPMENT” PTNSS CONGRESS-2010, Poland