INJECTION PRESSURE AS A MEANS TO GUIDE AIR UTILIZATION IN DIESEL ENGINE COMBUSTION

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MOTIVATION

soot versus injection pressure

<table>
<thead>
<tr>
<th>rail pressure - bar</th>
<th>soot - FSN</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>1.5</td>
</tr>
<tr>
<td>1000</td>
<td>1.0</td>
</tr>
<tr>
<td>1500</td>
<td>0.5</td>
</tr>
<tr>
<td>2000</td>
<td>0.0</td>
</tr>
</tbody>
</table>

10 bar IMEP
SN = 1.7
1200 rpm
THE QUESTION

How can higher injection pressure end up with lower engine out soot?

$t = 0.2 \text{ ms aSOI}$

![Graph showing soot versus injection pressure]
How can higher injection pressure end up with lower engine out soot?

- Can we understand the mechanisms?
- If so – how to exploit them?
- Which kind of analysis would we require?
1. Injection pressure – spray at nozzle exit
2. Spray interaction with in-cylinder gas
   - Momentum transfer
   - Heat transfer
3. Ignition
4. Premixed and diffusion flames
   - Soot formation
   - Soot oxidation
5. Enhancing soot oxidation
6. How things come together
   - Pressure temperature flow
7. Summary
1. Injection pressure - spray

Such flow is visualized in 2D model nozzle tests. E. Winklhofer et al.: „Basic flow processes in high pressure fuel injection equipment“, ICLASS 2003
1. Injection pressure - spray

Internal flow is visualized in 2D model nozzle tests. Liquid into liquid injection (Diesel)

Fuel flow is subject to cavitation in local shear and boundary layers.

High cross flow velocity gradients force static pressure to drop below vapor pressure.

Driving parameters are:
• Geometry
• Velocity gradients
• Pressure
• Vapor pressure of fuel

White: liquid phase (Diesel)
Black: gas phase (cavitation bubbles) at Diesel vapor pressure << 1 bar
1. Injection pressure - spray

Internal flow is visualized in 2D model nozzle tests. Liquid into liquid injection (Diesel)

Pressure field at inflow into nozzle hole

**Fuel pressure is discharged within fractions of a millimeter at the entrance to the nozzle hole.**

Geometry influence on local static pressure – and hence on cavitation - is highest in areas of high pressure drop.

Measurements were done as Diesel fluid was just below cavitation limit
1. Injection pressure - spray

Liquid into air: 2D model nozzle to see internal flow together with spray.
Average of 30 events

At high injection pressure we see
• Well developed cavitation down to nozzle hole exit
• Atomizing spray with highly stable spray cone angle

Note the dimensions: 0,8 mm nozzle hole + 0,8mm free spray

Conclusion: high injection pressure stabilises spray cone angle near nozzle exit.
2. Spray interaction with in-cylinder gas

Momentum transfer
Heat transfer

Fuel injection pressure

exit velocity: 
\[ \frac{V_{\text{spray}}}{V_{\text{Bernoulli}}} \approx 0.9 \]

1500 bar

spray diameter fluctuation

Spray observation in optical Diesel research engine:

Spray diameter fluctuation measurement to document spray targeting and spray fluctuation in far field
2. Spray interaction with in-cylinder gas
   Momentum transfer
   Heat transfer

Length - time and Diameter - time shadow traces of Diesel sprays in an optical engine

Spray tip propagation and spray core length.

Spray observation in optical Diesel research engine:

Spray diameter fluctuation measurement to document spray targeting and spray fluctuation in far field

Conclusion:

- high injection pressure stabilises spray targeting.
- Spray diameter fluctuations appear at ever higher frequency
2. Spray interaction with in-cylinder gas

Momentum transfer
Heat transfer

Spray in hot compressed in-cylinder gas

Heat transfer from gas into spray with resultant
- fast expansion of spray vapor plume
- and self ignition

T = 930 K
p = 53 bar

Schlieren imaging in optical research engine, 500 rpm
2. Spray interaction with in-cylinder gas

Momentum transfer
Heat transfer

P_{rail} = 300 \text{ bar} \quad P_{rail} = 800 \text{ bar} \quad P_{rail} = 1100 \text{ bar}

Spray in hot compressed in-cylinder gas

Heat transfer from gas into spray with resultant
- fast expansion of spray vapor plume
- and self ignition
- Injection pressure enhances fuel vapor transport

Average spray contours at 0.40 ms after SOI. Nozzle: 1x 0.115 mm

Schlieren imaging in optical research engine
3. Ignition

Ignition and spray – flame interaction in optical engine, 85 mm bore, p = 60 bar Combustion chamber is externally illuminated, high speed camera records of one cycle.

Time sequence shows
- sprays before ignition,
- combustion of premixed fuel vapor in „blue flame“ pockets,
- and start of diffusion combustion
3. Ignition

Ignition and spray – flame interaction in optical heavy duty engine, 127 mm bore, $p = 153$ bar

Time sequence shows
- combustion of premixed fuel vapor in "blue flame" pockets,
- and start of diffusion combustion

- Note that blue premixed flame is only visible at ignition for up to 100 $\mu$s (0.6 deg CA at 1000 rpm)
4. Premixed and diffusion flames
   Soot formation
   Soot oxidation

Diesel combustion movie
HD DIESEL OSCE WITH PISTON BOTTOM WINDOW

Fired operation for 15 cycles
HD DIESEL OSCE WITH PISTON BOTTOM WINDOW

Topic: 20 bar IMEP
1400 rpm

Fired operation for 15 cycles
4. Premixed and diffusion flames

Soot formation
Soot oxidation

„Metal engine“ soot measurement:
• Lower FSN at higher injection pressure

„optical engine“ flame evaluation shows
• Faster soot oxidation at higher injection pressure

Soot oxidation needs flame (soot) – air mixing

Data show that injection pressure has significant influence on air utilization = soot oxidation.

How can this happen?
4. Premixed and diffusion flames
   Soot formation
   Soot oxidation

How can it be that injection pressure improves air utilization?
4. Premixed and diffusion flames
   Soot formation
   Soot oxidation

At ongoing injection

- Backflow of flames into combustion chamber center following spray – vapor - flame reflection on piston bowl wall

After end of injection

- Speed up of swirl motion in center of piston bowl
4. Premixed and diffusion flames
   Soot formation
   Soot oxidation

A comparison with very low injection pressure
Spray momentum is too small for effective interaction with reflecting piston bowl wall

Conclusion 1
Injection pressure drives the flame back into areas of un-used air
4. Premixed and diffusion flames
   Soot formation
   Soot oxidation

How can it be that injection pressure improves air utilization?

1. It introduces flame transport into areas with un-used air

2. And further:
   flame transport enhances turbulent motion
5. Enhancing soot oxidation

Flame (soot) transport

Turbulence: data on local turbulent kinetic energy

At 8.5 EOI 12.5 16.5 21.5 deg CA

500 bar, FSN = 1.2

1000 bar FSN = 0.5

Significant rise of local turbulence with high injection pressure...
5. Enhancing soot oxidation

Flow field

Turbulence

...and fast decay of turbulence at end of injection

KINETIC ENERGY RELAXATION AFTER END OF INJECTION

\[ KE \sim \frac{u_x^2 + u_y^2}{2} \]

Kinetic energy vs CAD

Local Turbulent Kinetic Energy
5. Enhancing soot oxidation

Turbulence is driver for soot – oxygen mixing...

...and results in enhanced soot oxidation

Note: high turbulence for effective soot oxidation is only available right at the end of injection.
6. How things come together
pressure temperature flow

„Metal engine“ soot measurement:
• Lower FSN at higher injection pressure

„optical engine“ flame evaluation shows
• Faster soot oxidation at higher injection pressure

Soot oxidation needs flame (soot) – air mixing

Data show that injection pressure has significant influence on air utilization = soot oxidation.

How can this happen?

1. Transport soot to meet with air
2. Use turbulence for fast soot – air mixing

Examples have shown
• that and how both, transport and turbulence, are controlled by fuel injection and spray momentum reflection on piston bowl walls.
• Effective soot oxidation must happen close to the end of injection to benefit from high temperature oxidation rates.
7. Summary

INJECTION PRESSURE AS A MEANS TO GUIDE AIR UTILIZATION IN DIESEL ENGINE COMBUSTION

**Spray:**
Spray turbulence and atomization are driven by cavitation
Cavitation is controlled by shear and boundary layer flow under influence of local spray hole geometry
At usual temperatures (100 °C) and injection pressures (500 – 2500 bar)
„normal“ behaviour of Diesel sprays: liquid spray core of droplets and ligaments, fuel vapor and diffusion flame

**Flame:**
Temperature and pilot injection control ignition, soot formation in diffusion flame,

**Soot oxidation:**
Injection pressure is most effective to control flame transport and turbulent mixing for fast oxidation

**Analysis:**
in optical Diesel engines with realistic temperature, pressure and geometry parameters
INJECTION PRESSURE AS A MEANS TO GUIDE AIR UTILIZATION IN DIESEL ENGINE COMBUSTION

Thank you
6 MINUTES TO STOP THE ENGINE, CLEAN THE COMBUSTION CHAMBER AND START AGAIN
HD DIESEL OSCE WITH PISTON BOTTOM WINDOW

Fired operation for 15 cycles
HD DIESEL OSCE WITH PISTON BOTTOM WINDOW

Topic: 20 bar IMEP

Fired operation for 15 cycles
THE RISK OF GLASS DAMAGE

MOUNTING PRESSURE TEMPERATURE INERTIA FORCES LOCAL CONTACT UNKNOWN
1. Injection pressure - spray

Internal flow is visualized in 2D model nozzle tests. Liquid into liquid injection (Diesel)

\[ P_{\text{in}} = 400 \text{ bar} \]

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Driving parameters are:
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