Piston Bowl Optimization for a Diesel Engine with Variable Compression Ratio

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Why VCR?

Why Variable Compression Ratio (VCR)?

Thermal efficiency
Specific power / downsizing
Low friction powertrain

Real Driving Emissions
- Soot / NOx at high CR ↓
- EGR at full load with constant PFP CR ↓
- HC / CO at low load CR ↑

Cold Test -7°C for Diesel
- Cold start ability CR ↑
- HC, CO emission CR ↑
- Fuel conversion efficiency CR ↑
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4. Testing Results & Validation
5. Summary
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Multiple link mechanisms

- Articulated con-rod
- Swinging crank
- Linking gear rack
- Linking con-rod

Alteration of kinematic lengths in the crank train

- Crankpin eccentric
- Piston pin eccentric
- Piston height adjustment
- Con-rod length adjustment

Repositioning of unmoving parts

- Additional volume
- Tilting cylinder-block
- Lifting cylinder-block
- Shifting crankshaft axis

→ All suitable concepts have a variable squish gap height
Introduction / Challenges with VCR

Variation Range for VCR

- Determined based on GT-Power studies
- Selected variation range: CR = 11 … 20

Impact on Combustion Chamber Geometry

CR = 20 (Part Load) vs CR = 11 (Full Load)

- Reduced piston bowl volume for CR = 20 reduces free spray penetration length
- Changed top dead center position for CR = 11 leads to different spray targeting
- Piston bowl shape needs to be developed for VCR requirements
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Simulation Approach

- **Automated CFD meshing and model generation of segment models**
- **Define geometry based on a parametric piston bowl shape**
- **Piston bowl shape or selected parameters are scaled to fit a predefined compression ratio**
- **Call pro-STAR / STAR-CD®**
- **Automated Post-processing: Collecting simulation results in one txt/pdf-file**

**Input File**
- txt

**Parametric Bowl**
- CR = const.

**STAR-CD Sector Model**

**Results File**
- txt/pdf

**Analyze Results and Decide new Variants**
- Manually (by Engineer)
- Automatically (by Optimization Tool)

**IAV Tool**
## Automated vs. Manual Approach

<table>
<thead>
<tr>
<th>Automated Approach</th>
<th>Manual Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Requires less man power</td>
<td>+ Very suitable to investigate different bowl layouts</td>
</tr>
<tr>
<td>+ Very suitable to find a global optimum</td>
<td>+ Separation of secondary effects possible / plausibility checks</td>
</tr>
<tr>
<td>+ Effective usage of computational resources</td>
<td>- Normally the optimum cannot be detected</td>
</tr>
<tr>
<td>- Too much parameters if all geometric parameters have to be considered</td>
<td>- More time-consuming</td>
</tr>
<tr>
<td>- Useful only for ‘fine tuning’ of a geometry (global optimum)</td>
<td></td>
</tr>
<tr>
<td>- Need of more simulation runs to find an optimum</td>
<td></td>
</tr>
</tbody>
</table>

→ For the given task the manual approach has been selected
# Simulation Approach

## 1. Step:
**Definition of different piston bowl base concepts (3)**

<table>
<thead>
<tr>
<th>Concept</th>
<th>Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Omega</td>
<td><img src="omega.png" alt="Omega Diagram" /></td>
</tr>
<tr>
<td>Flat Dish</td>
<td><img src="flat_dish.png" alt="Flat Dish Diagram" /></td>
</tr>
<tr>
<td>Open W</td>
<td><img src="open_w.png" alt="Open W Diagram" /></td>
</tr>
</tbody>
</table>

## 2. Step:
**Optimization of Piston Bowl Main Dimensions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR</td>
<td>20.0</td>
</tr>
<tr>
<td>CR</td>
<td>11.0</td>
</tr>
<tr>
<td>Ds Quench</td>
<td>4.7 mm</td>
</tr>
<tr>
<td>Ds Quench</td>
<td>0.0 mm</td>
</tr>
</tbody>
</table>

## 3. Step:
**Optimization of Piston bowl features (collar, cone, …)**

- E.g. open w-bowl

![Graph](graph.png)
Consideration of 2 operating conditions

Part Load:
- Engine Speed: 1200 min\(^{-1}\)
- IMEP: \(~8.5\) bar
- Compression Ratio (CR): 20

Full Load:
- Engine Speed: 4000 min\(^{-1}\)
- CO\(_2\)-Reduction
- Power Increase or Reduction of Friction
- Compression Ratio (CR): 11
# Model Setup

## Turbulence / Heat Transfer

<table>
<thead>
<tr>
<th>Component</th>
<th>Model/Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulence Model</td>
<td>k-(\varepsilon)-model, high Reynolds</td>
</tr>
<tr>
<td>Wall Function</td>
<td>Kader</td>
</tr>
</tbody>
</table>

## Spray

<table>
<thead>
<tr>
<th>Component</th>
<th>Model/Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle model</td>
<td>MPI2</td>
</tr>
<tr>
<td>Atomization model</td>
<td>Huh</td>
</tr>
<tr>
<td>Break-up model</td>
<td>Reitz + Submodels</td>
</tr>
<tr>
<td>Droplet-Wall-Interaction</td>
<td>Bai</td>
</tr>
<tr>
<td>Liquid Fuel</td>
<td>C\textsubscript{12}H\textsubscript{26} (DF2)</td>
</tr>
</tbody>
</table>

## Combustion/Ignition

<table>
<thead>
<tr>
<th>Component</th>
<th>Model/Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignition model</td>
<td>Double Delay Ignition Model</td>
</tr>
<tr>
<td>Combustion model</td>
<td>ECFM-3Z</td>
</tr>
<tr>
<td>Evaporated Fuel</td>
<td>C\textsubscript{12}H\textsubscript{26} (DF2)</td>
</tr>
</tbody>
</table>

## Emissions

<table>
<thead>
<tr>
<th>Component</th>
<th>Model/Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>Zeldovich</td>
</tr>
<tr>
<td>Soot</td>
<td>ERC</td>
</tr>
</tbody>
</table>
Model Calibration

Spray Model Calibration

Combustion Model Calibration

\[ n = 1200 \text{ min}^{-1}, \text{ IMEP } \sim 8.5 \text{ bar} \]

\[ n = 4000 \text{ min}^{-1}, \text{ Full Load} \]
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Simulation Results

Soot – NO – ISFC – Trade-off

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<th>Constant:</th>
<th>Variable:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boost Pressure, EGR-Rate, Swirl at IVC, Inj. Fuel Mass, Injection Timing (PI, MI)</td>
<td>CA50 %, IMEP, pCyl,max</td>
</tr>
</tbody>
</table>

Bowl Concepts:
- omega
- flat dish
- open w

Single Variants:
- base (CR = 16.2)
- final w variant

Part Load, CR = 20

- NO<sub>x</sub> +37%; PM +34%
- ISFC -5.8%

Full Load, CR = 11

- PM -65%
- ISFC -1.1%

→ Piston geometry selected for max. ISFC benefit
→ Increase of Soot and NO unavoidable with CR=20
Simulation Results

Part Load (n = 1200 min\(^{-1}\), IMEP ~8.5 bar, 365 deg CA)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>CR</th>
<th>S\text{SQUISH}</th>
<th>Temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basis</td>
<td>16</td>
<td>0.9 mm</td>
<td></td>
</tr>
<tr>
<td>Omega-Bowl</td>
<td>20</td>
<td>0.9 mm</td>
<td></td>
</tr>
<tr>
<td>Flat Bowl</td>
<td>20</td>
<td>0.9 mm</td>
<td></td>
</tr>
<tr>
<td>w-Bowl</td>
<td>20</td>
<td>0.9 mm</td>
<td></td>
</tr>
</tbody>
</table>

Full Load (n = 4000 min\(^{-1}\), Full Load, 375 deg CA)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>CR</th>
<th>S\text{SQUISH}</th>
<th>Temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basis</td>
<td>16</td>
<td>0.9 mm</td>
<td></td>
</tr>
<tr>
<td>Omega-Bowl</td>
<td>11</td>
<td>5.6 mm</td>
<td></td>
</tr>
<tr>
<td>Flat Bowl</td>
<td>11</td>
<td>5.6 mm</td>
<td></td>
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<tr>
<td>w-Bowl</td>
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<td>5.6 mm</td>
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</table>
Simulation Results

Swirl and Wall Heat Losses

<table>
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<tr>
<th>Constant:</th>
<th>Variable:</th>
<th>Bowl Concepts:</th>
<th>Single Variants:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boost Pressure, EGR-Rate, Swirl at IVC, Inj. Fuel Mass, Injection Timing (PI, MI)</td>
<td>CA50 % IMEP, $p_{Cyl,max}$</td>
<td>omega, flat dish, open w</td>
<td>base (CR = 16.2), final w variant</td>
</tr>
</tbody>
</table>

- Smaller Swirl Number @ SOI due to smaller piston bowl volume
- Smaller piston bowl surface → potential for decreased wall heat losses
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Testing Results & Validation

Test-bench Environment

- Single Cylinder Engine (SCE)
- Replacement of piston
- Variation of CR by inserting washers between crank train and cylinder block
Testing Results & Validation

Comparison Test-rig / CFD Results

Part Load, CR = 20

- ISFC: +77% (+4.2% to -5.8%)
- Soot: +34% (+32% to +37%)
- NOx: +37%

Full Load, CR = 11

- ISFC: -1.3% to -1.1%
- Soot: -64% to -65%
- NOx: ±0% to -5%

<table>
<thead>
<tr>
<th>Injection</th>
<th>EGR</th>
<th>Fuel Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCE (testing)</td>
<td>Pilot injection control w.r.t. heat release</td>
<td>Ext. EGR controled w.r.t. Iso-NOx / Iso-Soot</td>
</tr>
<tr>
<td>CFD</td>
<td>const. Injection Rate</td>
<td>Fuel mass controled w.r.t. IMEP</td>
</tr>
</tbody>
</table>

→ Testing results confirm CFD predictions
→ Slight differences in predicted fuel consumption due to different conditions

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Summary

- Almost all technical solutions for a variable compression ratio (CR) have a variable squish gap height
- For a CR variation range from 11 to 20 the squish gap height must be changed by 4.7 mm → Big differences in spray-wall-interaction
- Manual, step-wise optimization of piston bowl design at 2 operating points
- Piston bowl optimization results:
  - ~5% reduction of ISFC/CO₂ at part load
  - The increase of NO/Soot emissions at part load caused by the increase of CR could not be prevented
  - At rated power slight reduction of ISFC/CO₂ (~1.2%) and strong decrease of soot emissions
- In general the simulation results were confirmed by single cylinder engine
Thank You

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