Modeling Water Injection in a High-Output Diesel Engine Using GT-POWER

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Contents

- Introduction
- Project Targets
- The Engine
- GT-POWER Model
- Simulation Results
- Summary
Introduction

Diesel vehicles have historically been associated as being industrial, smoky, slow and boring.
Introduction

Perceptions are slowly changing
Project Targets

Explore and push the performance limit of a streetable Diesel-powered car

- Most aftermarket tuning is done by intuition and experience (trial-and-error)
- Specific power, torque and RPM to exceed the Diesel tuning state-of-the-art using engineering principles and methods
- Target specs: 150 kW/L (200+ HP/L), 40 bar BMEP, 5500+ RPM max.
The Engine

Series engine specs:

- VW 4-cyl 2.0L 16V common-rail TDI Diesel
- Bore x stroke: 81 x 95.5mm (1968 cm³)
- Power / torque: 103 kW (140 HP) / 320 Nm
The Engine

- **Modified engine specs:**
  - 336 kW (450 HP), 658 Nm (485 lb. ft.)
  - Enlarged pistons (83 vs. 81mm) → 2067 cm³
  - Compression ratio reduced to 15:1
  - Custom common-rail fuel injection system and standalone engine control unit (ECU)
  - Regulated 2-stage turbocharging using variable turbine geometry turbos
The Engine

- Heavily-modified cylinder head
- Optimized valve timing using GT-POWER
- Custom piston pins, con rods, bearings
- Block reinforcement (ladder frame)
- Thermal barrier coating on flame-exposed surfaces
- Increased cooling/lube oil capacity
The Engine

Dual Turbochargers

- Garrett® VNT™
  (Variable Nozzle Turbine)

- Regulated 2-Stage charging adapted from author’s M.Sc. thesis (portions presented at 2009 GT-SUITE Users Conference by FEV/RWTH Aachen/BWTS)
The Engine

GT-POWER simulation results

![Graph showing power and torque vs. engine speed]
The Engine

All this is great, but we have a problem:

![Exhaust Gas Temperature at Collector graph]

Turbocharger $T_{\text{max}} = 850^\circ \text{C}$
The Engine

All this is great, but we have a problem:

Design $p_{\text{max}} \approx 225$ bar
The Engine

All this is great, but we have a problem:

$68kW \ (92HP) = \text{total brake } P_{\text{max}}$ of an economy car engine!
All this is great, but we have a problem:

4800W = total brake $P_{\text{max}}$ of a 6.5HP lawnmower engine!
The Engine

All this is great, but we have a problem:

5600W – compared to the heat output of a 19000BTU/hr BBQ!
The Engine

Solution: Water Injection
Thermodynamic Review

1\textsuperscript{st} Law for closed-systems

\[ \delta q - \delta w = du + d(KE) + d(PE) \]

\[ W = \int pdV, \quad V = m \cdot v \]

\[ W = \dot{m} \int pdv \]

\[ dU_{1 \rightarrow 2} = mC_v (T_2 - T_1) \]

\[ P v = mRT \]

\[ \left( \frac{T_2}{T_1} \right) = \left( \frac{V_1}{V_2} \right)^{(n-1)} = \left( \frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \]
Effects of increased water content on air working fluid properties. Source: Heywood (1988), from Taylor
GT-POWER Model
GT-POWER Model

- Added water injectors as shown
GT-POWER Model

Modelling considerations

- Enable Condense/Evaporate Water Vapour
GT-POWER Model

- Enable ‘Calculate Water Saturation (Dew) Temperature RLT’

Air-fuel ratio, effective lambda and volumetric efficiency give erroneous results.
Simulation Results

- EGT reduced >120 K

![Exhaust Gas Temperature at Collector](image)

Turbocharger $T_{\text{max}} = 850^\circ \text{C}$
Simulation Results

PCP reduced 25 bar

Design $p_{\text{max}} \approx 225$ bar
Simulation Results

**In-cylinder heat transfer reduced 28%**

**Engine In-Cylinder Heat Transfer**

- **No WI**
- **Intake Port WI**

<table>
<thead>
<tr>
<th>Engine Speed [RPM]</th>
<th>Heat Transfer [kW]</th>
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<tbody>
<tr>
<td>1500</td>
<td>20</td>
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<tr>
<td>2000</td>
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<td>5500</td>
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<tr>
<td>6000</td>
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</tbody>
</table>
Simulation Results

Combined Compressor Efficiency Maps - Corrected

- HPC - No WI
- LPC - No WI
- HPC - Intake Port WI
- LPC - Intake Port WI

Pressure Ratio

Corrected Mass Flow [kg/s]
Simulation Results

**Pressure**

- Crank Angle [deg]: BDC, CMP, TDC, POWER 180, EXH, 360 INTAKE, 540 BDC
- Pressure [bar]: 0, 50, 100, 150, 200, 250

**LogP-LogV Diagram**

- Volume/Vmax: 6, 7, 8, 9, 10
- Pressure [bar]: 2, 3, 4, 5, 6

**P-V Diagram**

- Volume/Vmax: 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0
- Pressure [bar]: 0, 50, 100, 150, 200

**Temperature**

- Crank Angle [deg]: BDC, CMP, TDC, POWER 180, EXH, 360 INTAKE, 540 BDC
- Temperature [K]: 250, 500, 750, 1000, 1250, 1500, 1750, 2000
Simulation Results

**Burned Zone Temperature**

Temperature [K]

Local Cylinder Crank Angle [deg]

-40 -20 0 20 40 60 80 100

-500 -1500 -2500 -3000

**Heat Transfer Coefficient**

HTR Coefficient [W/m²K]

Crank Angle [deg]

-180 CMP 0 PWR 180 BDC 380 EXH 540 INT 540 BDC

0 2500 5000 7500 10000 12500

**Heat Transfer Rate (Positive=Fluid To Wall)**

Heat Transfer Rate [kW]

Crank Angle [deg]

-180 CMP TDCF 0 POWER 180 BDC EXH 360 INTAKE 540 BDC

0 20 40 60 80 100

120

**Heat Flux (Positive=Fluid To Wall)**

Heat Flux [kW/m²]

Crank Angle [deg]

-180 CMP TDCF 0 PWR 180 BDC EXH 360 INTAKE 540 BDC

0 1000 2000 3000 4000 5000 6000 7000 8000

-2000 -1000 0 1000 2000 3000 4000 5000 6000 7000 8000
Summary

Water injection has been modeled in GT-POWER and shown to reduce mechanical and thermal stresses in a highly-rated turbocharged DI Diesel engine:

- Exhaust gas temperature reduced 120 K and remains below 850°C limit
- Peak cylinder pressure reduced 25 bar to below 225 bar
- In-cylinder heat transfer reduced 28%
- Burned zone temperature reduced
THANK YOU FOR YOUR ATTENTION!

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