Fuel injection and combustion integrated simulation for a marine diesel engine

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Presentation Overview

- Introduction
- Experimental set-up
- Analysis of the injector model
- Analysis of the engine model
- Integrated analysis of the injection model with the engine model
- Conclusions
In a previous study on a marine diesel engine* a DoE analysis was carried out in order to evaluate the effects on fuel consumption and NOx emissions of different combination of compression ratio, injection timing, injector nozzle holes size and number.

* GT-User Conference 2006; SAE paper 2007-01-0670
Introduction

Since the previous work demonstrated the good potential of the simulation tool as far as the combustion process was concerned, a further investigation was carried out, in order to evaluate the impact on fuel consumption and emissions of different injection cam profiles, by means of an integrated fuel injection and combustion simulation.
Experimental set-up

MAIN ENGINE FEATURES : Wärtsilä W6L26B2

<table>
<thead>
<tr>
<th>#</th>
<th>Engine speed [rpm]</th>
<th>BMEP [bar]</th>
<th>Load [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>24.0</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>947</td>
<td>21.5</td>
<td>85</td>
</tr>
<tr>
<td>3</td>
<td>906</td>
<td>19.9</td>
<td>75</td>
</tr>
<tr>
<td>4</td>
<td>794</td>
<td>15.2</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>629</td>
<td>9.5</td>
<td>25</td>
</tr>
</tbody>
</table>

- Type: Diesel, 4 stroke, 6 cylinders in line
- Bore/Stroke: 260 / 320 mm
- Displacement: 101 dm³
- Compression Ratio: 16 : 1
- Maximum Power: 340 kW/cyl at 1000 rpm
- Maximum BMEP: 24.3 bar
- Air System: Single Stage Turbocharger with Fixed Geometry Turbine and Aftercooler
- Valves: 4 valves/cylinder
- Combustion chamber: Quiescent
Experimental set-up

### MAIN INJECTION SYSTEM FEATURES

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection type</td>
<td>Unit pump injector</td>
</tr>
<tr>
<td>Pump plunger diameter</td>
<td>24 mm</td>
</tr>
<tr>
<td>Pump displacement</td>
<td>14.3 cm³</td>
</tr>
<tr>
<td>Pump max. pressure</td>
<td>2000 bar</td>
</tr>
<tr>
<td>Injector nozzle holes</td>
<td>9</td>
</tr>
</tbody>
</table>

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Injector components

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Injector model

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The comparison between simulated and experimental data was not satisfactory at the beginning, with injection pressure differences of over 200 bar and unacceptable differences in needle lift duration that required further model refinements.
The first step was to adjust the injection duration in order to fit the experimental needle lift, varying the duration of the initial and closing transient phases of the pump delivery, by adjusting the pre-stroke and the spill port opening parameters.
Injector model refinement

Then, the difference in the injection pressure was then attributed to an overestimate of the pump internal leakage. By reducing the leakage between pump plunger and cylinder the pressure rate a satisfactory agreement with the experimental data was obtained.
Moreover, the pressure trend in the injection line after the injection phase was not properly captured.

![Pressure decrease](chart.png)
This behaviour was caused by a too slow closure of the Control Pressure Valve (CPV) after the pump delivery phase that caused an excessive pressure drop in the injection line. An overestimation of the damping coefficient between the MDV and CPV valve in the injector model can cause this delayed closure; a more fast valve closure and a more limited pressure drop in the line was the obtained by reducing the damping coefficient.
A proper prediction of the pressure level in the injection line was then achieved.
Injector model

Comparison between experimental and simulated data for the needle lift and injection pressure profile

Load 100%

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**Injector model**

Comparison between experimental and simulated data for the needle lift and injection pressure profile

**Load 85%**

- **Introduction**
- **Experimental set-up**
- **Analysis of the Injector model**
- **Analysis of the Engine model**
- **Integrated analysis of the injection model with the W6L26B2 engine model**
- **Conclusions**
Injector model

Comparison between experimental and simulated data for the needle lift and injection pressure profile

Load 75%
Injector model

Comparison between experimental and simulated data for the needle lift and injection pressure profile

Load 50%

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The engine model available before the integrated analysis was based on the use of an imposed injected mass and injection pressure profile (obtained from experiments), with a predictive DI-Jet model for combustion and emissions prediction.
Engine model

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Imposed injection pressure from exp.

Engine model

Imposed injected total fuel mass

Cd calculated

Mass flow rate

Heat release rate

In-cylinder pressure
Engine model

Comparison between experimental and simulated data (engine “stand alone” model)

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In a integrated simulation the injection pressure profile is provided by the detailed injection model, while the in-cylinder pressure profile is calculated by the code.

In this way, it is possible to predict the effects of injection system geometry variations (e.g. the cam profile or the nozzle hole diameter), avoiding the need for any simplified hypothesis.

Moreover, if the injection model is properly calibrated, it is possible to obtain the pressure profile in parts of the injection system, where positioning a real pressure sensor would be very difficult or even impossible.
Integrated analysis

Pressure profile in parts of the injection system where no exp. meas. are available

Effects of injection system geometry variations

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Integrated analysis

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Integrated analysis

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Integrated model

Imposed discharge nozzle coefficient

- Injection pressure
- Heat release rate
- In-cylinder pressure

Graphs showing:
- Injection Pressure
- Heat Release Rate
- In-cylinder Pressure

Various parameters and models are discussed, including the nozzle coefficient and injection pressure.
Integrated analysis – model validation

Comparison between experimental and simulated data (integrated simulation)

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Integrated analysis – model validation

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Comparison between experimental and simulated data for different engine operating points

In-cylinder pressure profile

Heat release rate

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Load 100%
Integrated analysis – model validation

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**In-cylinder pressure profile**

**Heat release rate**

Load 85%
Comparison between experimental and simulated data for different engine operating points

- In-cylinder pressure profile
- Heat release rate

Load 75%
Integrated analysis – model validation

Comparison between experimental and simulated data for different engine operating points

In-cylinder pressure profile

Heat release rate

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Comparison between experimental and simulated data for NOx emissions at different operating points

In-cylinder NOx at EVO
- Simulation
- Experimental

NOx [ppm]

200 ppm

LOAD [%]

20 40 60 80 100
Once validated, the integrated model was then used to predict the effects produced by different injection system geometry configurations.

Afterwards, experimental tests were carried out in order to check the reliability of the model predictions.

<table>
<thead>
<tr>
<th>Config.</th>
<th>Inj. Cam</th>
<th>SOI</th>
<th>Inj. hole diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>[-]</td>
<td>[-]</td>
<td>[° bTDC]</td>
<td>[-]</td>
</tr>
<tr>
<td>1</td>
<td>Standard</td>
<td>+2 deg adv</td>
<td>Baseline</td>
</tr>
<tr>
<td>2</td>
<td>Slow</td>
<td>Baseline</td>
<td>Baseline</td>
</tr>
<tr>
<td>3</td>
<td>Slow</td>
<td>+2 deg adv</td>
<td>-15 % (area)</td>
</tr>
</tbody>
</table>
Integrated analysis

Comparison between different cam profiles

Standard inj. cam

Slow inj. cam

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Configuration 1

Configuration 2 & 3
Integrated analysis

Comparison between experimental and simulated data for different injection system configurations @950 rpm (load = 85%)

Injection pressure

- Configuration 1
- Configuration 2
Integrated analysis

Comparison between experimental and simulated data for different injection system configurations @950 rpm (load = 85%)

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Integrated analysis

Comparison between experimental and simulated data for different injection system configurations @950 rpm (load = 85%)

In-cylinder maximum pressure

Brake specific NOx

Introduction

Experimental set-up

Analysis of the Injector model

Analysis of the Engine model

Integrated analysis of the injection model with the W6L26B2 engine model

Conclusions
Conclusions

- A good correlation between experimental data and simulation results both for the injection system model and for the engine model could be achieved.

- The simplicity of integrating different models (i.e. engine and fuel injection models) in an single, fully comprehensive model allowed an easy assembly and integration after preliminary validations carried out for the single parts.

- An integrated simulation with a detailed engine model and a detailed injection model proved to be extremely helpful for the optimization of the whole engine performance.
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