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PERFORMANCE AND NO_X EMISSION MODELLING OF A COMMON-RAIL DIESEL ENGINE

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Abstract:
This paper presents the results of an analytical study for optimisation of the full-load operation of a compression ignition internal combustion engine with common rail fuel system. The model is built with the aid of the software simulation package Advanced Simulation Tools by AVL List GmbH. An existing engine is used as a prototype of the model – a PSA-manufactured DW10BTED4. The resulting performance data is compared with manufacturer data. A possible range of model improvements are also presented in the paper.

Keywords: *diesel engine, common rail system, combustion numerical modelling, engine performance.*

1. Introduction

Computer simulation is a key part of the internal combustion engine development process. In the modern engines most of the systems are electronically controlled. If a satisfactory numerical simulation of the physical processes (intake, combustion, injection, exhaust, heat exchange etc.) is achieved, it is possible to predict the output parameters of the engine by varying the input parameters. Many software products offer the opportunity of creating such models. In the current study AVL Boost s used.

2. Previous Studies

In a previous study [1] a model of the same engine was created using Ricardo WAVE software product. The results of the former study have led to the conclusion that the model used was both inaccurate describing the combustion in a common-rail direct injection diesel engine (provided that a simple Vibe function is used for heat release prediction) and unable to calculate the injection rate (it was predefined instead).

3. Theory

The simulation software used in this study (AVL Boost) utilizes a one-dimensional mathematical model based on the first law of thermodynamics. In this chapter a brief overview of the theory behind the mathematical model is given [2].

AVL Boost recommends using a proprietary model called Mixing Controlled Combustion for direct injection compression ignition engines. This model considers two phases of the burning process: Premixed Combustion (PMC) and Diffusion Controlled Combustion (MCC). According this the total heat release could be defined as follows:

$$\frac{dQ_{total}}{d\alpha} = \frac{dQ_{MCC}}{d\alpha} + \frac{dQ_{PMC}}{d\alpha} \qquad \text{(E1)}$$

Mixing-Controlled Combustion

The heat release during this phase is determined by the fuel quantity available (f_1) and the turbulent kinetic energy density (f_2):

$$\frac{dQ_{MCC}}{d\alpha} = C_{comb} . f_1 . f_2 \qquad \text{(E2)}$$

$$f_1 = \left(m_F - \frac{Q_{MCC}}{LCV} \right) . \left(w_{O,avail} \right)^{C_{EGR}} \quad \text{(E3)}$$

$$f_2 = C_{Rate} . \frac{\sqrt{k}}{\sqrt[3]{V}} \quad \text{(E4)}$$

where C_{comb}, C_{rate} and C_{EGR} are combustion, mixing rate and EGR influence constants, respectively; LCV – lower heating value of the fuel; α – crank angle; $w_{O,avail}$ – mass fraction of oxygen.

The f_1 parameter in equation (E3) is a function of the vaporized fuel mass (m_F) and the cumulative heat release (Q_{MCC}) and f_2 in (E4) – a function of the local density of turbulent kinetic energy (k) and cylinder volume (V).

The kinetic energy of the fuel spray (E_k) is determined by:

$$\frac{dE_k}{dt} = 0{,}5.C_{turb}.\dot{m}_F.v_F^2 - C_{Diss}.E_k^{1,5} \quad \text{(E5)}$$

$$k = \frac{E_k}{m_{F,I}\left(1 + \lambda_{diff}.m_{stoich}\right)} \quad \text{(E6)}$$

where C_{turb} and C_{Diss} are turbulent energy production and dissipation constants, respectively; $m_{F,I}$ – injected fuel mass; v_F – injected fuel velocity; m_{stoich} – stoichiometric mass of fresh charge; λ_{diff} – air excess ratio for diffusion burning.

Premixed Combustion

The premixed combustion model uses a Vibe function to describe the actual heat release:

$$\frac{\left(\frac{dQ_{PMC}}{Q_{PMC}} \right)}{d\alpha} = \frac{a}{\Delta\alpha_c}.(m+1).y^m.e^{-a.y^{(m-1)}} \quad \text{(E7)}$$

$$y = \frac{\alpha - \alpha_{id}}{\Delta\alpha_c} \quad \text{(E8)}$$

For calculation of Q_{PMC} the amount of fuel injected during the ignition delay phase is needed. The ignition delay is calculated by [3]:

$$\tau_{ID} = C_1 \frac{\lambda_P}{p_{cyl}^2}.e^{\left(\frac{C^2}{T_p} \right)} \quad \text{(E9)}$$

NO_X Formation

AVL Boost relies on the well-known Zeldovich mechanism for describing the formation of nitrogen oxides in the engine. Three additional chemical reactions are also taken into account. The resulting model considers the following six reactions [2]:

$$N_2 + O = NO + N$$

$$O_2 + N = NO + O$$

$$N + OH = NO + H$$

$$N_2O + O = NO + H$$

$$O_2 + N_2 = N_2O + O$$

$$OH + N_2 = N_2O + H$$

4. Analytical Model

The main parameters of the prototype engine are shown in table 1.

Table 1.

Manufacturer	PSA
Engine Code	DW10BTED4
Bore/Stroke	85/88 mm
Engine Volume	1997 cm^3
Compression Ratio	18:1
Maximum Injection Pressure	1600 bar
Power Rating	100 kW / 4000 min^{-1}
Torque	320 Nm / 2000 min^{-1}

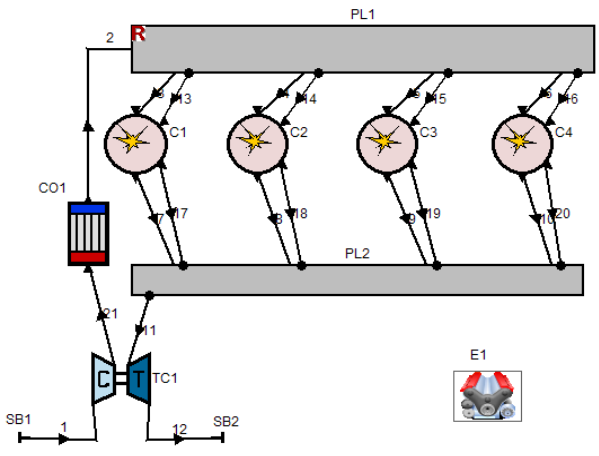

Fig 1. Diagram of the engine components (AVL Boost)

A simulation is performed for 6 different operating modes – all with full load and engine speeds between 1500 and 4000 min^{-1}, with a step of 500 min^{-1}. The goal of the simulation is to determine the optimum values of main operation parameters, including combustion duration and injection timing [4][5].

Compressor and turbine map data is taken from the Garrett online supercharger database [6].

The resulting performance curves (power and torque) from each simulation are compared to the manufacturer data [7].

The rate of injection is defined a square pulse, with a rise delay.

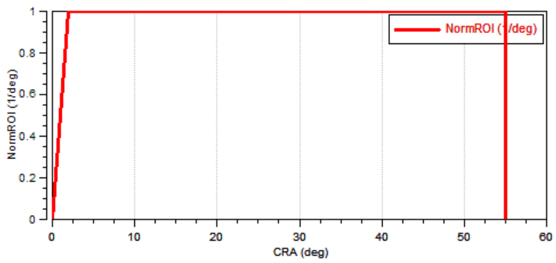

Fig 2. Pre-defined Rate of Injection (Normalized)

5. Results

The results of the study are shown on fig. 3-5.

The first chart (Fig 3.) is a comparison between the torque and power curves of the modeled engine (solid lines) and the data supplied by PSA (hollow line) for the prototype engine. The two curves show closer fit (max. error 1,6%) compared to Fig. 4 – a comparison between the current results (solid lines) and the results of the previous study (dashed lines) [1], with max. error exceeding 5%.

In the previous study a classical Vibe function is used to predict the heat release during the combustion process which could not describe the combustion satisfactorily when using common rail fuel system.

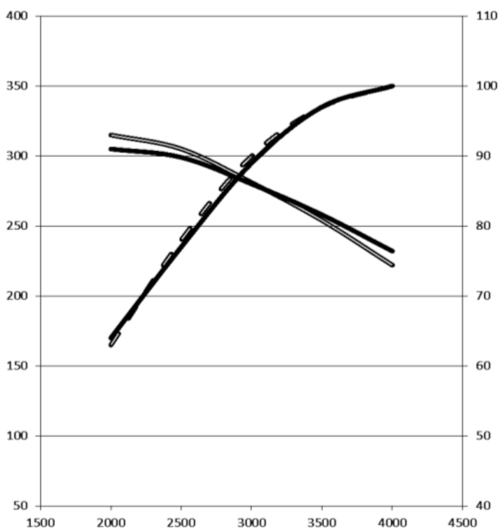

Fig 3. Power and Torque
DW10BTED4 data vs. AVL BOOST model

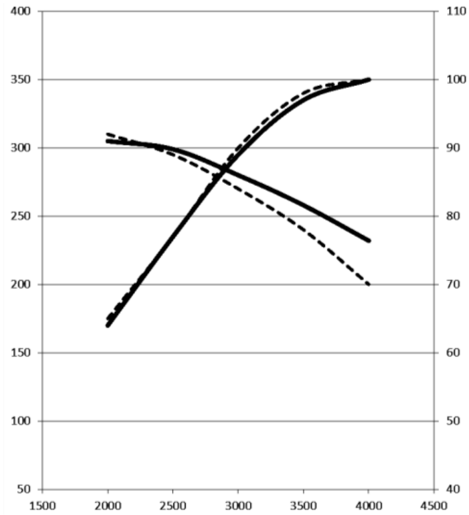

Fig 4. Power and Torque
Ricardo WAVE vs. AVL BOOST model

On Fig 5. the accumulated NOX during the combustion is compared – current results with solid lines and [1] with dashed lines. The trends of the two curves are similar. Without model calibration however these results could not be compared.

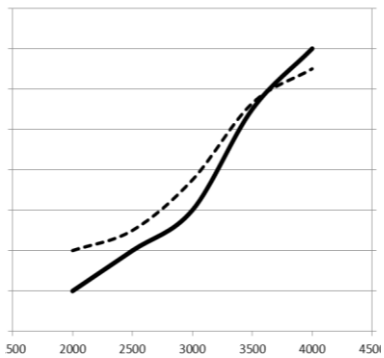

Fig 5. NO_X accumulation WAVE – BOOST

6. Conclusion

The analytical study helped successfully determining the optimum parameters for all 6 operating modes.

The current model proved to be more accurate in modeling the heat release (therefore the performance) of the engine. Nevertheless an experimental study is needed to determine a few parameters crucial to the injection rate prediction model.

Unfortunately the NO_X formation results could not be evaluated without experimental data. The resulting curve is compared with the result of the previous study [1] and the trend is similar for the respective operation modes; however this cannot be conclusive by any means.

7. Further Work

The resulting model should be refined in several aspects:

- The Rate of injection should not be pre-defined but predicted by the software itself. To achieve this goal additional data is needed – nozzle flow curve for the injectors and pressure curve during the injection process;
- The operating parameters are chosen to be optimal for each operation mode (the goal of the current study). The model however still remains to be calibrated and validated by an experimental study – the performance as well as the emission results;
- Another study must take place determining partial load operating modes.

8. Acknowledgements

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МОДЕЛИРАНЕ НА ЕФЕКТИВНИ ПОКАЗАТЕЛИ И NOX ЕМИСИИ В ДИЗЕЛОВ ДВИГАТЕЛ С ГОРИВНА СИСТЕМА COMMON-RAIL

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Резюме:

Настоящият доклад представя резултатите от аналитично изследване за оптимизация на работата при пълно натоварване на двигател със самовъзпламеняване на горивната смес и горивна система Common Rail. Моделът е изграден с помощта на симулационен софтуер Advanced Simulation Tools от AVL List Gmbh. Съществуващ двигател е използван за прототип на модела – PSA DW10BTED4. Получените ефективни характеристики са сравнени с данни от производителя. Редица възможности за подобрение на модела също са представени в доклада.

Ключови думи: *дизелови двигатели, Common Rail, числено моделиране на горивния процес, ефективни показатели.*