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Study on the combustion process in a modern diesel engine controlled by pre-injection strategy

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Abstract. The paper aims to study the combustion process in a modern diesel engine over the engine operating map. In order to study the rate of heat release (ROHR), an automotive diesel engine was experimentally tested using the injection parameters factory defined. The experimental test was conducted over the engine operating map as the engine speed was limited to 2400 rpm. Then, an engine simulation model was developed in AVL Boost. By means of that model the ROHR was estimated and approximated by means of double Vibe function. In all engine operating points we found two peaks at the ROHR. The first is a result of the pilot injection as the second corresponds to the main injection. There was not found an overlap between both peaks. It was found that the first peak of ROHR occurs closely before top dead center (BTDC) at partial load than full load. The ROHR peak as a result of main injection begins from 4°BTDC to 18°ATDC. It starts earlier with increasing engine speed and load. The combustion duration varies from 30 °CA to 70 °CA. In order to verify the results pressure curve was estimated by means of defined Vibe function parameters and combustion duration. As a result, we observed small deviation between measured and simulated pressure curves.

1. Introduction

In direct injection diesel engines for passenger cars the pre-injection strategy is widely use in order to control the pressure rise in the combustion chamber, respectively the noise produced by engine [1]. That strategy requires precise control of the pilot injection quantity and timing as well as the timing of the main injection over the engine operating map [2, 3]. Thus, the variation of injection parameters causes difficulties in prediction the rate of heat release (ROHR) in numerical simulation of direct injection diesel engines. Jaipuria and Lakshminarayanan proposed a one-dimensional model for the prediction of the ROHR in common-rail direct-injection diesel engines with pilot, main, and post injections [4]. The results were found to be closed to experimental data.

Breuer in [5] studied double Vibe function parameters on a DI diesel engine using diesel fuel, rape oil and rape methyl ester. In this paper a “logarithmic anamorphosis” was used in order to define the six parameters of the function. Nikolov presented numerical study using a single Vibe function [6]. The variation of the Vibe function shape parameter leads to variation of the combustion beginning in order to achieve the maximum indicated mean effective pressure (IMEP). The double Vibe function parameters have been experimentally determined in [7]. The engine was tested with biodiesel blend. In this study the shape parameter of the first Vibe function varied within the range of 2.9 to 3.1 while the shape of the second Vibe function ranged from 0.7 to 1.6. Most of the studies are related to determination the double Vibe function parameters in diesel engine with single injection. For that reason, this paper



aims to study the combustion process and the ROHR in direct injection diesel engine adapted to operate with pilot injection strategy.

2. Experimental set-up

In order to study experimentally the combustion process in a modern diesel engine an engine test bench was used. On that test bench the engine is coupled to a hydraulic engine brake which is manually controlled. An advanced engine management system was used in order to control the injection process as well as for data monitoring. This system is based on National Instruments real-time controller while the software is developed in LabVIEW. The combustion process was studied by means of in-cylinder pressure measurement. A piezo quartz pressure sensor was installed in the engine cylinder head. The indicated pressure was measured and registered by means of AVL indicating system. The scheme of the test facility is presented in Fig. 1.

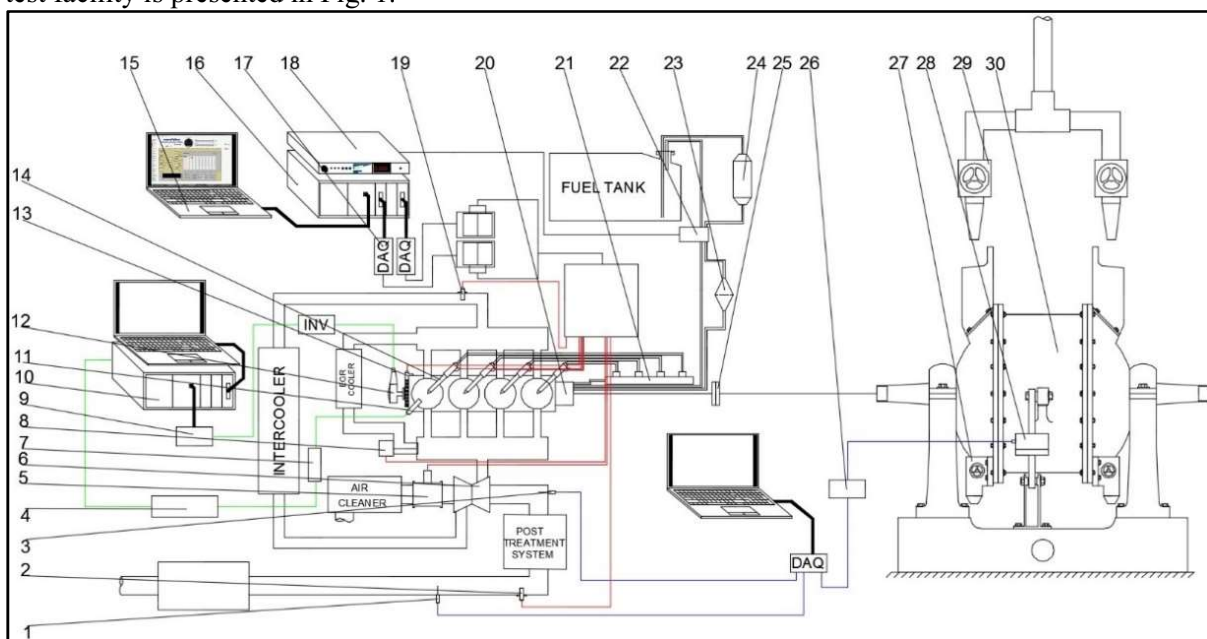


Figure 1. Engine test-bench schematic diagram

2.1. Studied engine

The engine under study is a direct injection diesel engine with displacement of 1998 cm³. This engine is equipped with a Common-Rail system for direct injection of the fuel in the cylinder, turbocharging system, exhaust gas recirculation system (EGR), catalytic converter and etc. The rated engine power is 101 kW at 4000 min⁻¹ and the maximum torque is 320 Nm at 2000 min⁻¹. The engine is equipped with a variable geometry turbocharger. The boost pressure is limited to 1.3 bar. The Common rail system of the engine is developed by Delphi. The maximum injection pressure is limited to 1600 bar. The main parameters of the engine are shown in Table 1.

Table 1. Engine main parameters

Engine type	HDI
Number of cylinders	4
Displacement	1998 cm ³
Bore	85 mm
Stroke	88 mm
Compression ratio	17,6
Valves per cylinder	4

2.2. Engine management system

The engine management system is based on National Instruments real-time controller. The hardware of the system consists of: PXI chassis - NI PXI-1031, Real-Time Embedded Controller - NI PXI-8106 RT, FPGA module - NI PXI-7813R, two R Series Expansion Chassis - NI CRIO 9151 as well as the modules developed by Drivven. In our project we used four modules: DI Driver – 2pcs, Low Side, AD Combo and O₂ sensor module. All of these modules are based on NI C series interface.

The entire system provides very large functionality for real-time control and monitoring of the engine control parameters such as: injection process control with up to five separate injections per cycle, injection pressure control, boost pressure control, exhaust gas recirculation (EGR) control, closed-loop control of injection by means of wide band oxygen sensor in exhaust gases and etc.

A LabVIEW project was developed in order to determine the control logic of the management system. The real-time data was visualized by means of the software CalVIEW developed by Drivven. The front panel of the software is presented in Fig. 2. This software was also used to set the operating parameters in real-time.



Figure 2. Engine management system with front panel of the control software

2.3. Cylinder pressure measurement

The measurement line consists of: In-cylinder pressure sensor AVL GH13P, Angle encoder AVL 364C, In-line converter PCB Piezotronics 422F01, Signal conditioner PCB Piezotronics F482B05 and indicating instrumentation AVL Indiskop 647. The pressure sensor is used in combination with a glow-plug adaptor AG04 a nearly flush mounted solution for diesel engines. It allows measurements without pipe oscillations. The measuring range of the sensor is up to 250 bar. In the measurement line an in-line converter and a signal conditioner were used. It provides signal converting to voltage without changing the signal level (converting 1pC to 1mV). The indicating system AVL Indiskop 647 was equipped with a two channel voltage amplifier 3065-A01.

3. Simulating model

In order to study the combustion process and to determine the ROHR a simulating model of the engine was developed by means of advanced software AVL BOOST. The block diagram of the model is shown in Fig. 3. It is a combination between 0D and 1D physical models developed for each specific element in the program. Our model consists of following elements: cylinders, plenums, pipes, air cooler, turbocharger, boundaries and the main engine element (E1).

Into the element called “cylinder” were defined geometrical parameters as well as the combustion model, heat transfer model and valve train mechanism by valve port specification, lift curve, flow coefficients and etc. The mathematical background is based on the first thermodynamics law applied to open control volume. The same 0D mathematical model is used in the plenums. AVL BOOST offers several approaches to modelling the turbocharger. In our case a simplified model was used that needs of target compressor and turbine pressure ratio as well as the constant isentropic and mechanical

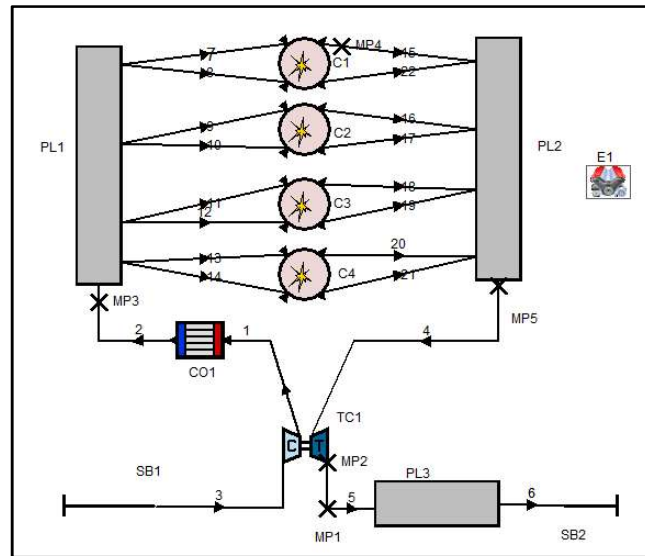


Figure 3. Engine simulating model in AVL BOOST

efficiency. The „Pipe” element connects the other elements of this model and represents the pipes of the manifolds. For each pipe were defined geometrical parameters such as the length and diameter. Also the friction coefficient and heat transfer coefficient between the wall and fluid were defined. A 1D model (Euler equation system) is used in order to define the fluid parameters along the pipe lines. The simulating conditions, friction losses and engine operating parameters were defined in the main “Engine” element.

In our study the simulating model was used in order to define the ROHR based on the experimental pressure curves. In this case a combustion model called “Target pressure curve” was chosen. Thus, the pressure curve was an input parameter in this study. Then, the ROHR was approximated by means of double Vibe function for each operating point. In order to assess this approach, estimated pressure curves were compared to these obtained experimentally.

The double Vibe function is defined as a sum of two simple Vibe functions in a correlation as follows:

$$\frac{dX}{d\varphi} = a_1 \cdot \frac{6,9}{\varphi_{z1}} \cdot \left(\frac{\varphi_1}{\varphi_{z1}}\right)^{m_1} \cdot (m_1 + 1) e^{(-6,9 \cdot \frac{\varphi_1}{\varphi_{z1}})^{(m_1+1)}} + a_2 \cdot \frac{6,9}{\varphi_{z2}} \cdot \left(\frac{\varphi_2}{\varphi_{z2}}\right)^{m_2} \cdot (m_2 + 1) e^{(-6,9 \cdot \frac{\varphi_2}{\varphi_{z2}})^{(m_2+1)}}$$

where:

$$a_1 + a_2 = 1$$

4. Results and discussion

4.1. Experimental results

The experimental study was carried-out over the engine operating range from 1400 min⁻¹ to 2400 min⁻¹, by an interval of 200 min⁻¹, and the engine load varies from idle to full load. This study was limited to that operating points due to the fact that the hydraulic brake is manually controlled which does not allow to keep the constant engine speed over 2400 min⁻¹. The results concerning the in-cylinder pressure variation are presented in Fig. 4. The maximum measured pressure at this engine speed of 1400 min⁻¹ is 130.8 bar at BMEP of 15.2 bar. This value was measured at an angle position of the crankshaft 13 °CA after TDC. At engine speed of 1800 min⁻¹, the pressure reaches a maximum value of 168.9 bar at BMEP of 19.5 bar. This value is measured at an angle position of the crankshaft 11 °CA after TDC. At engine

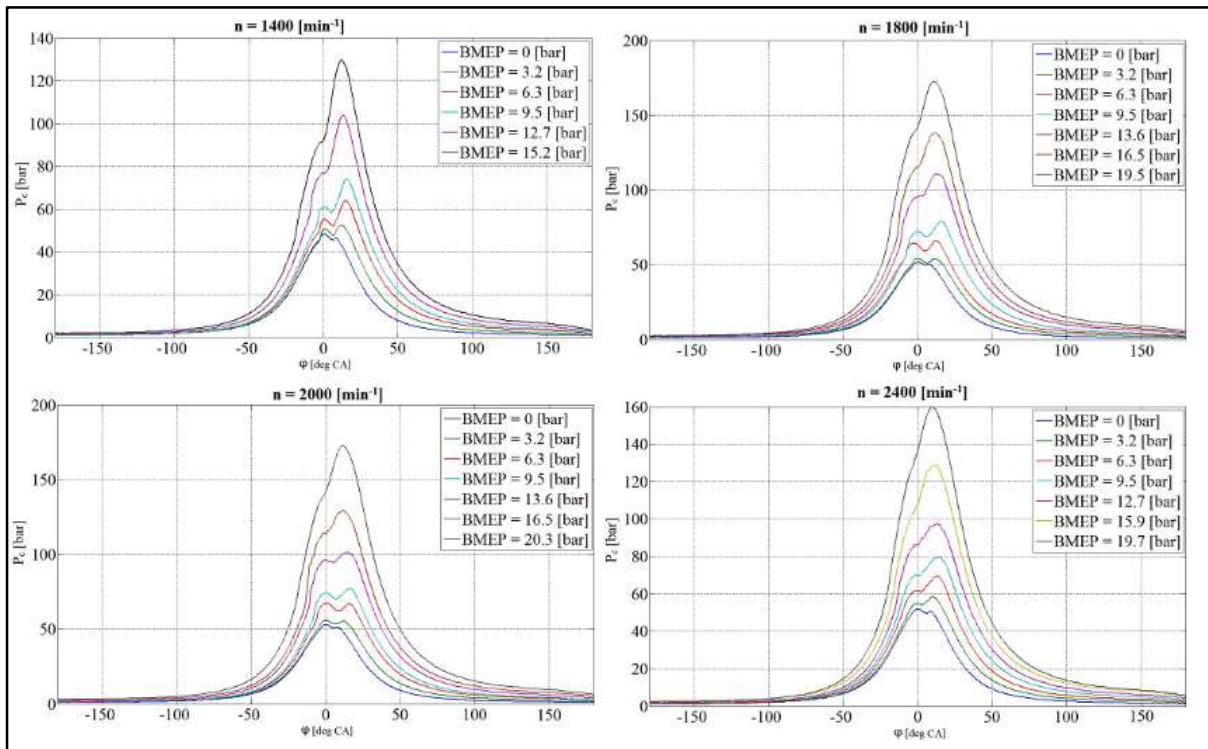


Figure 4. In-cylinder pressure measured experimentally

speed of 2000 min^{-1} , the maximum cylinder pressure is 172.5 bar, this value is measured at an angle position of the crankshaft 11 °CA after TDC. At engine speed of 2400 min^{-1} , the pressure reaches a maximum value of 159.9 bar at BMEP of 19.7 bar. This value is measured at an angle position of the

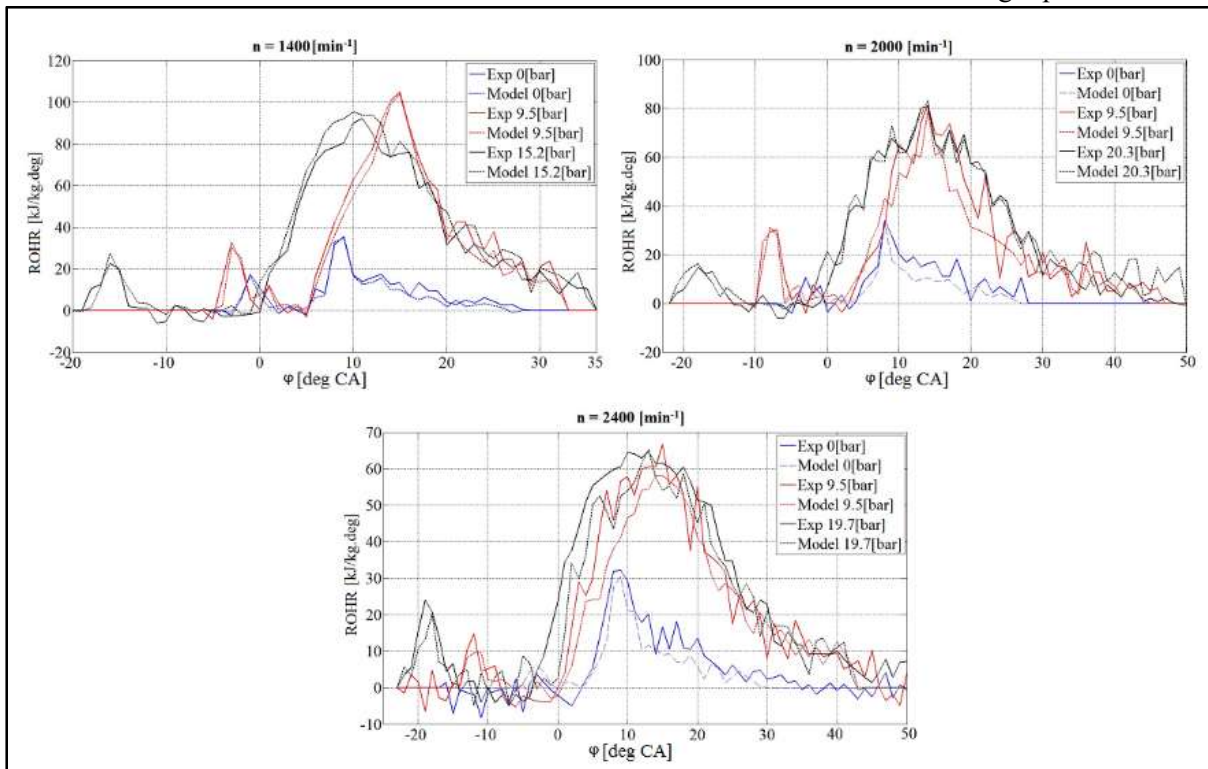


Figure 5. Rate of heat release

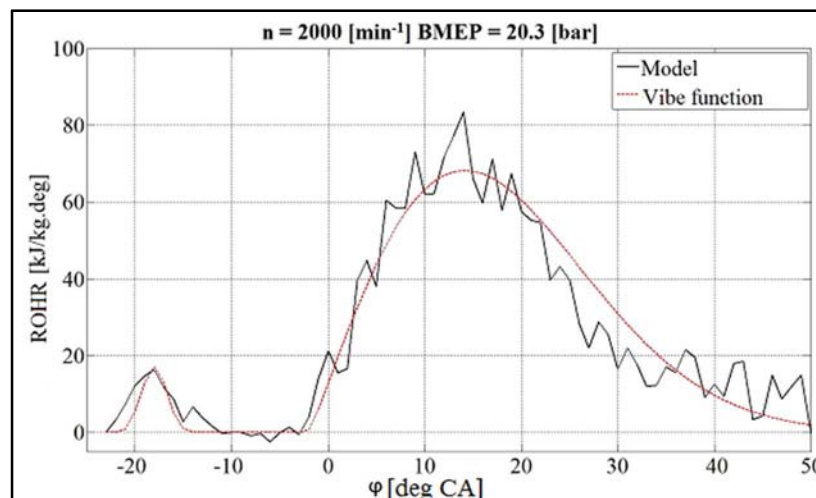


Figure 6. Approximated ROHR by double Vibe function

crankshaft 10 °CA after TDC. At all studied operating points the pilot injection strategy is applied. Thus, it was observed slightly increased in-cylinder pressure before TDC due to the pre-injected fuel which causes higher pressure value at TDC than compression pressure. The results revealed that the maximum in-cylinder pressure occurs at the operating point corresponding to the maximum engine torque at 2000 min⁻¹. By increasing the engine speed over 2000 min⁻¹ the maximum pressure slightly decreases.

4.2. Rate of heat release

The ROHR was estimated both by indicating instrument AVL Indiskop 647 and simulating model using the measured pressure curves and combustion algorithm “Target pressure curve”. The results for engine speed of 1400, 2000 and 2400 min⁻¹ are presented in Fig. 5. It was observed small deviation between curves estimated by both methods for all operating points. Dash line presented the results estimated by the engine model while the solid line was used in order to present the value estimated by Indiscop 647.

The results presented in Fig. 5 revealed that pilot injection strategy reduces the maximum value of the ROHR during the premixed combustion period. For each operating point we found two peaks at the ROHR. The first one is in result of the pilot injection while the second function is due to the main injection. There was not found an overlap between the peaks. It was observed slightly increasing ROHR after the start of main combustion without extremely high value due to the relatively small ignition delay period. The higher values for the ROHR were observed at low engine speed due to the lower mixing rate. The maximum value of 102 kJ/kg.deg is observed at BMEP of 9.5 bar. At full engine load the maximum of the ROHR is lower as it accounts to 94 kJ/kg.deg. At 2000 min⁻¹ maximum value of ROHR as a result of the main injection was 90 kJ/kg.deg at 17 °CA after TDC.

4.3. ROHR approximation by double Vibe function

Due to the fact that the ROHR in diesel engine combustion simulation is easy to be defined by Vibe function or double Vibe function than real ROHR estimated by means of pressure curve we approximated the real ROHR by double Vibe function. It was done for each of studied engine operating points by defining the Vibe function parameters: shape parameter (m_1 and m_2), combustion duration (φ_{z1} and φ_{z2}) and the start of combustion. On the basis of obtained parameters as well as the combustion and mixing phenomena we defined the Vibe function parameters at whole engine operating range. Thus, we can study numerically the engine performances as well as the pollutant formation by means of our simulating model. Fig. 6 shows both ROHR estimated on the bases of pressure curve and approximated by double Vibe function. It concerns engine operating point at 2000 min⁻¹ and full load (engine maximum torque). In order to validate the engine simulation model, we compared the experimentally

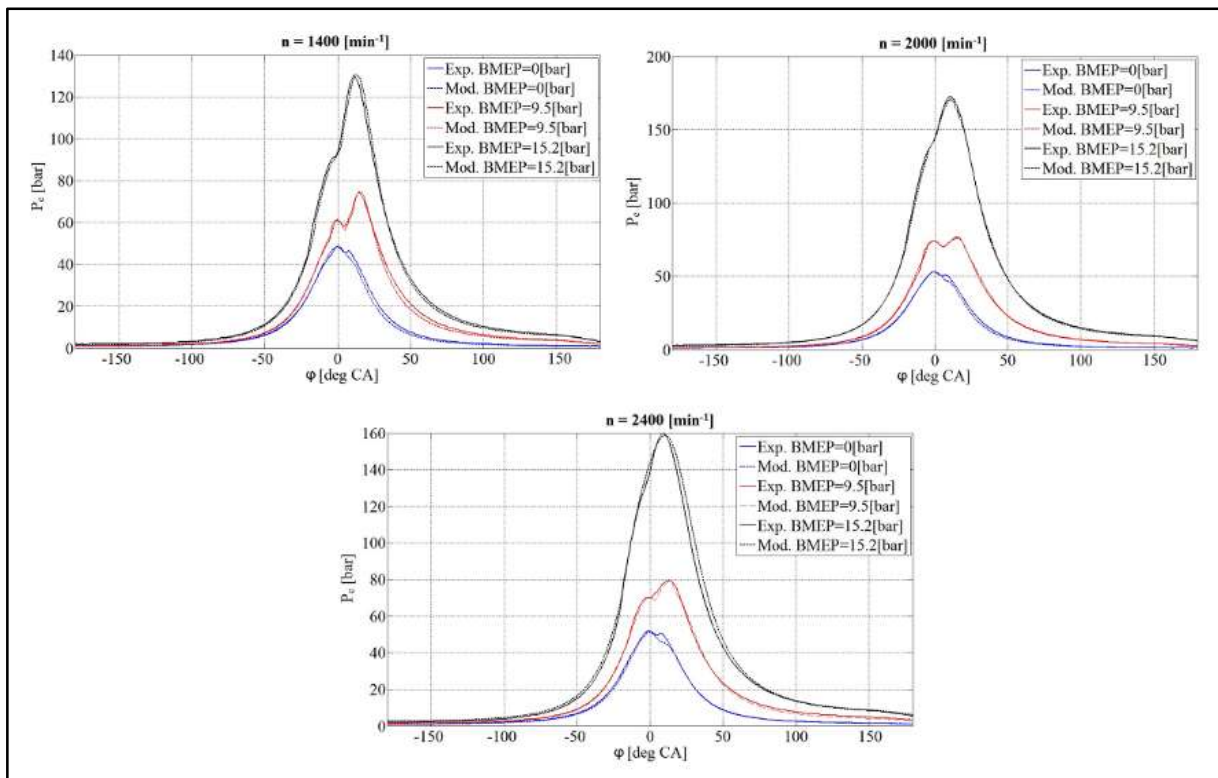


Figure 7. In-cylinder pressure model validation

measured cylinder pressure and those calculated by the model using the rate of heat release calculated by double Vibe function. The results are presented in Fig. 7. At 1400 min⁻¹ we observed maximum

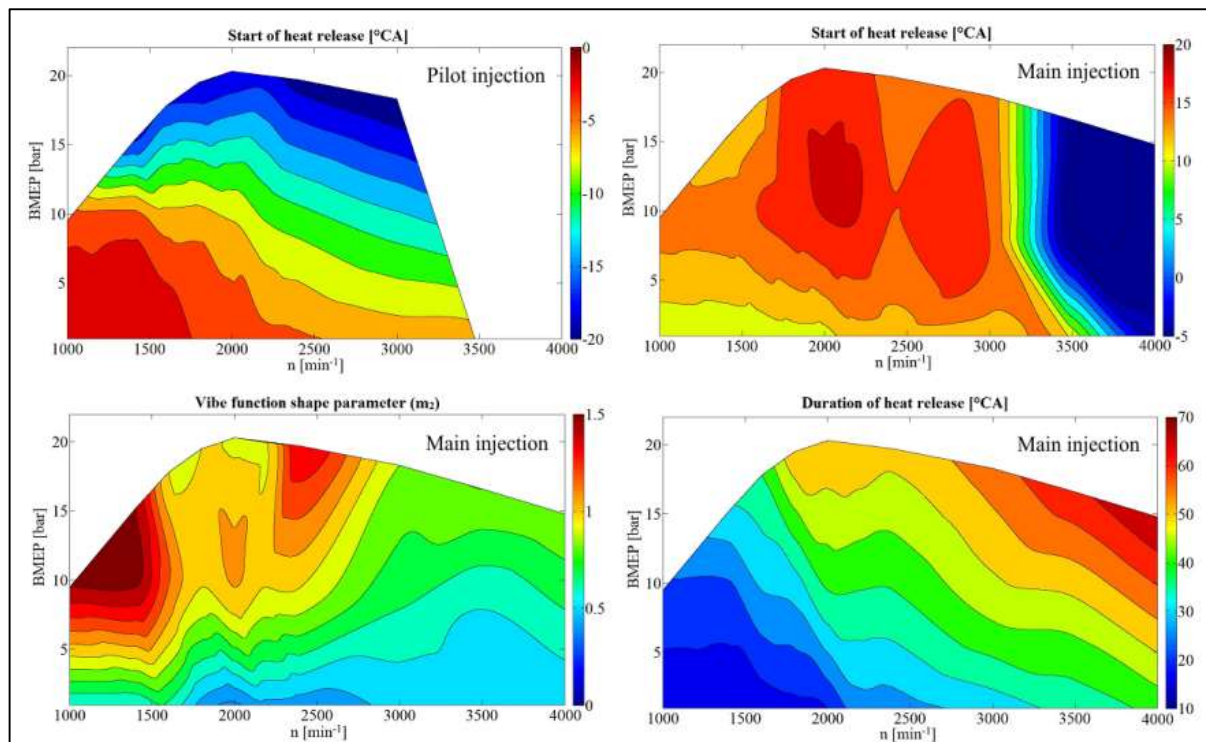


Figure 8. Parameters of the Vibe function

deviation between experimental and simulated values of 7 %. In absolute value it accounts to 3.25 bar at idle. At full load the maximum deviation was 6.3 %. At 2000 min⁻¹ the maximum deviation of 7.4 % was estimated at idle. At other operating points the deviation is lower than 1.9%. At 2400 min⁻¹ it was found the deviation of 9.1 % concerning operating point at idle and 8.9 % at full load.

The parameters of the Vibe function in the engine operating range outside the experimental range from 1400 min⁻¹ to 2400 min⁻¹ were determined as it was followed the trend of parameters variation taking into consideration the injection parameters and operating conditions as well. However, the engine operates with not pre-injection in the operating range above 3500 min⁻¹, thus a single Vibe function is used. In the zone without pilot injection, the Vibe function parameters were determined based on commonly used values adapted to direct injection diesel engines. Over the non-experimentally studied operating range, the validation of the model was carried-out by means of the maximum value of in-cylinder pressure. Therefore, the Vibe function parameters were determined over the engine operating range and the values are presented in Fig. 8. The meaning of colour fields is presented at the top of each diagram. Vibe shape parameter and duration concerning the pilot injection are not presented here due to the fact that the values are relatively constant over the whole operating range. The shape parameters were constantly equal to 2.5 and the duration ranged from 4 to 6 °CA.

5. Conclusions

A comprehensive analysis of the combustion process in a modern direct injection diesel engine is presented in this study. In order to study the ROHR an experimental test was conducted as the in-cylinder pressure was measured. Then, the ROHR was approximated by means of engine simulating model developed in advanced simulation product AVL BOOST. A double Vibe function was used in order to approximate the ROHR over the engine operating range when the pre-injection strategy is applied. Outside this area, a single Vibe function was used. The Vibe function parameters was determined and verified on the bases of estimated ROHR within the operating range from 1400 min⁻¹ to 2400 min⁻¹. However, the Vibe parameters over 2400 min⁻¹ was also determined follows the function variation trends and the injection parameters. The engine simulation model using double Vibe function was verified as the simulated in-cylinder pressure was compared to the measurement values. The maximum deviation was found to be 9.1 %. The results revealed that the Vibe shape parameters concerning the main injection varies from 0.6 to 1.5 over the engine map while the combustion duration of the main injection varies from 30 °CA to 70 °CA.

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