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THE INFLUENCE OF COMMON-RAIL ADJUSTMENT ON THE PARAMETERS OF A DIESEL TRACTOR ENGINE

Lukáš Tunka[1], Adam Polcar[1]

[1] Department of Technology and Automobile Transport, Faculty of AgriSciences, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic

Abstract

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The article deals with the issue of high-pressure indication of a diesel tractor engine Z 1727, which was fitted with a modern electronically controlled common-rail injection system. The aim of the study is to evaluate the influence of the adjustment of the fuel system – start of injection (SOI) timings and the rail pressure (PRAIL) – on the pressure development in the cylinder (PCYL), the heat release (HR) and the combustion noise level (CNLA). Furthermore, the article examines the influence of pilot and post fuel injections on the CNLA. The experiments were conducted at constant speed (1480 rpm) with four PRAILs and different SOI timings. As the results of measurements have shown, higher rail pressure causes higher pressure and a release of a larger amount of heat in the cylinder. These two parameters are the basic prerequisite for higher engine efficiency – higher power output of the engine at lower fuel consumption and decreased production of harmful emissions. Other advantages of the common-rail fuel system include the potential of dividing the main injection dose into the pilot injection and main injection, as well as the potential post injection. The measurements have further demonstrated that including a pilot injection phase significantly contributes to a decrease in combustion noise level as well as a more even, quieter operation of the engine.

Keywords: cylinder pressure, start of injection timings, rail pressure, combustion noise level, heat release

INTRODUCTION

Every tractor manufacturer who wants to be successful on the European market must make use of engines with a modern, electronically controlled injection system. Tractor engines are being subjected to ever increasing demands, which the manufacturers must fulfil so that their tractors are competitive and can at the same time fulfil all the requirements of homologation tests. From a legislative standpoint, these requirements concern mainly the emission of gas pollutants, pollutant particles in exhaust gasses as well as so called mechanical pollutants, such as noise and vibrations. The customer demands above all low fuel consumption, since it is the only component of agricultural equipment whose financial costs of operation can be decreased. That is, of course, while also maintaining the best possible engine parameters, the highest possible lifetime period, reliability, low maintenance requirements and preferably also lowest possible price (Bauer *et al.*, 2013). The above requirements are today only achievable with an engine fitted with a common-rail injection system. This system enables communication between the control unit responsible for the preparation of the fuel mixture and other control units (transmission mechanism, chassis or connected machinery etc.) via a digital CAN bus. This modern solution allows a decrease in fuel consumption, heat stress, power dissipation, wear and, above all, the negative effects of engine operation on the environment (Bauer *et al.*, 2013; Vlk, 2003).

Research, development and optimization of modern combustion engines is not possible without detailed knowledge of the processes inside the engine cylinder. The measurement and analysis of pressure development in the cylinder is the only source of data required for the optimization of efficiency, power output of the engine, fuel consumption, emissions, combustion noise level and, last but not least, the lifetime period of the engine. Reciprocating combustion engines are heat engines, in which a transformation takes place via combustion with air from chemical energy contained in the fuel to heat energy and mechanical work of a crank mechanism (Macek, 2007). Manufacturers thus strive for the most efficient conversion of energy possible, and thus also increasing the mechanical work, which in turn increases the efficiency of the engine. Therefore, the aim is to bring the fuel along with air into the combustion chamber at the right moment, in the required state and in the proper amount (Beroun, 2013). The fuel system of the diesel engine also has a marked influence on this process. The regulation of fuel supply must be accurate, simple and smooth and must correspond with the desired course of the engine torque. Today, tractors use engines with internal mixture creation, i.e. direct fuel injection, where the combustion area lies directly in the piston. The fuel must be perfectly dispersed in the combustion area, which is achieved by high injection pressures and several independent injections, which places high demands on the injection mechanism (Bauer *et al*., 2013). This benefits significantly from the modern, electronically controlled injection system with pressure reservoir. The functionality and capabilities of the fuel system thus determines the course of the combustion in the engine cylinder and thus also the engine parameters reached (Beroun, 2013).

The course of the combustion in the cylinder can be determined based on the changes of the status of the cylinder filling. The combustion of the mixture, and the subsequent heat supply, results in a change in pressure, which can be measured with the required accuracy. The measured quantity is thus the pressure of the filling in the cylinder based on the angle of the crankshaft. Measurement of the rotation angle of the crankshaft is converted to the immediate value of the combustion chamber volume. This data then allows the calculation of the temperature in the cycle, the amount of heat released, work and other information (Blažek, 2012). Measurement and thermodynamic analysis of the pressure course in the cylinder provide the data required for the optimization of engine parameters (Beroun, 2013; Pistek and Stetina, 1991).

The article deals with the issue of high-pressure indication of a diesel tractor engine which was fitted with a modern electronically controlled common-rail injection system. The aim of the study is to evaluate the influence of the adjustment of the fuel system (SOI timings and rail pressure) on the pressure development in the cylinder (PCYL), the heat release (HR) and the combustion noise level (CNLA). Furthermore, the article examines the influence of pilot and post fuel injection on the CNLA.

MATERIALS AND METHODS

The Zetor Tractors company fits models of the Forterra and Proxima series with its own engines, which use the traditional injection system, which, from today's perspective, can be almost viewed as historical – inline fuel injection pump with mechanical regulation of fuel dosage. A certain degree of innovation was introduced to this injection system in 2014, when the mechanical regulator was replaced with an electromagnetic one. This was done primarily for the purposes of meeting the stringent emission standards Stage IV or Tier 4f, which demand an injection of an urea solution (AdBlue) into the exhaust tract to reduce the amount of problematic nitrogen oxides in the emissions. At the same time, the nominal engine power increased from 95 kW to 103 kW. Further modernization of the engine has proven to be inevitable due to the reasons described in the introductory chapter. Research has been carried out on a diesel tractor engine Zetor innovated with an electronically controlled common rail injection system. The engine is designed for the above mentioned model series, since others are fitted with engines purchased from Deutz.

The measurement was performed at the workplace of Research and Development of Zetor Tractors company. The engine is fitted with direct fuel injection. The combustion chamber is undivided and is formed directly in the piston. The engine is not equipped with any device for reducing

I: *Selected parameters of measured engine (manufacturer's data)*

Manufacturer	Zetor
Type	Z 1727
Nominal power [kW/HP] – ECE 24 R 03	103/140
Fuel system	common-rail injection
Injector	solenoid
Discharging of the engine	turbocharger with intercooler
Intercooling	air/air
Number of cylinders (disposition)	4 (inline engine)
Number of valves	16
Volume [cm^3]	4,156
Nominal engine revolutions [rpm]	2,200
Idle [rpm]	800
Compression ratio	17
Fuel	diesel
Maximum torque [Nm]	585
Cooling	fluid

the content of harmful substances in exhaust gasses. Other selected engine parameters are listed in Tab. I.

Measurement Chain

- Diesel tractor engine – mounted on a test bench and connected to a dynamometer;
- Electromagnetic eddy current dynamometer (see Tab. II);
- PC with software ETAS INCA V7.1 for calibration, diagnostics, and validation of automotive electronic systems;
- Current probe Fluke 80i-110s AC/DC (100A) – measures injection pulses of fuel injector and it is connected to KiBox;
- Kistler devices for engine combustion analysis:
  - Piezoelectric cylinder pressure sensor 6056A – mounted in glow plug adapter 6542Q, which is mounted in cylinder head instead of glow plug. Sensor is connected to KiBox;
  - Crank angle adapter set 2619A – connected to inductive sensor on a crankshaft and also to KiBox;
  - System for combustion analysis KiBox® To Go 2893AK1;
  - PC with Kistler software KiBoxCockpit – connected to KiBox via ethernet.

II: *Technical parameters of the dynamometer used*

Manufacturer	Carl Schenck AG
Type	Schenck W230
Maximum power	$P_{max.} = 230$ kW
Maximum torque	$M_{tmax.} = 750$ Nm
Maximum revolutions	$n_{max.} = 5{,}000$ rpm
Dynamometer regulator	MEZSERVIS Vsetín 230VDR6990
Tensile force sensor	HOTTINGER U2 – 200 kg

The measurement methodology is not set by any standard or other regulation, since measuring was performed in the first testing week of a brand new engine. The first cylinder was indicated and only the main fuel injection was turned on. Before testing itself, the engine had to be warmed up to the operating temperature. During measurement, the engine was set to constant revolutions and torque (static mode). The rpm level was chosen so that an economical mode is reached, resulting in lower fuel consumption. The torque represents the engine load, with the chosen value corresponding to one half of the maximum load. Under these conditions, changes were made to the rail pressure and the SOI timings due to the piston top dead centre (TDC), as stated in Tab. III. The authors used abbreviations BTDC and ATDC, which means before, respectively after TDC.

The SOI timings and the rail pressure were changed using INCA software for engine adjustment, which allows the sending of signals directly into the electronic control unit. This methodology was used to measure the influence of the two above mentioned variables on the development of the cylinder pressure, the amount of heat release and the combustion noise level. In connection with CNLA, additional test measurement was performed with the goal to determine the effect of pilot and post fuel injection on the noise level of the combustion process. When measuring, first only the main fuel injection was active, gradually joined by the pilot and then the post fuel injection, with the studied quantity being the pressure development in the cylinder; the value is then used to determine the acoustic pressure level. The dependent variable is thus this quantity, while the independent variable is the number of cycles. The data was recorded for 100 cycles. The measurement was performed at the same engine speed (rpm), but with torque 200 Nm, PRAIL 1,100 bar and SOI 6°BTDC. The combustion noise level is measured as acoustic pressure level and corrected by an A-weighting filter according to the sensitivity of the human ear. The resulting unit is thus a decibel weighted by an A-type filter [dB(A)] (Smetana, 1998). The calculation is performed according to the relation:

III: *Input measurement values*

Engine speed [rpm]	1,480
Engine load (torque) [Nm]	295
Rail pressure [bar]	900; 1,100; 1,300; 1,500
SOI timings due to the TDC [°CA]	−18, −16, −14, −12, −10, −8, −6, −4, −2, 0, 2

$$L_p = 20 \cdot \log \frac{p}{p_0} \text{ [dB]}, \tag{1}$$

where p is the effective value of the acoustic pressure (PCYL) [Pa] and p_0 is the reference value of acoustic pressure (for air, $p_0 = 2.10^{-5}$ Pa).

The indicator kit is equipped with a fully automated system of data collection which recorded an aggregate from 200 work cycles, with each work cycle being thermodynamically analysed, determining the basic combustion parameters and work process parameters. The aggregate thus allows for simple acquisition of the median values listed in this article. The thermodynamic calculation of the heat released is based on the first law of thermodynamics. The calculation works on the basis that the heat released in the cycle equals heat brought by the fuel reduced by the heat conducted into the walls of the cylinder. This allows a simplified calculation in real time. The calculation of the heat released operates in the range of 30°BTDC to 90°ATDC. After adjustments, we reach the following:

$$\frac{dQ}{d\alpha} = \frac{1}{\kappa - 1} \cdot \left[\kappa \cdot p \cdot \frac{dV}{d\alpha} + V \cdot \frac{dp}{d\alpha} \right] \text{ [J/°CA]}. \tag{2}$$

The data logger and software by Kistler company calculates the heat released in the evaluated element of volume change (calculation step) by the relation:

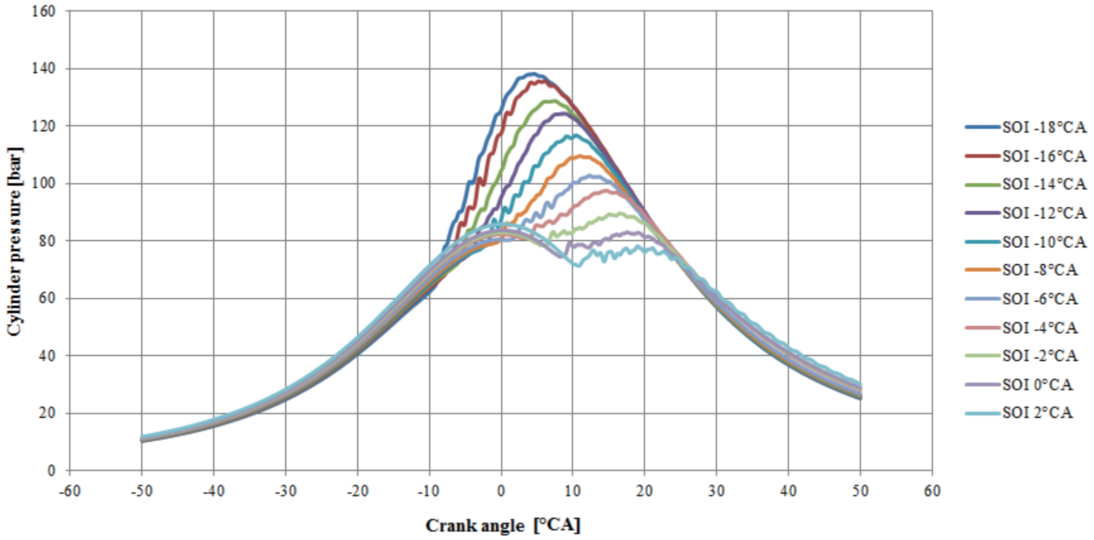
$$Q_i = \frac{\text{konst.}}{\kappa - 1} \cdot \left[\kappa \cdot p_i \cdot (V_{i+n} - V_{i-n}) + V_i \cdot (p_{i+n} - p_{i-n})\right] \text{ [J]}, \quad (3)$$

where
Q ... heat released in the cycle [J],
V.... immediate volume above the piston [m³],
p .... absolute pressure in the cylinder [bar],
α .... crank angle due to the TDC [°CA],
κ .... coefficient (depends on the specific heat capacity at constant volume c_V) [-],
i ..... position of the evaluated element of volume change [°CA],
n .... size of the element of volume change (calculation step – 10°CA).

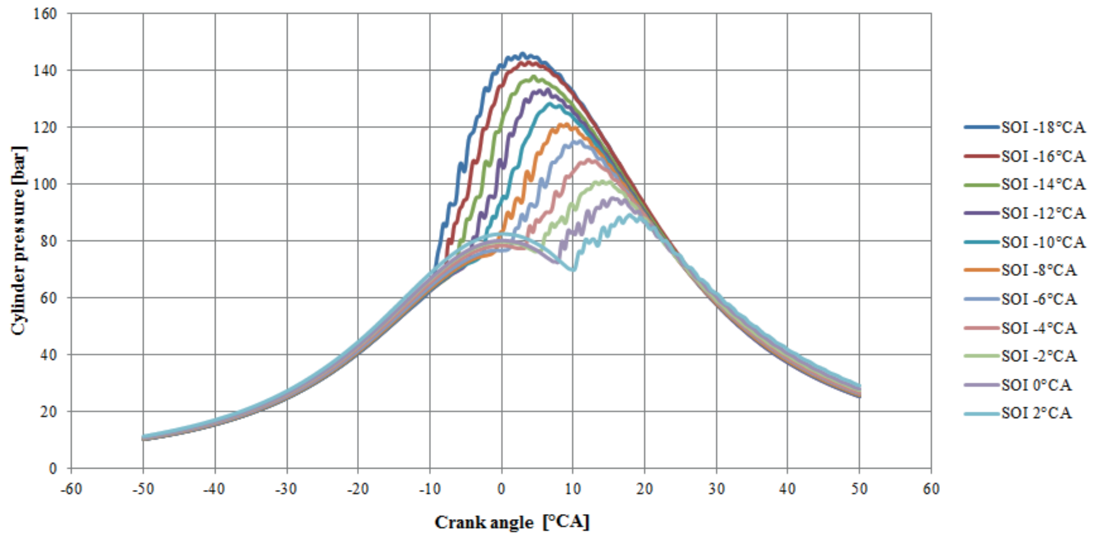
RESULTS AND DISCUSSION

The first evaluated dependency was the influence of the setting of the fuel system on the pressure development in the cylinder, since this is the most important parameter of thermodynamic engine analysis. The results of measurement are presented for SOI timings, but only for the lowest and highest values of rail pressure (900 and 1,500 bar) to better demonstrate the difference. The graphical dependencies are shown in Figs. 1 and 2.

In terms of optimal operation of the engine, the maximum pressure in the cylinder should be reached between 6–10°ATDC (Bauer, 2013). Fig. 1 shows that injection of fuel close to the TDC results in the compression pressure being higher than the expansion pressure, since the chemical energy contained in the fuel is not being optimally used for mechanical work. When SOI was retarded and it



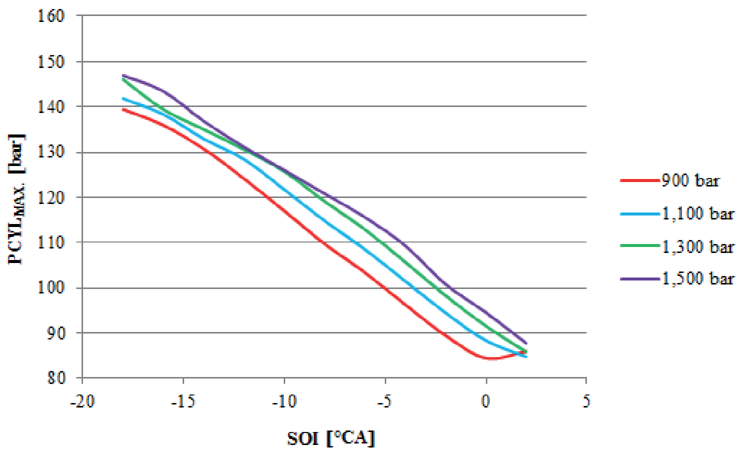
1: *Development of cylinder pressure at rail pressure 900 bar*



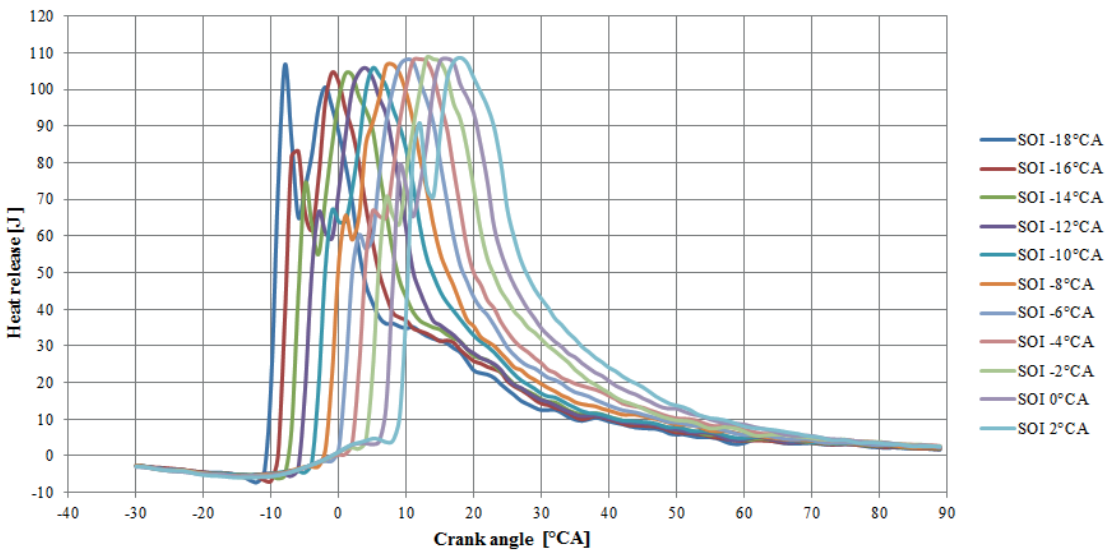
2: *Development of cylinder pressure at rail pressure 1,500 bar* came closer to TDC in compression stroke, ignition delay became shorter, which led to higher fuel fraction burning in diffusion combustion thereby lowering maximum cylinder pressure. Avinash Kumar Agarwal *et al.* (2013) published similar measurement, but with different values of constant engine speed, injection pressures and SOI timings. However the development of cylinder pressure for various SOI timings is quite similar. Expansion occurs only after TDC, which leads to a decrease in engine effectiveness, since the heat released quickly exits through the exhaust. Therefore, both engine effectiveness loss and exhaust temperature increase. The above graphical dependencies also show that higher rail pressures causes higher increase in pressure in the cylinder, since the fuel is dispersed better, creating a less heterogeneous mixture. Increasing the rail pressure causes better fuel atomization, which improves the combustion process and results in higher engine efficiency (Mohan *et al.*, 2013). This fact is also confirmed by Fig. 3, which captures the dependency of all SOI timings and rail pressures (see Tab. III) on the maximum pressure in the cylinder.

Figs. 4 and 5 display the amount of heat release (HR) depending on the crank angle. As mentioned above, HR was calculated based on equation (3). The results of measurements are again listed for all SOI timings, but also only for the lowest and highest values of rail pressure (900 and 1,500 bar).

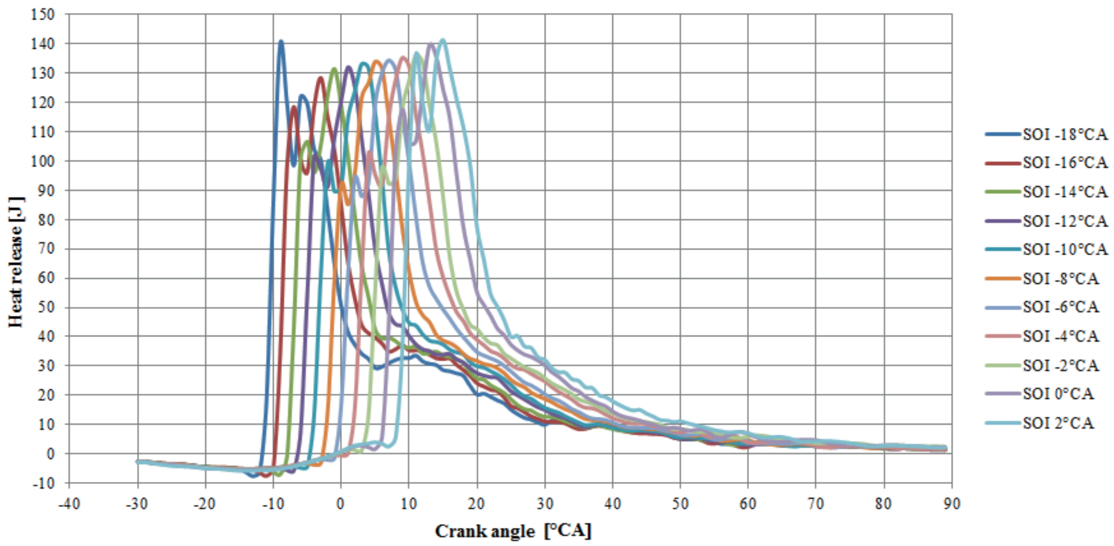
When analysing these dependencies (Figs. 4 and 5), it is necessary to note that the HR is calculated from pressure in the cylinder and volume. The influence of rail pressure was evident on a number of parameters. Firstly, there is an apparent increase in heat released. Increasing the rail pressure by 600 bar resulted in an approximate increase in heat released by 30 J/°CA. The dependency of PRAIL on HR was studied, among others, by Kyunghyun (2013) who reached comparable conclusions to the



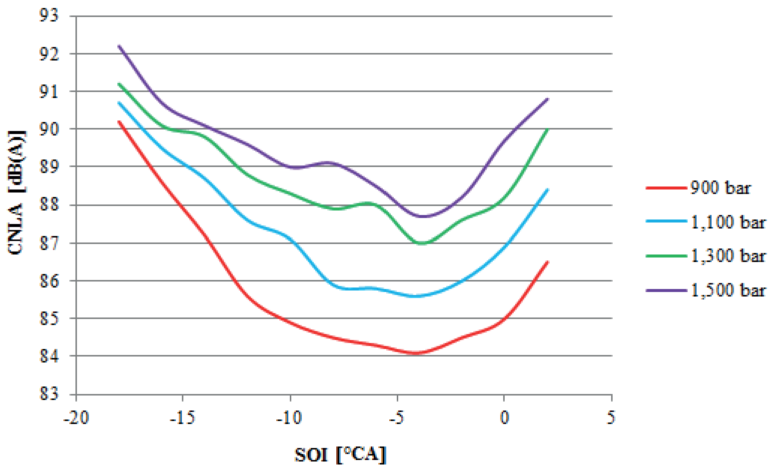
3: *The dependency of rail pressure and SOI timings on maximal cylinder pressure*



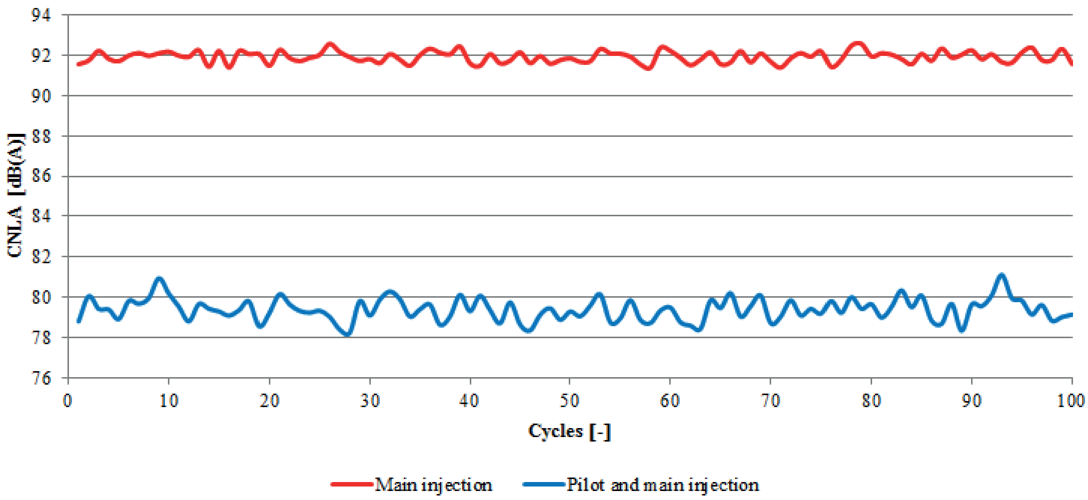
4: *The dependency of start of injection timings at rail pressure 900 bar on heat release*



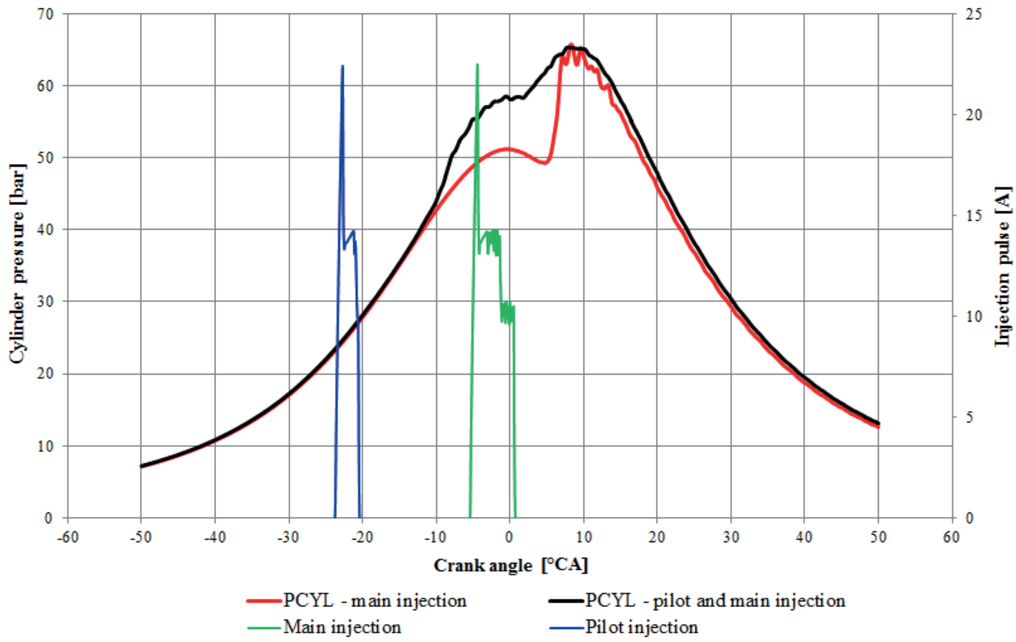
5: *The dependency of start of injection timings at rail pressure 1,500 bar on heat release*



6: *The dependency of rail pressure and SOI timings on combustion noise level*



7: *The influence of pilot injection on combustion noise level*



8: *Development of cylinder pressures with pilot and main injections*

ones presented by our measurements. In the second case, higher rail pressure leads to lower ignition delay.

The results of HR negatively correlated with the development of pressure in the cylinder. The higher the cylinder pressure, the lower the amount of heat release. An exception is presented by the development measured at SOI 18°BTDC, where a sharp increase in the amount of heat released occurs due to high temperature in the cylinder. The temperature in the cylinder in equation (3) is accounted for by the coefficient κ. Despite the growing HR with the shifting of SOI timing closer to the TDC, this heat cannot be transformed into mechanical work, as it exits through the exhaust. This is confirmed by the development of the cylinder pressure (Figs. 1 and 2).

The next dependency evaluated was the effect of the fuel system settings on the combustion noise level. Fig. 6 presents the graphical dependencies as measured by the methodology stated in Tab. III. All input values of SOI timings and rail pressures are included.

The rail pressure and SOI timing affect the combustion noise level (see Fig. 6). The lowest values are achieved at SOI 4°BTDC for all rail pressures. The higher the rail pressure, the higher the noise level (CNLA). This fact is related to the sharper increase of pressure in the cylinder, as shown in Figs. 1 and 2. Fig. 7 shows the effect of including a pilot fuel injection on the CNLA. Fig. 8 then presents the cylinder pressure development for main injection and for main and pilot injection, as well as courses of main and pilot injection. The measurements have demonstrated that the influence of post injection on the CNLA is negligible, which is why the dependency is not listed.

The effect of pilot fuel injection on the combustion noise level in PCCI (premixed charge compression ignition) engines was studied by Torregrosa *et al.* (2013). The authors further determined that the inclusion of pilot fuel injection is an effective tool for the reduction of combustion noise level. Fig. 7 shows that the inclusion of pilot fuel injection before the main injection leads to a decrease in combustion noise level by 12 dB(A). The reason can be seen in Fig. 8, where the pressure in the cylinder with both pilot and main injection increases gradually (black curve) when compared to pressure development with main injection only (red curve). There is also a smaller delay in ignition (evident on the drop of the red curve ATDC before the pressure increase due to expansion), as the combustion chamber is preheated by the pilot fuel injection. This fact also positively affects the lifetime period of the engine, since the crank mechanism does not have to withstand such a sharp increase in pressure. Another option of decreasing the combustion noise level and optimizing the engine parameters is the possibility of adding a second and third pilot fuel injection, which is effortlessly facilitated by the common rail system. d’Ambrosio and Ferrari (2015) published an article focused on the influence of including a secondary pilot fuel injection on the output parameters of a diesel engine. The study determined that with two pilot fuel injections before the main injection at lower engine load and revolutions, a higher mean combustion pressure is reached with lower heat release, shorter ignition delay and lower fuel consumption. Furthermore, there is a decrease in combustion noise level and pollutant content in exhaust gasses.

CONCLUSION

The measurements were aimed towards evaluating the effect of rail pressure and start of injection timings on the development of cylinder pressure and the amount of heat released. Among others, the study also assessed the influence of pilot injection on combustion noise level.

The ever stricter emission limits force the manufacturers of combustion engines to constantly develop more modern equipment in order for the engine to fulfil these criteria. One of the options, aside from catalytic systems and particle filters, is the use of high-pressure injection equipment. As the results of the measurements have shown, higher rail pressure promotes better fuel atomization in the cylinder and creates a better mixture with air. As a result, higher pressures are reached and higher amount of heat is released in the cylinder. These two parameters are the basic prerequisite for higher engine efficiency – higher power output of the engine at lower fuel consumption and decreased production of harmful emissions.

Other advantages of the common-rail fuel system include the potential of dividing the main injection dose into the pilot injection and main injection, as well as the potential post injection. The measurements have further demonstrated that including a pilot injection phase significantly contributes to a decrease in combustion noise level as well as a more even, more quiet operation of the engine.

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Contact information

Lukáš Tunka: lukas.tunka@mendelu.cz
Adam Polcar: adam.polcar@mendelu.cz