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Shaping of Injection Rate for Reducing Emission Level of High-Speed Engine

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Abstract

The key issue in modern engine development is improving emission characteristics. In this context, designing a fuel injection system which reduces emission level becomes an essential task. In this study, the effect of boot length and pressure of injection rate on NOx-soot emission of a new generation diesel engine were considered. Recommendations for injection shape control were suggested for the entire engine map.

Keywords: optimization, diesel engine combustion pressure, emission level, injection rate shape, operation modes, EGR, modeling.

INTRODUCTION

The most serious challenge of the next decade in development of modern engines is tightening of emission limits according to international standards.

There are several ways of improving NOx-particulates emission level: in-cylinder process control and exhaust gas management, specifically, exhaust gas recirculation (EGR) and/or the usage of catalytic converters. It should be noted that reduction of emissions inside the combustion chamber is preferred, due to less engine modifications [1] especially for Common Rail fuel injection systems with continuous pressure rate modulation [2].

Today in-cylinder process control by means of the fuel injection system not only increases the maximum pressure up to 400 MPa [3], but also shapes the injection rate. This fact is especially important for medium and high-speed diesel engines of locomotive and marine applications when steady-state test cycles mainly focus on high-load engine operation points and injection timing provides the shaping of the injection rate over a wide range (Figure 1).

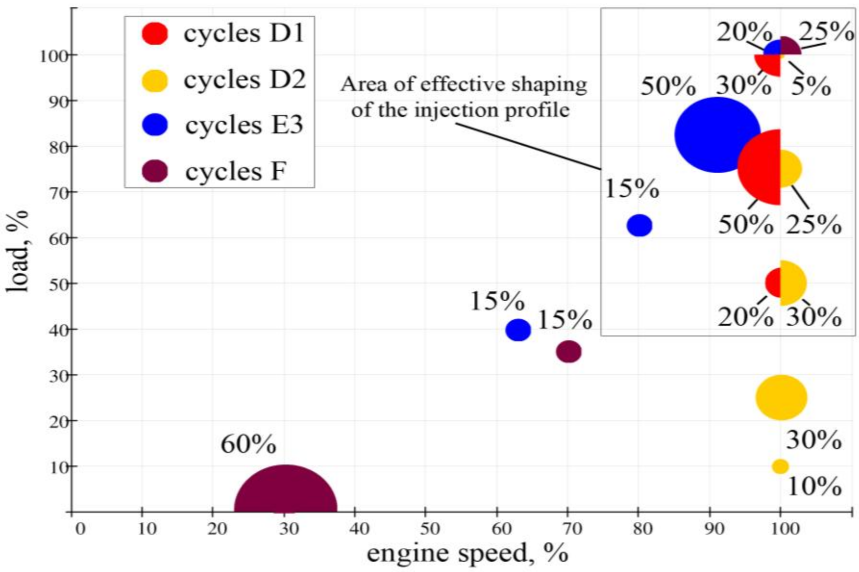
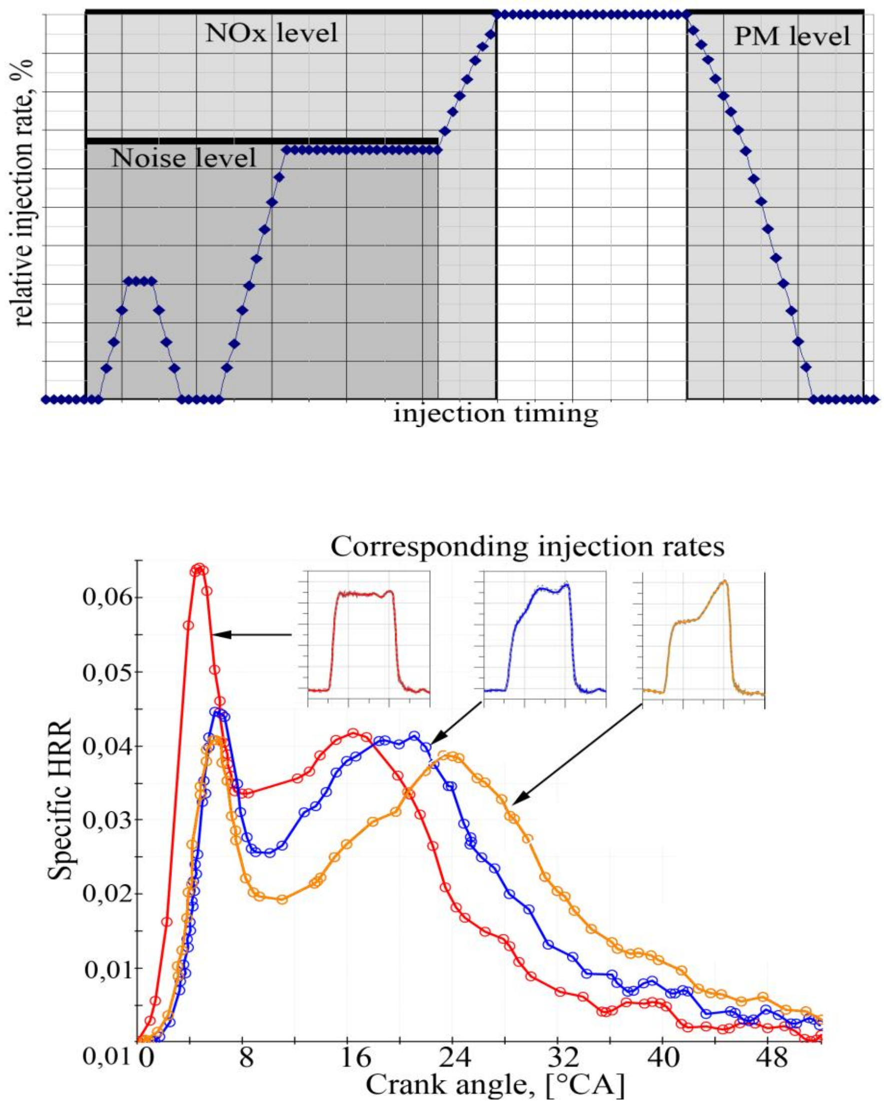


Figure 1: Test cycles : D1 – constant speed power plants, D2 – constant speed generating sets with intermittent load, E3 –marine application propeller-law heavy duty engines, F – locomotive engines, according to ISO 8178-4-2013

A lot of studies, for example [4, 5], provide general recommendations for the strategy of injection rate shaping in terms of emission regulation. At the same time, Grzeschik et al. [6] noted that the injection pressure profile also has a significant impact on combustion noise level (Figure 2 a) and slower rate of fuel injection at the beginning of the injection duration favorable for noise reduction. The results of studies [6, 7, 8] showed a coupling of heat release rate (HRR) and injection rate shapes. The continuous (boot profiles) and discontinuous (with pilot injections) injection shaping resulted in lower peak HRR during the premixed combustion phase (due to the reduction of fuel evaporated in the ignition delay period) and higher heat release rates during the diffusion controlled combustion which led to a significant reduction of NOx emissions. These statements were confirmed by the experimental work of Fink et al. [9], who investigated different injection rate shapes on a 1 VDS 18/15 single cylinder research engine (Figure 2 b).

Kuleshov et al [10, 11] also noted that the continuous injection approach is more preferable from the fuel consumption standpoint. IAV automotive engineering made the same conclusions [12] that continuous injection rate shaping avoids premature heat release before TDC and also permits a compact release of heat with phasing optimized for high thermal efficiency.



(b)

Figure 2: Fuel injection profile studies

a) recommendations for injection profile shaping [4,5,6];

b) specific heat release rate (*IMEP* 11.5 bar, 1500 rpm)[9]

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An important task is not only optimizing the combustion process for a particular mode but also identifying the optimum injection-rate shapes over the entire engine map according to international emission regulations [13]. Recommendations are mentioned in several works for injection shaping across the engine speed and load range, for example Tanabe et al. [14] conducted research for a heavy duty DI diesel engine and showed that in the high-load region a boot shape is more advantageous until the engine speed reaches the medium speed region, for higher engine speeds it is better to use square-shaped rate.

An investigation of injection rate shaping with EGR is also a significant task. Mahr [15] showed that rate shaping with EGR is less important than the injection pressure level.

OBJECT OF INVESTIGATION

In this study, the effects of injection pressure shaping are numerically investigated using the thermodynamic full-cycle engine simulation software DIESEL-RK [10] in terms of boot length and boot pressure on the combustion and emission characteristics. The thermodynamic approach with a detailed kinetic mechanism for correct prediction of NO emission, in contrast to the widely used CFD modeling doesn't require significant time and resources for a single numerical experiment and allows a wide range of engine design parameters to be taken into account.

The investigation was conducted on a new-generation turbocharged engine with a common rail fuel injection system. (Table 1).

Table 1: Specifications of the engine

Engine	direct injection, four stroke, V12, turbocharged engine
Application	Marine
Piston stroke *S*, mm	175
Cylinder bore *D*, mm	150
Compression ratio, ε	14:1
Engine speed, rpm	2100
Cylinder output , kW	120
Brake mean effective pressure BMEP, MPa	2.22
Cylinder peak pressure p_{max}, MPa	22
Injection pressure p_{inj}, MPa	200

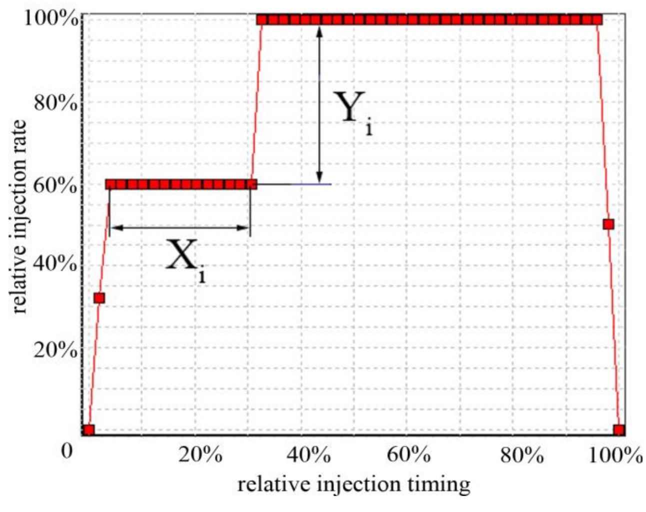
The following data were used for the engine identification process in the DIESEL-RK software:

- geometry of combustion chamber (design of a piston bowl), intake and exhaust manifolds and injector nozzle;
- material of the piston, cylinder head, average thickness of the cylinder head wall;
- exhaust and intake valve timing diagrams;
- arrays of other design and operational parameters of the engine.

Identification of the engine’s thermodynamic model was carried out based on experimental specific HRR for IMEP=1.16 MPa at 1550 rpm.

METHODOLOGY

In the simulations, the boot pressure was varied in terms of 80%, 60% and 40% of maximum injection pressure; the boot length was varied in terms of 15%, 30% and 45% of total injection duration. (Figure 3). The maximum injection pressure was constant; therefore the duration of injection was increased to inject the same fuel quantity.



Combination of relative boot length and pressure (X/Y)		
15% / 20%	30% / 20%	45% / 20%
15% / 40%	30% / 40%	45% / 40%
15% / 60%	30% / 60%	45% / 60%

Figure 3: Characteristics of injection rate profile

The field of engine design parameters includes the following values: number and diameter of the injector nozzles, the boot length and pressure of injection, EGR ratio, start of injection (SOI) timing. Simulations were carried out for modes according to ISO 8178-4 for the selected range of loads (Figure 1).

The following restrictions were used: cylinder peak pressure (p_{max}< 22 MPa), maximum injection pressure (p_{inj} = 200 MPa) and maximum rate of pressure rise ($dp/d\varphi \leq 0.65$ MPa/deg).

In accordance with the considered engine design parameters the following plan for the numerical experiment was suggested: EGR rate, number and diameter of the injector nozzles were kept constant and the start of injection (SOI) was varied from 0^0 to 25^0 CA before TDC for each injection profile. The supercharger's parameters has been selected at θsoi=15^0 bTDC for each series of experiments using existing performance maps. After that the different levels of EGR (0, 0.065 and 0.13) and different injector nozzle designs were investigated.

Full load mode (rated power 1440 kW at 2100 rpm).

The emission level was examined using a pollutant ratio diagram NOx/PM for each injection profile and different EGR rates (Figure 4). The points in the graph correspond to SOI timing: θsoi = 25^0, 20^0, 15^0, 10^0, 5^0 bTDC.

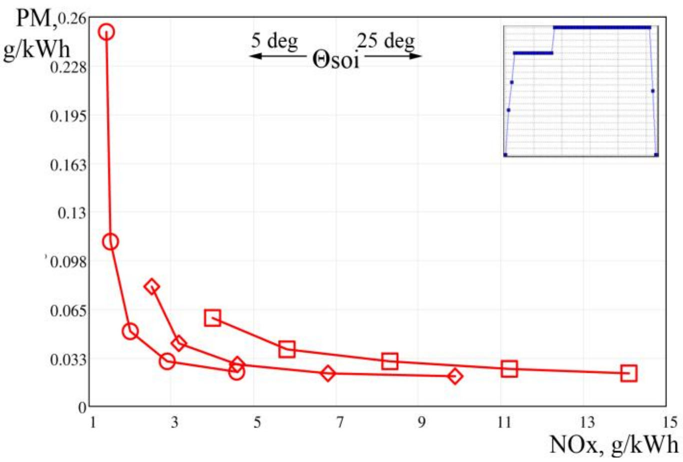


Figure 4: PM/NOx trade off for injection profile - 0.45/0.2:

- w/o EGR - EGR 6.5 % - EGR 13%

Increasing of EGR rate leads to higher level of particulates (PM) and reduction nitrogen oxides (NOx) over full range of design parameters. In addition, increasing ERG at SOI 20^0 bTDC leads to critical increase in NOx formation; at the same time, for early SOI (less than 5^0 bTDC), NOx emission level does not change with significant grows in PM level.

The restrictions of cylinder peak pressure and maximum rate of pressure rise do not allow the following SOI timing for selected injection profiles to be used:

- for profiles 0.15/0.20, 0.30/0.20, 0.15/0.40, $\theta soi \leq 10^0$ bTDC;
- for profiles 0.45/0.20, 0.15/0.60, $\theta soi \leq 15^0$ bTDC;
- for profiles 0.30/0.40, $\theta soi \leq 20^0$ bTDC.

For an illustration of simulation results the pollutant ratio diagram for different EGR rate and injection profiles is shown below (Figure 5, 6, 7).

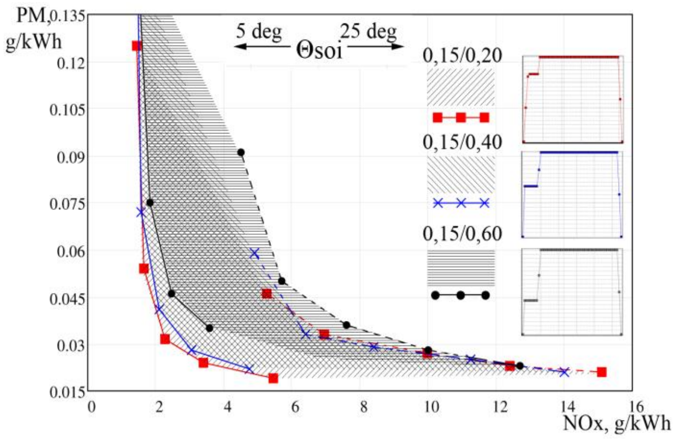


Figure 5: PM/NOx trade-off for different injection rate shapes at full load point

● - 0.15/0.20, × - 0.15/0.40, ■ - 0.15/0.60

(EGR 13%, w/o EGR)

From Figure 5,6 and 7 it can be seen that with the constant boot length and decreasing of injection pressure the emission level increases for all EGR rates, but for points without EGR this effect is less evident.

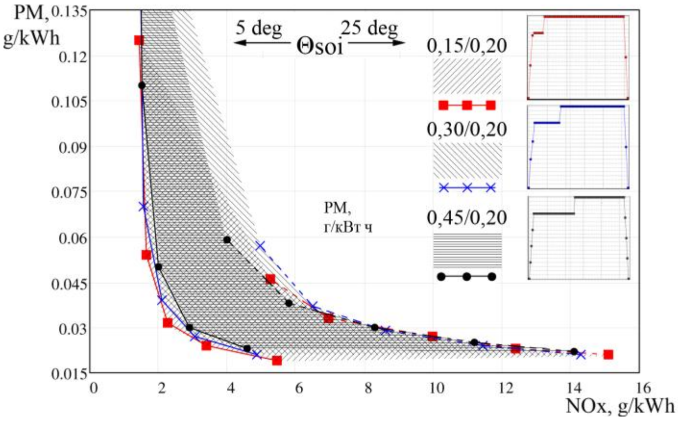


Figure 6: PM/NOx trade-off for different injection rate shapes at full load point

● - 0.15/0.20, ✕ - 0.30/0.20, ■ - 0.45/0.20

(——— EGR 13%, - - - - - - w/o EGR)

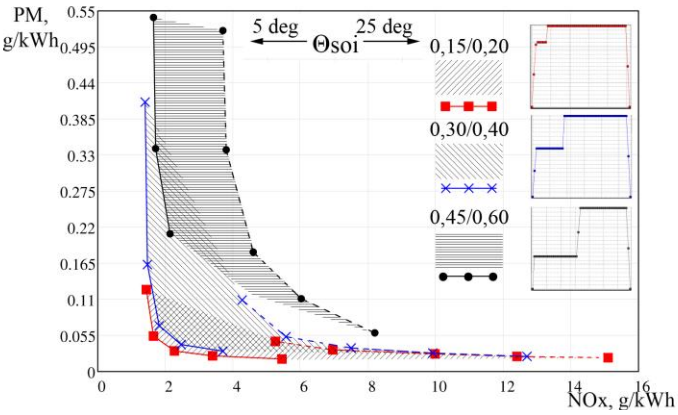
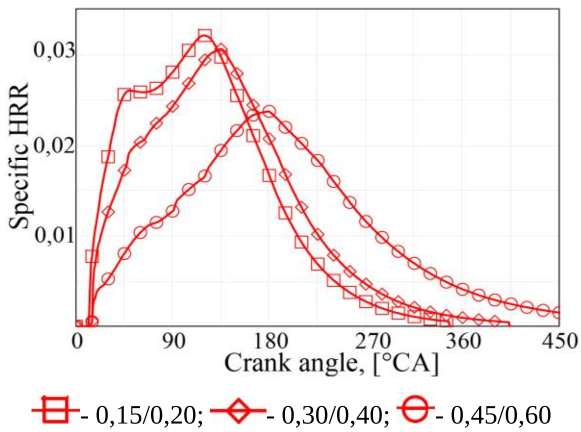


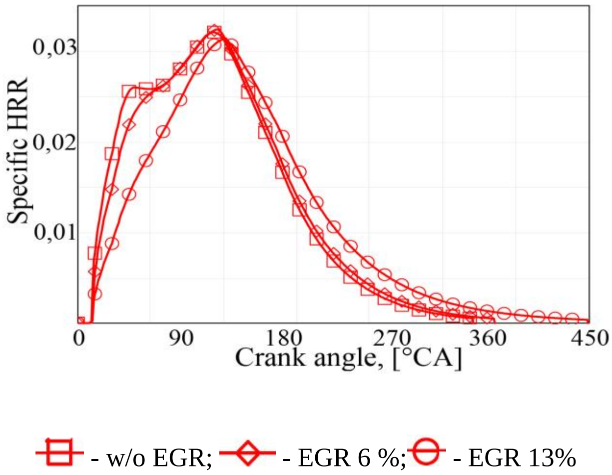
Figure 7: PM/NOx trade-off for different injection rate shapes at full load point ● - ● -0.15/0.20, ✕ - 0.30/0.40, ■ - 0.45/0.60

(——— EGR 13%, - - - - - - w/o EGR)

The injection profiles with lower boot pressure (0.30/0.40, 0.45/0.40, 0.30/0.60, 0.45/0.60) result in lower engine efficiency; the specific fuel consumption grows approximately up to 25 g/kWh compared to the square profile. This occurs because of the lower specific HRR during the premixed combustion phase (Figure 8 a) and is accompanied by increasing PM and decreasing NOx emissions. Increasing of EGR level had a smaller impact on specific HRR within the investigated boundaries compared to the effect of shaping the injection profiles (Figure 8 b).



(a)



(b)

Figure 8: Specific heat release rate at SOI 15^0: a) for different injection rate shapes (w/o EGR), b) for different EGR level (the injection profile 0.15/0.20)

With the increase of EGR, the best results were obtained for the following injection profiles: 0.15/0.20, 0.30/0.20, 0.45/0.20 and 0.15/0.40. Identical points in NOx/PM coordinates can be realized at different SOI.

Part load mode (rated power 824 kW at 1911 rpm).

Similar to full load mode simulations, a series of numerical experiments were conducted. On part load mode, results were plotted on pollutant ratio diagram (Figure 9, 10, 11).

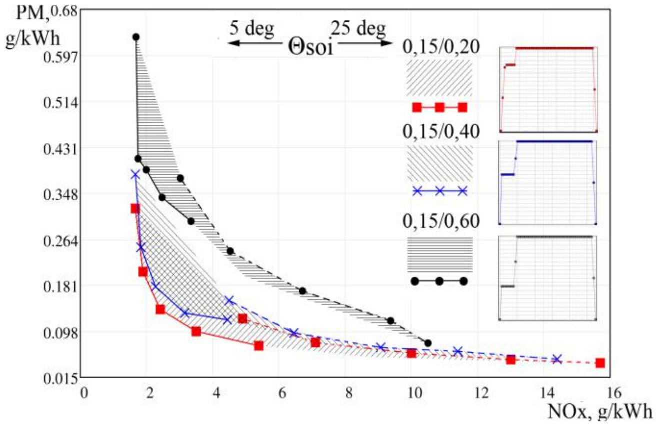


Figure 9: PM/NOx trade-off for different injection rate shapes at part load point

● - 0.15/0.20, ✕ - 0.15/0.40, ■ - 0.15/0.60

(——EGR 13%, - - - - - - w/o EGR)

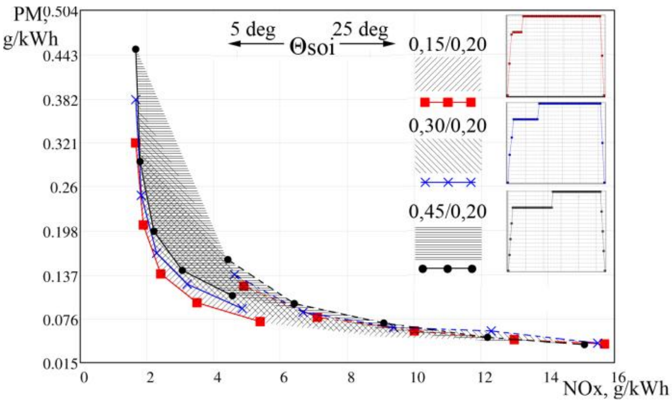


Figure 10: PM/NOx trade-off for different injection rate shapes at part load point ● - 0.15/0.20, ✕ - 0.30/0.20, ■ - 0.45/0.20

(——EGR 13%, - - - - - - w/o EGR)

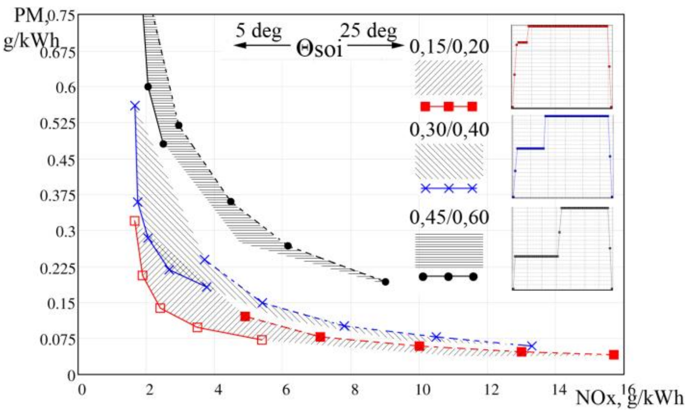
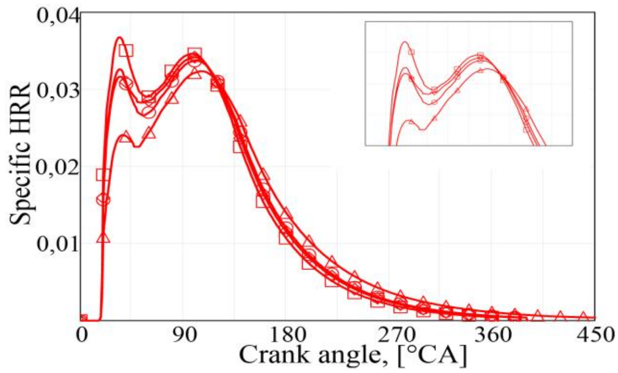


Figure 11: PM/NOx trade-off for different injection rate shapes at part load point ● - 0.15/0.20, ✕ - 0.30/0.40, ■ - 0.45/0.60

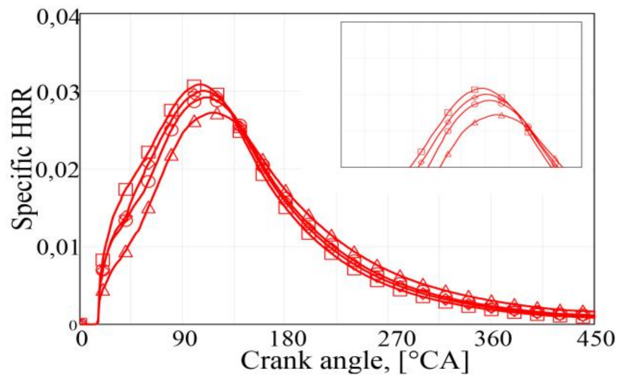
(——EGR 13%, - - - - - - w/o EGR)

An increase of PM is observed which is a typical situation for medium speed regions with lower BMEP (1.4 MPa). Injection profile shaping becomes less significant with increasing EGR rate, which was also noticed in full load mode. In this mode, the emission level for the following profiles: 0.30/0.40, 0.45/0.60, 0.15/0.60, 0.30/0.60, 0.45/0.40 were significantly higher than those for the 0.15/0.20, 0.30/0.20, 0.45/0.20 and 0.15/0.40 shapes. The areas of emission points for different shapes (Figure 11) do not overlap.

The characteristics of boot type injection have a strong impact on all stages of the combustion process. The peak of the premixed heat-release rate decreases for the following injection profiles: 0,15/0,20, 0,30/0,20, 0,45/0,20 and 0,15/0,40 [16] while the mixing controlled phase of the specific HRR magnitudes are essentially the same. In other cases the specific HRR decreases throughout the combustion process (Figure 12 a). This was also found to be true when EGR rate were increased (Figure 12 b). Such results allow us to expect a decrease in NOx emission and rate of pressure rise for long boot lengths and high boot pressure injection rates.



(a)



(b)

Figure 12: Specific heat release rate at SOI 15^0 for different injection rate shapes:

- 0.15/0.20 - 0.30/0.20 - 0.45/0.20 - 0.45/0.20 - 0.30/0.40

a) w/o EGR, b) EGR 13%

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The injection profiles: 0.15/0.20, 0.30/0.20, 0.45/0.20 and 0.15/0.40 provide similar emission level. In this context the values of specific fuel consumption, cylinder peak pressure, and maximum rate of pressure rise could be used as additional criteria (Table 2).

Table 2: Values of the engine parameters under the study (w/o EGR)

Operation mode	θsoi	**n=2100 rpm, P = 1440 kW**			**n=1911 rpm, P = 824 kW**		
Injection profile		**15%/20%**	**30%/20%**	**45%/20%**	**15%/20%**	**30%/20%**	**45%/20%**
Specific fuel consumption sfc, g/kWh	5	208	211	212	208	209	210
	10	202	204	204	204	205	205
	15	199	200	201	203	204	204
	20	199	200	200	206	206	206
	25	203	203	202	211	210	211
Cylinder peak pressure p_{max}, MPa	5	178	175	173	109	106	105
	10	197	193	192	126	123	122
	15	222	216	214	142	139	138
	20	250	243	241	157	153	153
	25	280	273	269	169	166	165
Maximum rate of pressure rise, MPa/deg	5	3.7	3.7	3.6	2.1	2.05	2.05
	10	4.4	4.25	4.25	4.0	3.6	3.5
	15	7.2	6.7	6.5	5.41	5.1	5.0
	20	8.3	7.8	7.5	5.95	5.63	5.58
	25	9.1	8.6	8.5	6.1	5.87	5.84

The best option is selected without considering EGR, as in this case the variation of argument in Table 2 is determined directly by mixture formation and the combustion process. At both modes, the increase of a boot length with constant pressure level at 80% leads to higher specific fuel consumption while the level of cylinder peak pressure and maximum rate of pressure rise decrease. This effect is especially important at the full load mode when the boot length extension make it possible to satisfy strong demand for engine reliability at the expense of the fuel economy. At the same time, for the part load mode, the long boot shaped injection profiles can be effectively used to obtain PM/NOx trade-off.

It should be concluded that the injection profiles: 0.15/0.20, 0.30/0.20 and 0.45/0.20 can be applied for the marine application engines as they provide the optimal performance for selected modes.

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Possibility of the leading edge shaping in Common Rail fuel systems.

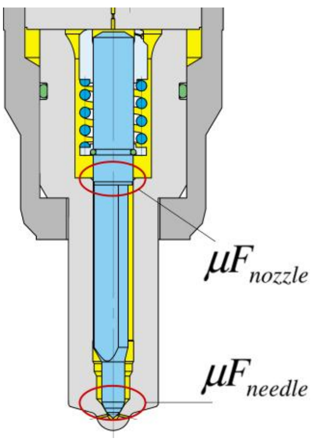
The most important finding of the study cycles is substantiation of the need to control the injection rate leading edge. Another important aspect is that for various engine operation modes it is possible to effectively use the profiles with identical leading edge parameters. Selection of one leading edge profile from several optimal solutions allows abandoning the injector designs that are difficult to implement, such as those with two control chambers and a control piston.

Hence, several injector designs were developed for Common Rail fuel systems that are able to control the leading edge of an injection profile. In particular, it is possible to implement the control method that is typical for direct acting fuel systems, i.e. an injector with an additional controlling section in the nozzle (Figure 13, a).

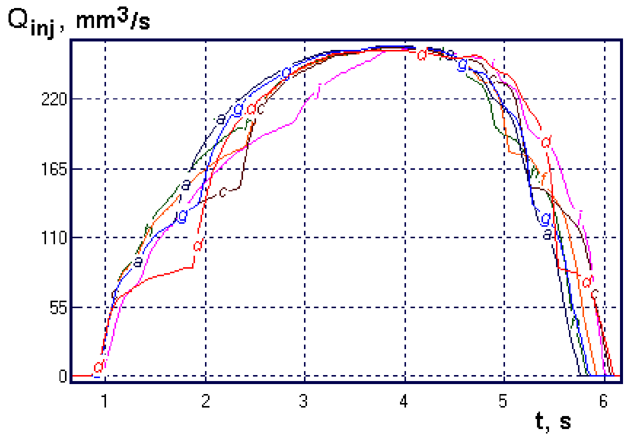
At the start of injection, the needle lift is small, and the fuel overcomes two hydraulic resistances. The first one is additional controlling section μF_{nozzle}, and the second one is needle sealing cone controlling section μF_{needle}. With small needle lifts, the μF_{nozzle} section is defined by the size of the gap between the needle and the nozzle body. During this period, the flow rate of fuel is low due to reduced pressure.

With some lift of the needle, the μF_{nozzle} section virtually ceases to influence the fuel flow, and the determinant here becomes the μF_{needle} section, which continues to increase up to the maximum value.

The dependency of the injector flow for a two-stage injection process is illustrated in Figure 13, b. The injector parameters for the engine is as follows: maximum needle stroke: 0.30 mm, needle diameter: 6 mm, sac hole diameter: 1.9 mm, number and diameter of the nozzle orifices: 8x0.31 mm, longitudinal compliance factor: 2.1 mm^{-1}.



(a)



(b)

Figure 13: Injector with additional controlling section

a) – nozzle design, b) calculated injection profile for various fuel system parameters (see the legend in Table 3).

Table 3: Injector design parameters

Parameter	a	c	d	f	g	h	j
Needle stroke to open additional controlling section, mm	0.07	0.15	0.15	0.15	0.1	0.15	0.15
Radial clearance between needle and nozzle body, μm	20	20	10	20	20	40	40
Effective section of control chamber inlet orifice, mm²	0.03	0.03	0.03	0.03	0.03	0.03	0.033

In this case, simplicity of the technical design is assured by the fact that modifications apply only to the nozzle and the needle; and moreover, one more assembly dimension has to be preserved, i.e. the needle stroke in order to open the additional controlling section. A combination of these parameters determines the characteristic profile suitable for a marine engine's basic power variability range.

CONCLUSIONS

1. The mathematical model of the DIESEL-RK software package allows for assessing the impact of fuel injection equipment on the toxicity level in a specified range of loads.
2. Substantial influence on the rated mode optimization is exercised by the limitation of the maximum permissible cylinder pressure and cycle robustness. They lead to the

necessity of shaping a stepped leading edge of the fuel injection profile with a height of 80% and variable duration of 15%, 30%, and 45%.

3. The greatest effect from injection profiling is achieved without EG recirculation. As long as it increases, the effect decreases.
4. In intermediate modes, injection profiles 0.15/0.20, 0.30/0.20 and 0.45/0.20 allow for decreasing the intensity of the kinetic combustion stage by reducing the amount of fuel evaporating in the combustion chamber during the ignition delay period.
5. There are promising outlooks for designing fuel injection equipment that would allow for shaping injection profiles applicable to each individual mode with 80% relative height of the first section and variable duration.
6. For shaping of an optimal injection profile, relatively simple technical designs in the injector can be implemented. Appropriate selection of design parameter values ensures the efficiency of the method for a locomotive engine’s power variability basic range.

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