Effect of pressure boost on the diesel performance and gaseous emission with fuel spray pressure up to 3000 bar

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Abstract. The study presents the results of a single-cylinder engine modeling that assesses the effect of turbochargers on diesel performance and gaseous emission with the fuel injection pressure up to 3000 bar. 3D modeling is performed in Fire ESE Diesel. The results show that indicator power, soot, HC increase, and BSFC, NOx decrease when using turbochargers. The boost pressure increases from 1 to 3.5 bar, the indicator power and BSFC vary tremendous, while the boost pressure increases from 3.5 to 4.5 bar, the indicator power, and BSFC change slowly. Indicator power grows by 15 %, BSFC reduces 16.6 %, NOx value goes down by 85 % and soot value goes up by 92.9 %, the maximum value of HC goes up by 51.6 % with a boost pressure of 4.5 bar and SOI at 17° BTDC. When the SOI falls, BSFC reduces and the maximum value of this reduction is 6.4 %, while indicator power increases by 5.6 % with the boost pressure of 3.5 bar. NOx value goes down by 70.3 % and soot value goes up by 88.6 % with the boost pressure of 4.5 bar. With the SOI of 5° BTDC, the turbocharging pressure from 2.5 to 4.5 bar, gaseous emissions meet the EURO V standard without the use of exhaust gas after-treatment systems.

Keyword: heavy-duty diesel, NOx, soot, HC, combustion, fuel injection pressure 3000 bar, turbocharge.

1. Introduction
The exhaust gas after-treatment technology of modern diesel engines is researched and applied to reduce emissions and meet the emission standards that are becoming strictly. EURO emission standards are shown in table 1 [1].

| Stage  | Date    | Test  | CO (g/kWh) | HC (g/kWh) | NOx (g/kWh) | PM (g/kWh) |
|--------|---------|-------|------------|------------|-------------|------------|
| Euro III | 1999.10 EEV only | 1.5 | 0.25 | 2.0 | 0.02 |
|        | 2000.10 | 2.1 | 0.66 | 5.0 | 0.10⁴ |
| Euro IV | 2005.10 | ESC & ELC | 1.5 | 0.46 | 3.5 | 0.02 |
| Euro V  | 2008.10 | WHSC | 1.5 | 0.46 | 2.0 | 0.02 |
| Euro VI | 2013.01 | WHSC | 1.5 | 0.13 | 0.4 | 0.01 |

⁴ PM = 0.13 g/kWh for engines < 0.75 dm³ swept volume per cylinder and a rated power speed > 3000 min⁻¹
In order to meet these emissions levels, there are three groups of solutions, namely, biofuels and additives in lubricating oil, exhaust gas after-treatment, and engine design. Additionally, operating mode and controlling technologies play an important role in reducing emission and improving the productivity of the engine and vehicle [1, 2]. In the group of engine design, improvement of the fuel system can be used, which includes increasing fuel injection pressure, changing the nozzle diameter, etc. When increasing the fuel injection pressure with other modifications, including optimized nozzle geometries, engine design and other engine advances, fuel efficiency could improve 4 % [3, 4]. Improving the pressure booster, high fuel injection pressure, adjustment of start of injection (SOI) angle and using EGR can meet EURO VI standards for the engine without the use of exhaust gas after-treatment.

Increasing of injection pressure is the basic development trend of the common rail fuel system [5, 6] which ensures multiple injection with the desired shape of the front edge of the basic injection rate [7, 8] and organization of fuel distribution in the combustion chamber [9, 10].

The desired fuel injection law at any operation mode of the engine is formed by variation of the control impulse duration [7, 8, 11, 12] and pressure in the common rail. It also depends on the wave phenomenon originating in the high-pressure line and affects considerably the fuel injection process in case of a multistage injection [13].

Currently, four engine simulation packages are used in the automotive industry, including Ricardo, GT-Suite, AVL-Suite and Lotus Engine Simulation (LE Soft), which helps to reduce the time for engine design and costs. AVL-ESE Diesel is a part of the AVL-Fire package. It is used to set up, analyze, simulate and optimize combustion and emission formation in Diesel engines [14, 15]. In this research, the effect of rising the pressure booster is studied with fuel injection pressure up to 3000 bar and adjustment of fuel injection start angle. The results of modeling will give overview of increasing pressure booster on diesel engine performance and gaseous emissions.

## 2. Simulation model

The sub-models, engine specifications, initial and boundary conditions are shown in tables 2, 3 and 4. The single-cylinder has a displacement of approximately 1.47 (l) and compression ratio of 15.4:1.

| **Table 2. AVL-FIRE Sub-Models** |
|----------------------------------|
| Spray model                     | Wave                                      |
| Spray wall interaction model    | Walljet1                                  |
| Droplet Evaporation model       | Dukowicz                                  |
| Turbulence model                | k-zeta-f                                  |
| Ignition model                  | Auto - ignition                           |
| Combustion model                | ECFM-3Z model                             |
| NO formation                    | Extended Zeldovich                       |
| Soot formation                  | Kinetic                                   |

| **Table 3. Engine Specifications** [16] |
|---------------------------------------|
| Bore $D$, mm                         | 120                                      |
| Stroke $S$, mm                       | 130                                      |
| Connecting rod length, mm           | 224                                      |
| Number of cylinders                  | 1                                        |
| Displacement, l                      | 1.47                                     |
| Compression ratio (-)               | 15.4                                     |
| Number of valves                     | 4                                        |
| Spray angle                          | 160°                                     |
| Number of nozzle holes               | 8                                        |
| Nozzle hole diameter, $d_c$ (mm)     | 0.24                                     |

| **Table 4. Initial and boundary conditions** |
|---------------------------------------------|
| Engine speed, (rpm)                        | 1400                                     |
| Intake air temperature (K)                 | 300                                      |
| Intake air pressure (bar)                  | 3.5                                      |
| Cylinder head temperature (K)              | 550.15                                   |
| Piston top temperature (K)                 | 575.15                                   |
| Fuel injection temperature (K)             | 330.15                                   |
| Cylinder wall temperature (K)              | 475.15                                   |
The geometry of the piston and the combustion chamber are shown in figure 1. The computational mesh is shown in figure 2 with 57504 elements. Figure 3 illustrates the rate of fuel injection which is used in the model. The rate of injection is determined from the experiment signal.

3. Simulation results

3.1. Combustion characteristics
Figures 4, 5 and 6 demonstrate the change of mean pressure, rate of heat release and mean temperature in the cylinder when the pressure increases.
As the boost pressure increases, the mean pressure also raises. When the SOI is 17° before top dead center (BTDC), the mean pressure in the combustion chamber increases with increasing boost pressure and reaches the maximum value at the top dead center (TDC). The maximum value of the mean pressure rises to 2.75 times with boost pressure of 4.5 bar (figure 4a). The SOI at 5° BTDC, the time of achieving the maximum value of mean pressure varies from 9.5 to 4.7° after top dead center (ATDC) that corresponds to the boost pressure from 1 to 4.5 bar. The maximum value of the mean pressure goes up 2.9 times with boost pressure of 4.5 bar (figure 4b).

When using turbochargers, the maximum rate of heat release will move closer to the SOI. The rate of heat release will go up when boost pressure rises and the SOI is 17° BTDC. The maximum value of the rate of heat release climbs 2.9 times with boost pressure of 4.5 bar (figure 5a). While the SOI at 5° BTDC, the rate of heat release increases when the boost pressure increases from 1 to 2.5 bar, however it decreases when the boost pressure goes up from 2.5 to 3.5 bar and slightly changes when the boost pressure rises from 3.5 to 4.5 bar (figure 5b).

In contrast, the mean temperature goes down with turbocharging. It is because the boost pressure is small, the temperature at the end of the compression period decreases, the air density is low, the combustion process extends so the mean pressure cannot leap (figure 6). Therefore, the mean temperature in the combustion chamber will increase as the boost pressure decreases.

3.2. BSFC and indicator power
The results of BSFC, the indicator power and increasing of the boost pressure are shown in fig. 7.

It can be noticed that the indicator power engine goes up and BSFC decreases with increasing of boost pressure. When the boost pressure rises from 1 to 3.5 bar the indicator power and BSFC vary tremendous, while the boost pressure increases from 3.5 to 4.5 bar, the indicator power and BSFC change slowly. The boost pressure at 3.5 bar, indicator power increases by 13.6 %, BSFC goes down
by 15%. And indicator power grows by 15%, BSFC reduces by 16.6% with a boost pressure of 4.5 bar.

![Figure 7. BSFC and indicator power when boost pressure rises](image)

3.3. Gaseous emission

NO\textsubscript{x} value decreases and soot increase when boost pressure goes up. The result is shown in figure 8a. NO\textsubscript{x} is formed by the reaction of oxygen and nitrogen at high temperatures. It is because the mean temperature falls, at the same time, the contact area between the air and nitrogen reduces, so NO\textsubscript{x} goes down with increasing boost pressure. The SOI at 17° BTDC, the soot value is the opposite of NO\textsubscript{x}. NO\textsubscript{x} value goes down by 85% and soot value goes up by 92.9%. While the SOI at 5° BTDC, NO\textsubscript{x} value declines by 70.3% and soot value raises by 88.6%.

![Figure 8. Gaseous emission when boost pressure rise](image)

HC volume is the unburnt fuel. The boost pressure increases, the contact area between the air and the fuel decreases, at the same time, the burning process is quickly so the HC value rises. The result is shown in fig. 8b.

The results of spray length and temperature field in the combustion chamber are shown in fig. 9–12. From the results, can be see that spray length and spray cone diameter decrease, the combustion area also goes down when the boost pressure increases. Because air density, temperature in the combustion chamber increase, the combustion process is quick, so the indicator power upraises and gaseous emissions reduces.

It is found that the SOI at 5° BTDC, the turbocharging pressure from 2.5 to 4.5 bar, gaseous
emissions meet the EURO V standard without the use of exhaust gas after-treatment systems. To ensure the economy when using the booster, the boost pressure should use less than 3.5 bar.

Figure 9. Temperature field in the combustion chamber with the piston at 10\(^\circ\) BTDC, start of injection 17\(^\circ\) BTDC.

Figure 10. Temperature field in the combustion chamber with the piston at TDC and SOI of 17\(^\circ\) BTDC.
Figure 11. Temperature field in the combustion chamber with the piston at TDC and SOI of 5° BTDC

Figure 12. Temperature field in the combustion chamber with the piston at 6° ATDC and SOI of 5° BTDC
4. Conclusions

In this study, the effect of boost pressure on diesel performance, emissions gaseous is simulated by AVL Fire software. The summary results are as follows:

- As the air pressure increases, the combustion of fuel take place is earlier and moves toward the SOI;
- With 3000 bar of fuel injection pressure, it is necessary to combine turbocharging with adjustment of SOI for increasing indicator power, reducing BSFC and improving emissions;
- As the boost pressure rises, the indicator power of engine goes up, BSFC decreases. The boost pressure increases from 1 to 3.5 bar, the indicator power and BSFC vary tremendous, however the boost pressure raises from 3.5 to 4.5 bar, the indicator power and BSFC change slowly. Indicator power grows by 15 %, BSFC reduces 16.6 % with a boost pressure of 4.5 bar. Reducing SOI, the maximum value of BSFC reduction is 6.4 %, while indicator power increases by 5.6 % with the boost pressure at 3.5 bar;
- NOx goes down with increasing boost pressure. The SOI at 17° BTDC, NOx value reduces by 85 % and soot value goes up to 92.9 %, while the SOI at 5° BTDC, NOx value falls to 70.3 % and soot value raises to 88.6 %;
- When the boost pressure grows, the HC value rises. The maximum value of HC increase is 51.6 %;
- The SOI at 5° BTDC, the turbocharging pressure from 2.5 to 4.5 bar, gaseous emissions meet the EURO V standard without the use of exhaust gas after-treatment systems. To ensure the economy when using the booster, the boost pressure should use less than 3.5 bar.

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