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Effect of injection pressure on engine parameters of a high power density heavy duty diesel engine for armored fighting vehicles

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Abstract. This paper presents the results of a parametric study on the effect of varying the fuel injection pressure of a turbocharged multi-cylinder heavy duty off-highway diesel engine. The study is based on one-dimension engine models simulated in AVL BOOST™ engine simulation software. The base engine model has been validated using performance data from test bench. The fuel injection pressure has been varied and the start of injection has been swept at each injection pressure and speed. As a result, a collection of data has been obtained from which the injection pressure and the start of injection for the most efficient engine performance would be obtained as a function of speed. The generated data could serve as an input for detailed CFD simulations for further optimisation.

Keywords: Fuel injection pressure, heavy duty off-highway diesel engine, one-dimensional engine model, AVL BOOST, start of injection.

1. Introduction

With advancement in technology, it has now been made viable to use high pressure fuel injection systems with electronic engine controls under challenging environmental conditions, such as the ones encountered in military applications. These high pressure injection systems have the advantage of increased specific power, increased fuel economy, reduced pollutant emissions, noise and vibrations [1].

Compared with gasoline, diesel is more viscous and hence more difficult to pulverize upon direct injection in to combustion chamber. Imperfect mixing leads to more un-burnt elements, hence more pollutant, lesser fuel economy and power. High pressure injection systems are intended to improve this pulverization process. Solenoid/piezoelectric valves give precise control with respect to the injection time and quantity, and higher pressure leading to better fuel atomization. Higher pressure enables the injected fuel jet inside the chamber at high velocity and atomize into small-sized droplets resulting in rapid evaporation and completely utilise the air charge within the combustion chamber in the available time.

Many have attempted to predict the effect of injection pressure on engine performance and emissions [2][3]. Though these studies were on performance base, the main concentration was given on emissions. In this work an effort is made to establish the injection pressure effect on engine performance of a Armoured Fighting Vehicle diesel engine.

With the above objective, it has been decided to increase the injection pressure of the existing 1000 hp engine from 680 bar injection pressure to 1800 bar injection pressure to ascertain its effect on performance of the engine. The purpose of the study is made to predict the injection pressure and injection timing effects for the above engine using AVL BOOST one dimensional engine stimulation tool. This study has been considered with the constraint of not changing the existing combustion package. In order to further optimise engine performance, the engine's electronic control unit can inject the fuel in multiple injections, thus affecting the explosiveness and vibration, which is beyond the scope of this present work.

2. Engine modeling

AVL BOOST is used to simulate a wide range of engine parameters based on one dimensional engine models. The pressures, temperatures and flow velocities calculated from the gas dynamic equations represent mean values over the pipe cross-section. Flow losses dimensional effects and locations in the engine are considered by flow coefficients. Engine dimensions are based on measurements made on 1000 hp twin turbocharged 12-cylinder diesel engine and thermodynamic parameters have been input based on the experimental data measured on the same engine. The test engine specification is shown in Table 1. Engine model built in AVL BOOST is shown in figure 1. The thermodynamic data at various points of the inlet and outlet have been input as corresponding initialization values in the model. The engine consists of articulated connecting rod and hence its motion is defined by normalized piston displacement as a function of engine crank angle.

Table 1. Specification of test engine.

Engine	Up-rated V46-6 Engine
Type	Direct injection water cooled diesel engine
Bore	150 mm
Stroke	180mm (LH);186.7mm (RH)
Compression Ratio	14:1
Rated Power	1000 hp @ 2000 rpm
Maximum Torque	3850 Nm @ 1400 rpm
Injection Pressure	650 bar
Start of Injection	30 deg. BTDC (static)

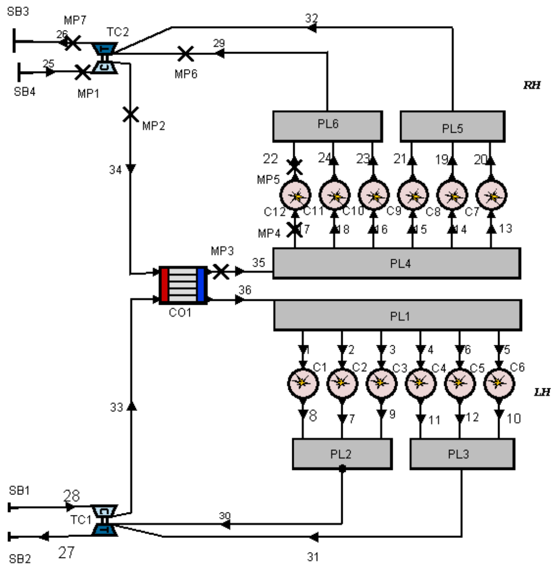

Figure 1. Engine model in AVL BOOST.

The simplest approach for combustion modeling recommended by AVL BOOST is by rate of heat release. Heat release of an engine is determined by the measured cylinder pressure. Using the total heat supplied per cycle, determined from the amount of fuel in the cylinder and air-fuel ratio, AVL BOOST calculates the heat input per crank angle degree. In order to calculate the injection pressure effect on parameters in direct injection compression ignition engines, the above approach is not viable and hence the approach of using the AVL Mixture Controlled Combustion (MCC) model to predict the combustion characteristics is used for this study.

3. Engine model validation

It is important to validate the base engine model with the experimental data before any parameter variation could be simulated. Hence the engine model has first been simulated in AVL BOOST with its existing injection parameters and with BMEP control mode to produce the same power as the experimental engine. A comparison of the simulated results with the experimental data is produced in Table 2. and figure 2. The results show that the simulated data are in agreement with experimental results obtained.

Table 2. Comparison of simulated results with experimental data.

Data	Experimental	Simulated	Percentage Variation (%)
Speed (rpm)	2000	2000	-
Power (kW)	672.6	674.2	0.24
Torque (N.m)	3211	3219.1	0.25
BSFC (g/kW.hr)	231	238.5	3.23
BMEP (bar)	10.6	10.4	1.85
Fuelling (mg/cyc)	213.8	222.7	4.15
Air mass flow rate (kg/hr.)	4484	4553.3	1.55
Avg. AFR	29	28.92	0.27
PFP (bar)	134.9	126.5	6.27
PFP crank angle (deg.)	7	5.14	--
Peak pressure rise (bar/deg)	4.55	5.84	0.96
PPR at crank angle (deg)	-9	-13.16	--

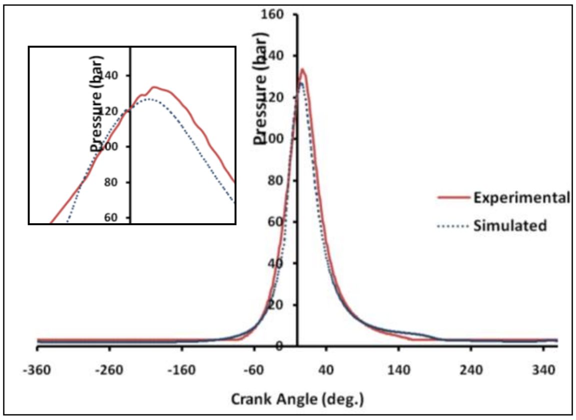

Figure 2. Pressure - Crank Angle at 100% load and 2000 rpm.

4. BMEP control

In AVL BOOST, the BMEP Control provides a way to obtain a target BMEP value. This is controlled by the injected fuel mass to the Cylinders. According to equation (1) the injected fuel mass of the engine cylinders is controlled [4].

$$vc = vc_{guess} + \left(vc_{upper} - vc_{lower}\right) \frac{i}{t_{CDUR}} \int_0^t (BMEP_{des} - BMEP)\,.dt \quad (1)$$

It was observed that due to the assumption of fuelling to achieve the target BMEP, maintaining a constant target BMEP is not possible, and a marginal variation in calculated BMEP was obtained as seen in figure 3. This is accepted since the variation is found to be less than 0.04%.

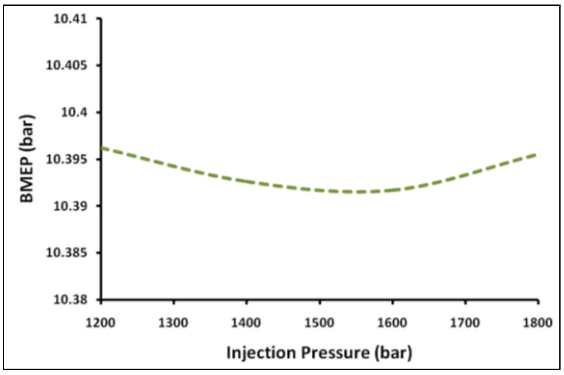

Figure 3. Trend in BMEP estimation.

5. Injection timing optimization

Fuel-Injection timing essentially controls the start of combustion. While the air, in to which the fuel is injected varies as injection timing is varied, and thus ignition delay may alter, these are calculated. Also the fuel-injection rate and fuel nozzle design (including number of holes) all affect the diesel fuel spray characteristics and its mixing. At fixed speed and constant BMEP, the engine shows a minimum BSFC at a particular start of injection for a given injection pressure as seen in figure 4. This optimum start of injection was found to vary from 16 deg. BTDC (dynamic) at 1200 bar pressure to 12 deg. BTDC (dynamic) at 1800 bar pressure, as shown in Table 3. Any advancement or retard of injection timing from this shows high BSFC levels, as seen in figure 4. However for the purpose of comparison, 16 deg. BTDC has been chosen as the standard timing for start of injection in this analysis.

Table 3. Optimum SOI vs injection pressure.

Injection Pressure (bar)	1200	1400	1600	1800
Start of Injection (deg. BTDC)	16	15	14	12

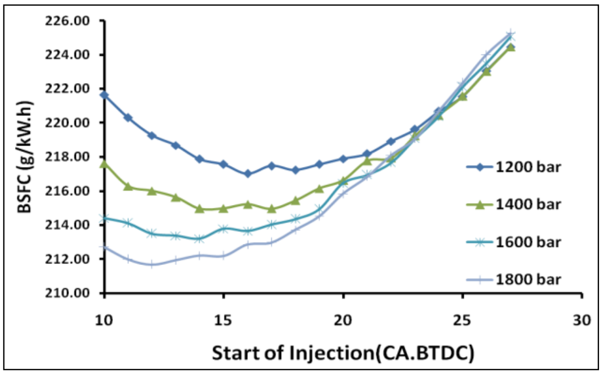

Figure 4. BSFC vs. Start of fuel injection**.**

6. Effect of injection pressure on ignition delay

Ignition delay of a given fuel is critical in deciding the performance of the engine in areas such as thermal efficiency, silent operation, misfiring, smoking and knocking of the engine. With longer ignition delay, most fuel is injected before ignition and this will lead to very rapid rate of pressure rise, due to higher combustion rate, and high peak pressure after ignition. In the most severe cases, the rate of combustion is so rapid that detonation of the whole fuel - air mixture occurs and results in audible knocking. With a smaller ignition delay, ignition starts before all fuel is injected. Therefore, the rate of combustion, subsequently the rate of pressure rise are controlled by fuel injection rate which results in smooth engine operation [5].

Ignition delay involves a physical and a chemical delay. The physical delay involves the atomization vaporization and mixing of the fuel vapor with air. The chemical processes which are the pre-combustion reactions of the fuel, air, residual gas mixture which lead to auto-ignition. It is generally agreed [6-11] that injection pressure and subsequently the size of the droplets injected influence the atomization and mixing of the fuel vapor. An increase of injection pressure may enhance the atomization of fuel, the extent of spray penetration and provide a more distributed vapor phase and hence results in a better mixture. In this work it is observed that the injection pressure increase will tend to decrease the ignition delay, as shown in figure 5.

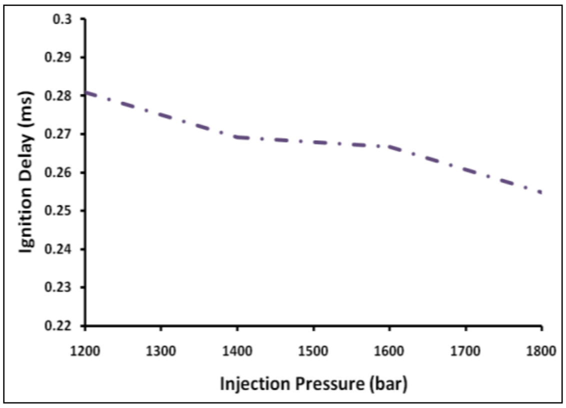

Figure 5. Ignition delay vs. injection pressure.

7. Effect of Injection Pressure on BSFC, fuelling

BSFC varies with injection pressure, showing a marginal decreasing trend with increasing injection pressure. The BSFC decreases by about 2% for the pressure from 1200 bar to 1800 bar. This is due to improved characteristics of the spray, atomization, spray penetration and mixing of fuel with air at higher injection pressures [2]. By increasing injection pressure, the quality of fuel-air mixture in the combustion chamber reaches its peak hence un-burnt fuel is less than the lower injection pressure, which also contributes to the minor improvement in BSFC and fuelling, as shown in figure 6 and figure 7.

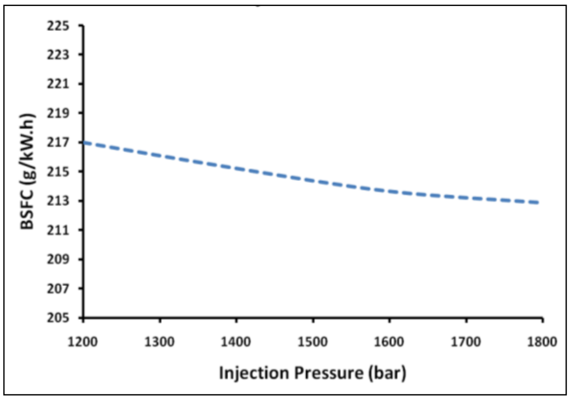

Figure 6. BSFC vs. injection pressure.

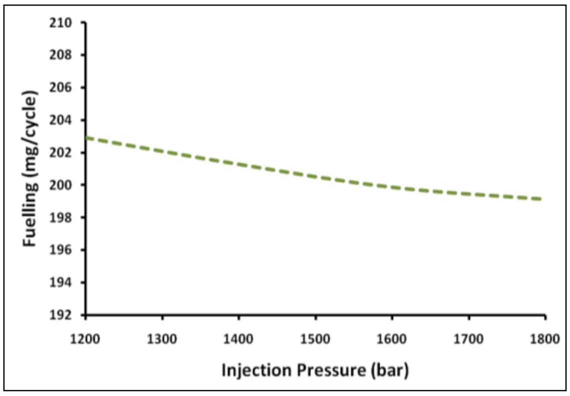

Figure 7. Fuelling (cylinder 1) vs. injection pressure.

8. Effect of injection pressure on PFP

It is observed that the Peak Firing Pressure of the cylinders increases with Injection Pressure, as seen in figure 8. This increase in Peak Firing Pressure is about 5% for an increase in injection pressure from 1200 bar to 1800 bar. This may be due to the fact that for a given nozzle geometry, with increase in injection pressure the rate of injection also increases as shown in figure 9. This increase in injection rate accounts for an increased fuel amount being injected during the ignition delay period, increases the heat released during the premixed combustion phase and hence the PFP, as predicted by heat release curve in figure 10 and the Pressure Crank angle plot in figure 11. A decrease in PFP could be expected when multiple injections are performed [3], which could be analyzed at a later stage.

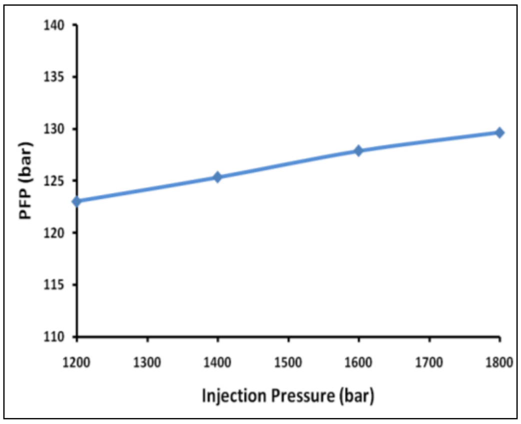

Figure 8. PFP (cylinder 1) vs. injection pressure.

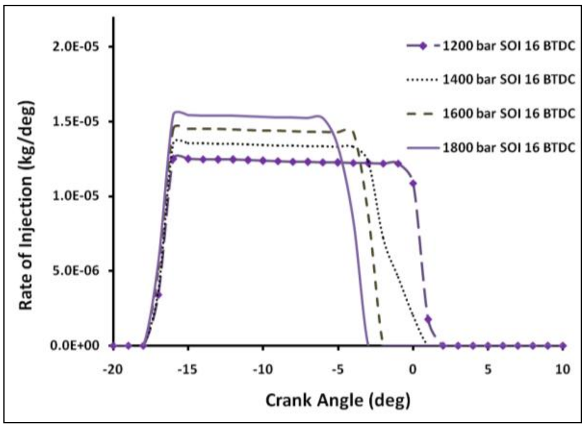

Figure 9. Rate of injection (cylinder 1) vs. crank angle.

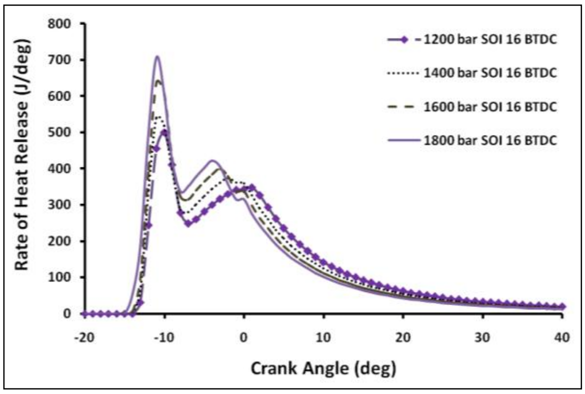

Figure 10. Rate of heat release (cylinder 1) vs. crank angle.

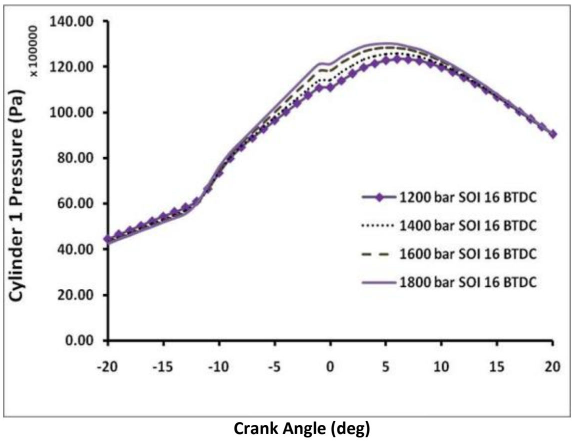

Figure 11. Pressure (cylinder 1) vs. Crank angle.

9. Conclusions

The effect of Fuel Injection Pressure on parameters have been studied at 2000 rpm (rated speed) at full load, in order to understand the behaviour of various key engine performance parameters, specific to the engine under consideration, with the constraints as explained above. It was observed, with higher fuel injection pressure, Ignition delay decreases, BSFC decreases by 2% and Peak firing Pressure increases by 5%. This study provides a good insight and direction for future design of combustion parameters including injection timing. The generated data could serve as an input for optimizing the injection strategy and for detailed CFD simulations for further optimization of the combustion package.

ABBREVIATIONS

vc	Injected Fuel Mass in kg(Controlled Value)
vc guess	Initial value for controlled value(kg)
vc upper, vc lower	Upper and lower limit for controlled value (kg)
i	Integral Control gain (1/Pa)
t_{CDUR}	Cycle Duration (s)
BMEP des	Target BMEP (Pa)
BMEP	Current BMEP (Pa)
PFP	Peak firing pressure (bar)
BSFC	Brake specific fuel consumption (g/kWhr)
CA	Crank Angle (deg.)
BTDC	Before Top Dead Centre (deg. CA)
SOI	Start of Injection (deg. CA)

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