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Environmental Pollution Assessment of Different Diesel Injector Location Of Direct-Injection Diesel Engines: Theoretical Study

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Abstract: An Analytical investigation on the effect of injector location of a four-stroke DI diesel engine on its pollutants' emissions was carried out under different injector locations ranging from central to peripheral at different engine speeds ranging from 1000 rpm to 3000 rpm. The simulation results clearly indicated the advantages and disadvantages of the central location over the peripheral one. It revealed that near central location gave less carbon dioxide, smoke level and particulate matter on one hand, and higher levels of NOx, cylinder temperature and pressure (hence increased the mechanical and thermal stresses) on the other hand. Further, near central location resulted in more rapid rate of burning and less duration of combustion and rapid rate of NOx formation per crank angle.

Keywords: Diesel engine emissions, variable injector location, simulation of diesel engine.

INTRODUCTION

After the unprecedented rise in oil prices, the Government of Jordan became more interested in using diesel fuel to power vehicles running on the road. This is due to its economy and to reduce the fuel bill on the government. This was accompanied with growing concern over its environmental impact. To reduce its environmental impact, the Government of Jordan made it mandatory for all types of diesel vehicles to put a Diesel Particulate Filter (DPF or CDPF) to try to curb the increasing levels of exhaust pollution.

Extensive research was conducted on diesel engines to reduce the level of pollutants emitted and improve its performance. Significant improvement in the engine's emission levels was achieved. This research can be broadly classified into two areas (1) engine fuel improvement and (2) improving the engine design.
Pugazhvadivu *et.al.*[1] investigated the use of preheated waste frying oil as fuel. They reported an improvement in the engine performance and a reduction in carbon monoxide (CO) and smoke level with the waste frying oil. Shi et .al.[2] investigated the emission characteristics of using methyl soyate-ethanol-diesel blend as fuel. They reported moderate improvement on CO levels for all blends, while the 20% (v/v) blend produced less total hydrocarbon (THC) and for that of pure ethanol there was an increase in the THC levels. Ramadhas et.al.[3] evaluated the performance and emission characteristics of diesel engine using methyl esters of rubber seed oil. They reported a reduction of exhaust gas emissions with increase in biodiesel concentrations. Puhan et.al. [4] also studied the performance and emission characteristics of using Mahua oil ethyl ester in 4-stroke natural aspirated DI engine. They found that exhaust pollutants were reduced significantly with the addition of this oil. Zhang et.al. [5] studies the combustion characteristics of diesel engine operated with diesel and burning oil of biomass. They reported lower fuel consumption at the various loading and significant improvement of carbon dioxide (CO2) emissions. Usta [6] studied the effect of tobacco seed oil methyl ester on the performance and exhaust emissions of a diesel engine. They reported reduction of CO and sulfur dioxide (SO2) emissions while causing slightly higher nitrogen oxides (NOx) emissions. It was also found that tobacco seed oil slightly improved the engine power and efficiency. Yi Ren et.al. [7] studied the combustion characteristics of diesel-dimethoxy methane blends under various fuel injection advance angles. They reported an increase of smoke level and decrease of NOx levels as the injection advance decreased. Xiaolu Li et.al. [8] studied the combustion and emission characteristics of

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a two-stroke diesel engine operating on alcohol. They reported lower NOx emissions and 2-3% higher effective thermal efficiency. Xiaolu Li et.al. [9] studied the combustion and emission characteristics of diesel engine operating on dimethyl carbonate. They reported lower NOx emissions and 2-3% higher effective thermal efficiency. Nabi et.al. [10] studied the effect of diesel-biodiesel blends on the diesel engine emission.

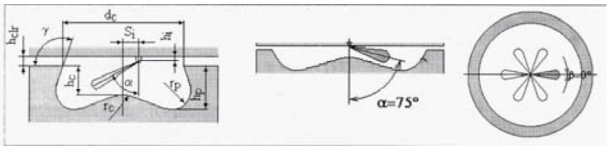

Fig. 1: injector location (Si) configuration.

They found that the CO and smoke levels reduced while that of NOx increased without exhaust gas recirculation (EGR) and slightly reduced with EGR. Chan et.al. [11] conducted a real-world on-road diesel vehicle emissions of CO, HC and NO in nine cities in Hong Kong using a regression analysis approach based on the measured vehicle emission data. They established a unique database of the correlation of the diesel vehicle emission factors on different model years and vehicle types for urban driving patterns in Hong Kong. De-gang Li et.al. [12] studied the physico-chemical properties of ethanol-diesel blend fuel and its effect on the performance and emissions of diesel engines. They reported an increase in the total HC and reduction of smoke and NOx levels. Besides the many other researchers like Parlak [13] and Hong [14]. This area is gathering lots of momentum and more research is been conducted to try to reduce the environmental impact of diesel fuel exhaust pollutants.

This paper is inline with these criteria of research i.e. modifying engine design. It presents different approach (though not new since it is used for SI engines [15]) but it has never been studied (to the best of the authors' knowledge) for compression ignition engines. It is called the variable injector location technology.

The Study: This study was conducted using the Diesel-RK software as in [16]. In this study, the injector location (S_i), which represents the distance between spray center and bowl axis shown in Fig. 1. This parameter was varied as shown in Table (1) below. The injector location ratio is the distance from the center of spray from bowl edge (r_c-S_i) divided by the bowl external diameter (d_c). The injection timing and compression ratio were kept constant at 20 degrees before top dead center, 15:1 while the engine speed was varied from 1000 rpm to 3000 rpm with an increment of 500 rpm. The bowl diameter is 125mm.

Table 1: injector location and its ratio used in this study

Injector Location (S_i) mm	Injector Location Ratio (S_i / d_c)
0	0.000
15.625	0.125
31.25	0.250
46.875	0.375
62.5	0.500

The engine used for this study is the KamAZ-7405 truck. It is a 4-Stroke, six-cylinders, 150 mm cylinder bore, 0.281 ratio of crank radius to rod length, stroke length of 180 mm, 15:1 compression ratio, angle of injection equals 20^o BTDC and injector nozzle bore is 0.249 mm engine. The fuel properties were: pure Diesel with specifications of C (0.87) H (0.126) O (0.004) on mass basis, calorific value 42.7(MJ/Kg), the molecular weight is 190 kg/kmol, Cetane number of 45 and fuel density of 825 kg/m^3.

Software verification with experimental one is first done to study its suitability and accuracy as simulation tool for this study.

The comparison between the model and experimental results were carried out using the data available for the diesel KamAZ-7405 truck. The Piston bowl and fuel jets design are shown below in Fig. 2.
The injector design and operating parameters are summarized in the Table 2.

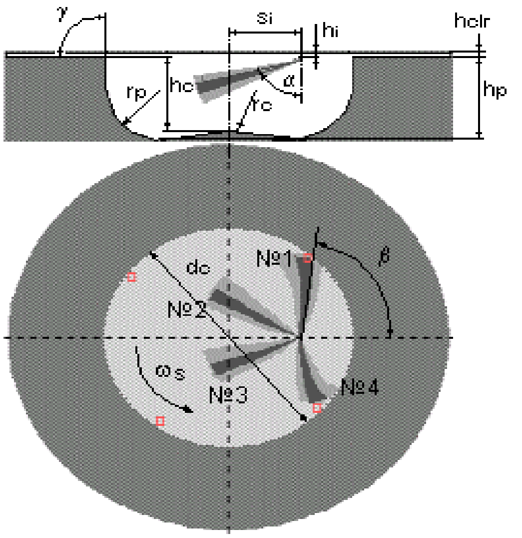

Fig. 2: Piston bowl design and fuel jets orientation.

Table 2: Injector design parameters

Number and size of the identical jets	4 x 0.33
Angle β :	0 Deg
Angle α :	60 Deg
External diameter, dc	64mm
Radius of sphere in centre, rc	20mm
Radius of hollow chamfer in periphery, rp	5mm
Depth of bowl in centre, hc	23.2mm
Depth of bowl in periphery, hp	23.2mm
Inclination angle of bowl forming to a plane of the piston crown, γ	90 Deg
Piston crown - cylinder head clearance, hclr	1mm
Displacement of a spray from bowl axis, si	0
Displacement of a spray from the bottom of a cylinder head, hi	2mm

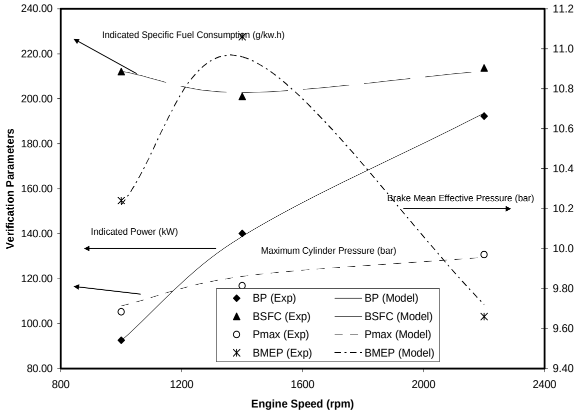

Fig. 1: Experimental and Model verification for some engine performance parameters.

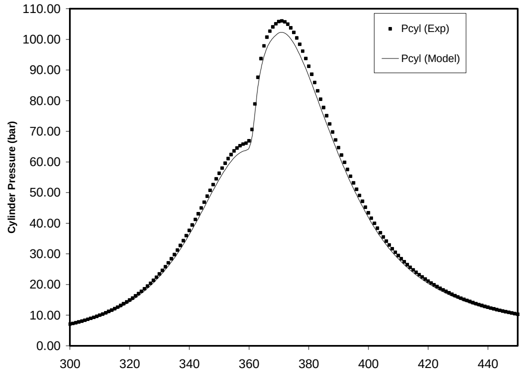

Fig. 2: Experimental and Model verification for the cylinder pressure at 1000rpm.

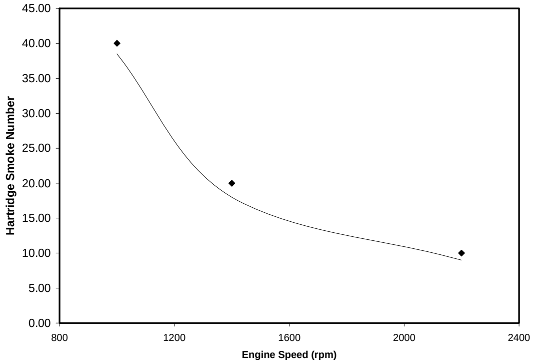

Fig. 3: Experimental and Model verification for the Hartridge smoke level.

Let H be a swirl number defined as a relation between swirl angular velocity ωs (in the cylinder at the end of intake) and rotation velocity ωr.: 1.586

The performance comparison between calculated and experimental data is shown in Figs. 1,2 and 3. These figures clearly show the accuracy of this software to simulate the CI engine performance.

Further details on the model verification data and model can be seen in the following website: http://energy.power.bmstu.ru/e02/diesel/d212eng.htm

RESULTS AND DISCUSSION

The emissions studied were the carbon dioxide, nitrogen oxides, nitrogen dioxide, particulate matter and Bosch smoke number. The results of the study are presented in Figs. 4 to 14. The study was conducted with basic aim to study the effect of various injector locations on engine combustion process and pollutants' formation. The effect of injector location on some of the in-cylinder combustion parameters is shown in Figs. 4 to 7.

Figs. 4 shows the effect of injector location on the mass fraction burned of the fuel at three different speeds (low, medium and high speeds).

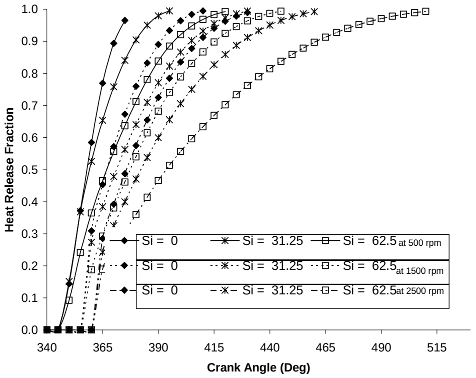

Fig 4: Variation of heat release fraction with injector location and engine speed.

It clearly shows that for a given engine speed, as the injector location is shifted away from the center, the combustion duration increases (shown by the longer duration for the mass fraction to reach unity). Further, it can be seen from the graph that as the engine speed increases, the effect of the injector location becomes more influential and of more effect on combustion process.

In order to try to understand this effect, Figs. 5 and 6 are presented. These figures show the effect of the injector location on the cylinder pressure and temperature inside the cylinder.

Fig. 5 clearly show the effect of injector location on the cylinder pressure variation. It shows that, for a given engine speed, the cylinder pressure decreases as the injector location is brought away from the center. Further, this effect is greater at higher engine speed with the peak portion of the curve is more flat at the top.

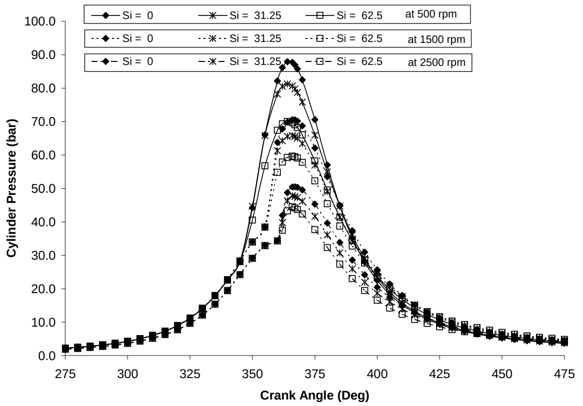

Fig. 5: Variation of cylinder pressure with injector location and engine speed.

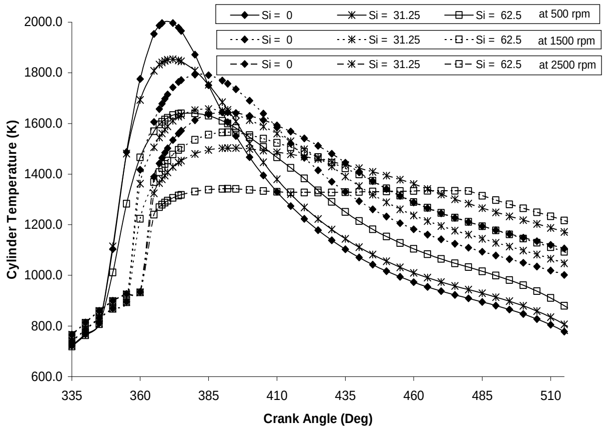

Fig. 6: Variation of cylinder temperature with injector location and engine speed.

Similar and clearer effect is shown in Fig. 6 which presents the effect on cylinder temperature. The reduction in the peak cylinder temperature with injector been moved away from the center and the shift of the peak cylinder temperature later in the expansion stroke.

These effects are direct result of the prolonged duration of combustion and increased losses of heat to the coolant and other cylinder parts.

Viewing this parameter (i.e. shifting the injector location away from the center) from in-cylinder emission formation point of view it can be noticed from Fig. 7 the direct effect of lower cylinder temperature on the nitrogen oxides (hereinafter referred to as NOx) formation. The reduction of cylinder temperature leads to less formation of NOx pollutants. This however must be followed by further analysis on the effect of injector location on other pollutants as presented in the coming section.

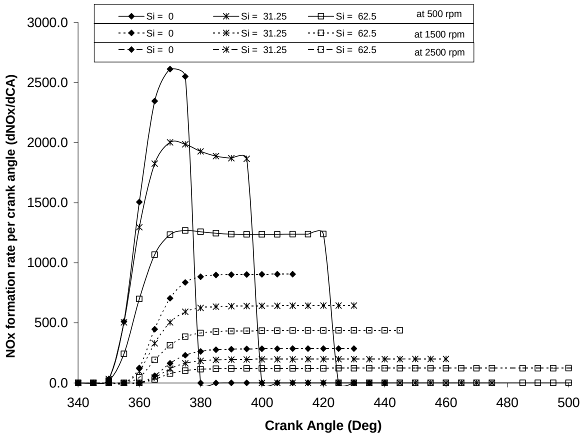

Fig. 7: Variation of cylinder NOx production rate (dNOx/dCA) with injector location and engine speed.

As a conclusion to the first section, the injector location has greater influence on the combustion process. Shifting the injector away from the center towards the periphery the mass fraction burned for a given crank angle at a given engine speed reduces, while the burning duration is prolonged. This leads to creation of non-favorable environment manifested in the reduced cylinder pressure and temperature, while for certain pollutants like NOx, it seems highly favorable.

These figures can be well understood with the help of Figs. 8 to 14. The increased cylinder temperature for central locations at all engine speeds studied, caused the Bosch smoke number (Hereinafter referred to as BSN),, shown in Fig. 8, specific particulate matter (Hereinafter referred to as SpPM), shown in Fig. 9, and specific carbon dioxide level, shown in Fig. 10, to decrease.

This may be attributed to the improved combustion process which resulted in improved cylinder temperature and pressure.

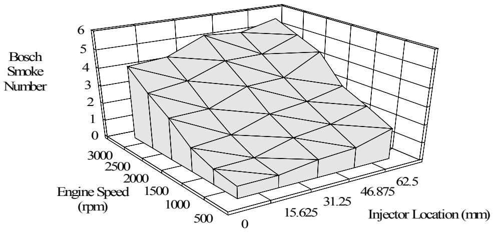

Fig. 8: Variation of Bosch smoke number with Injector location and engine speed.

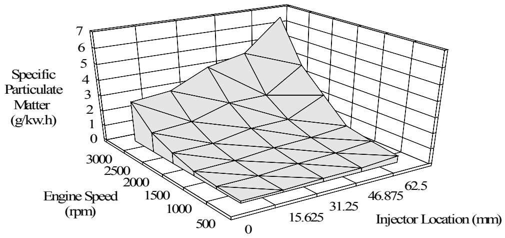

Fig. 9: Variation of Specific Particulate Number with Injector location and engine speed.

This increase in the cylinder pressure and temperature is mainly due to the shortening of the combustion duration and ignition delay period, shown in Fig. 11 as the injector is brought nearer to the center.

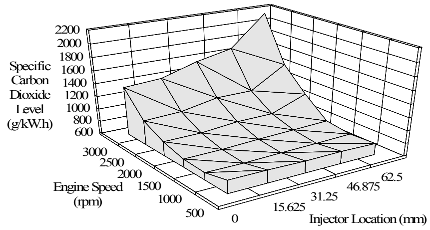

Fig. 10: Variation of specific carbon dioxide emissions with Injector location and engine speeds.

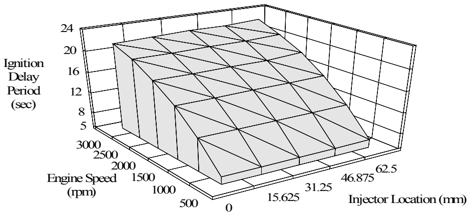

Fig. 11: Variation ignition delay with Injector location and engine speed.

This caused less amount of heat to be lost to the coolant through cylinder liner as shown in Fig. 12; hence more of the heat energy liberated is converted to useful work.

On the other hand, shifting the injector location towards the center increased the rate of NOx formation inside the cylinder as well as the NOx emitted to the environment, this is shown in Fig. 13.

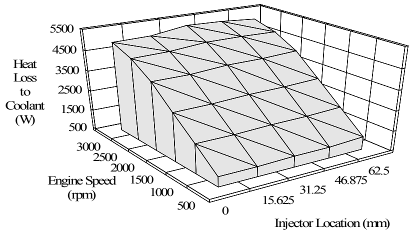

Fig 12: Variation heat losses with Injector location and engine speed.

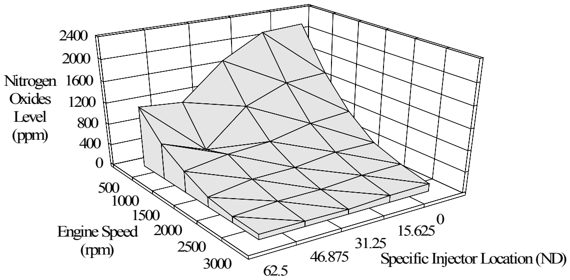

Fig. 13: Variation of Nitric Oxides emissions with Injector location and engine speeds.

This is a direct result of the improved combustion process which resulted in higher cylinder temperature which is one parameter that affects the NOx formation. Another disadvantage of the central-injector location is the high temperature of exhaust gasses that the cylinder valves have to handle. This results in increased level of thermal stresses. This is shown in Fig. 14.

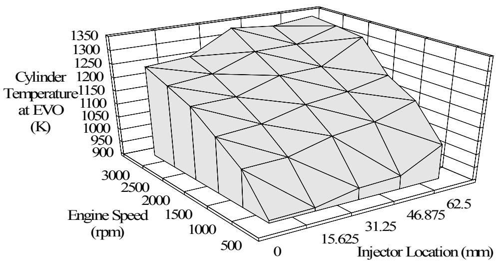

Fig. 14: Variation cylinder temperature at EVO with Injector location and engine speed.

Finally, to complete this analysis, a comparison between the central and peripheral location is done. The study shows that at low engine speed, a maximum reduction of about 9% was achieved for specific CO2 for central locations, and a reduction of about 50% was achieved in smoke level for same injector location and 65% for the specific particulate matter. Though this looks very tempting, however, the NOx emission level increased by an amount of 100%. Further, the amount of increase in the stress (thermal and mechanical) that the engine is subjected to by increasing the maximum cylinder temperature to about 18% and that for the cylinder pressure to about 15% with respect to those at the periphery and the reduction of the heat loss by almost 7.5%.

On the other hand, the exhaust system will work under less severe conditions of about 8% reduction in the exhaust pressure and temperature which reduces the thermal and mechanical stresses on the exhaust valve. This may reduce thermal pollution of the exhaust gasses to the atmosphere as well.

At higher engine speeds, there is noticeable change in the values. While the maximum reduction in CO2 was around 30%, that for the smoke level was 35% and a reduction of 60% was achieved for the PM. The NOx emission level, on the other hand, increased by 130%.

From the engine design point of view (thermal and mechanical stresses) there was an increase of about 20% for the peak cylinder pressure while 15% increase for maximum cylinder temperature. From the energy loss point of view, there was 4% reduction in the energy lost to coolant accompanied with around 9% reduction in the exhaust temperature and pressure. This reduces the load and stress on the exhaust system at higher engine speeds.

Therefore, from pure environmental point of view the central location of the injector gave overall favorable performance, though at the cost of the engine stresses, this may be little improved is the injector is put slightly away from center at about 0.35 to reduce emissions and improve engine life (by reducing stresses).

CONCLUSION

1. Central injector locations give more efficient combustion by reducing the combustion duration and heat losses.
2. As the injector is shifted towards the periphery, the peak cylinder pressure and temperature is reduced and is achieved late in the expansion stroke. This adversely affects the engine power parameters.
3. The engine’s specific particulate matter, specific carbon dioxide and Bosch smoke number was significantly reduced at injector location near the center.
4. The oxides of nitrogen on the other hand, increased with central injector locations.
5. Near central locations caused the engine pressure and temperature to increase hence, may cause reduction in engine life.
6. The amount of heat loss to engine coolant have reduced with near central locations at higher engine speeds, this may cause the engine efficiency to improve.
7. The increased exhaust pressure and temperatures for the central locations, means more energy is been wasted with the exhaust. This may cause the engine efficiency and specific fuel consumption to reduce.

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