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STUDY OF ADVANCE AND DELAY OF PILOT AND MAIN INJECTIONS FOR DIFFERENT ENGINE OPERATING LOADS

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Abstract. *This work presents an experimental study carried out on a test bench using a single cylinder compression ignition (CI) research engine that is coupled to an active alternating current dynamometer. The diesel engine is instrumented to enable the measurement of some parameters such as: pressure in the combustion chamber, temperature of the exhaust gases, temperature and pressure in the air intake and temperature of the coolant, among others. The engine was adapted to receive the Ducted Fuel Injection-DFI concept, which makes the injected fuel pass through a duct installed downstream of the injection nozzle, making the air/fuel mixture more efficient, making it more homogeneous, improving so combustion. Therefore, an analysis was made for three different operating loads varying their injection point in order to obtain the lowest soot formation value and the highest IMEP value. This study also aimed to analyze the formation of soot and emissions in general such as THC, CO, NOx and Soot for each case. Emissions were measured with Fourier Transform Infrared Spectroscopy – FTIR equipment, and soot was measured with Laser Induced Incandescence – LII equipment. For each load studied, an optimal point was found for the advance and for the delay in the "pilot" and "main" injections, the advance and delay for each injection was analyzed independently, in order to evaluate which injection and if advanced or delayed brings more benefits in emissions and thermodynamic. The variation in the injection point showed that for the DFI mode, the delay in the "main" injection is more beneficial in the cases presented, considering that the IMEP value increased, the soot formation decreased and the NOx formation also decreased, not presenting a trade -off between soot-NOx.*

Keywords: Engine Diesel, DFI, Soot, Emissions.

1. INTRODUCTION

The objective of this Research is to evaluate comparatively the application of the concept of fuel injection in duct - DFI, in relation to the conventional system of direct fuel injection in engines of the Diesel cycle (Free spray). The work was conducted using an AVL single cylinder research engine, compression ignition, with the main criterion of reducing the soot generated in combustion.

Another objective of this work is to verify whether the DFI concept can, in addition to reducing soot, also improve combustion efficiency. GEHMLICH et al. (2018) suggest that the increase in the quality of the mixture may reduce the variations of the equivalence ratios along the length of the Lift-Off, thus reducing the regions with very poor mixture in the spray periphery, which potentially can increase the combustion efficiency and reduce emissions of unburned hydrocarbons and carbon monoxide.

The DFI was based on the Bunsen burner, this burner is a metal tube with the gaseous fuel injected in the center of it there are openings at the base of the Bunsen burner that allow air to enter the tube (Bunsen, et. al. 1857). The high velocity of the fuel jet pulls air into the tube and thus the air mixes with the fuel along the tube. Better entrainment and mixing make combustion more efficient, resulting in less soot. DFI technology can bring several benefits when applied to internal combustion engines. The presence of the duct can dramatically increase the velocity gradients that lead to turbulent mixing, reducing the equivalence ratio of most of the spray (Schlichting, 1857). Soot formation can be avoided if the equivalence ratio is maintained at approximately two or less in the auto-ignition zone. The second advantage is that the presence of the duct can prevent excessive mixtures that are poorer in fuel, potentially increasing combustion efficiency by reducing hydrocarbon and carbon monoxide emissions. The proximity of the ducts at the inlet valve can cause them to be colder than the gases in the cylinder, causing the mixture to be colder inside the duct, allowing mixing to occur during ignition delay (Polonowski, et al. 2011). Another benefit of DFI is that it can prevent or delay the carryover of combustion products into the spray upstream of the established takeoff length, thus preventing unwanted shortening of the takeoff length, which causes further soot formation. In addition, leaner mixtures may have ignition delays at the exit of the pipeline, allowing longer time for premixing (Curran, et. al. 1998).

Previous work has explored the effectiveness of DFI versus Free Spray, a variety of designs have been tested in a constant volume combustion vessel which has influenced designs to test ducts in internal combustion engines (Mueller, et. al 2017), (Gehmlich, et al. . al. 2018), which is the case of this work. For this work, the same terminology as in previous studies was used. The nomenclature for the duct parameters is as follows: D (diameter), L (duct length), G (Standoff) and H (lift-off length). These parameters can be seen in Figure 1. All values are given in millimeters.

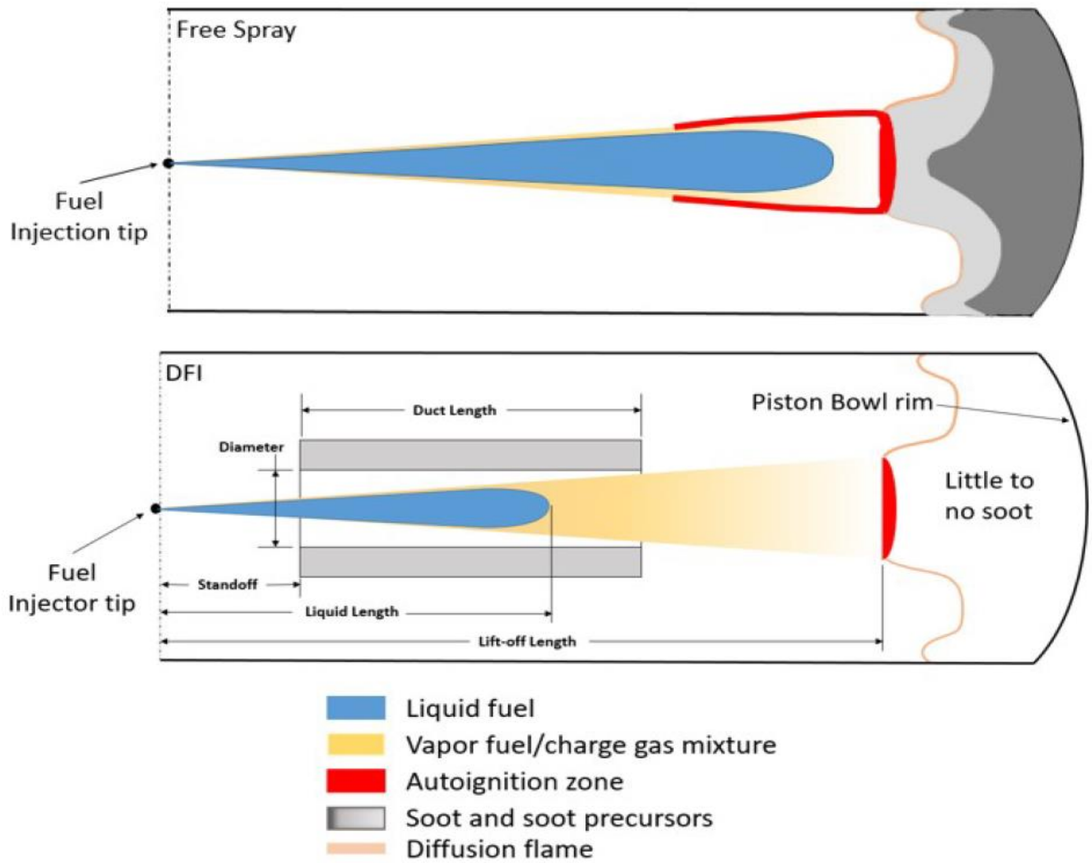

Figure 1 - DFI parameters.

The idea of the development of the ducts started from a bronze sleeve. This arrangement consists of a bronze sleeve installed on the injector nozzle, with the objective of increasing the life span of the injector nozzle by protecting it from thermal stress. When the engine brake is applied, for example, the fuel is not being injected into the combustion chamber, and the injector is not cooled by the fuel flow. Thus, the bronze bushing has been used to protect the injector nozzle, so that even when the engine is not injecting fuel, the injector nozzle is protected from high temperatures. Figure 2 shows the bronze sleeve installed in the injector nozzle and figure 3 shows the prototype in section.

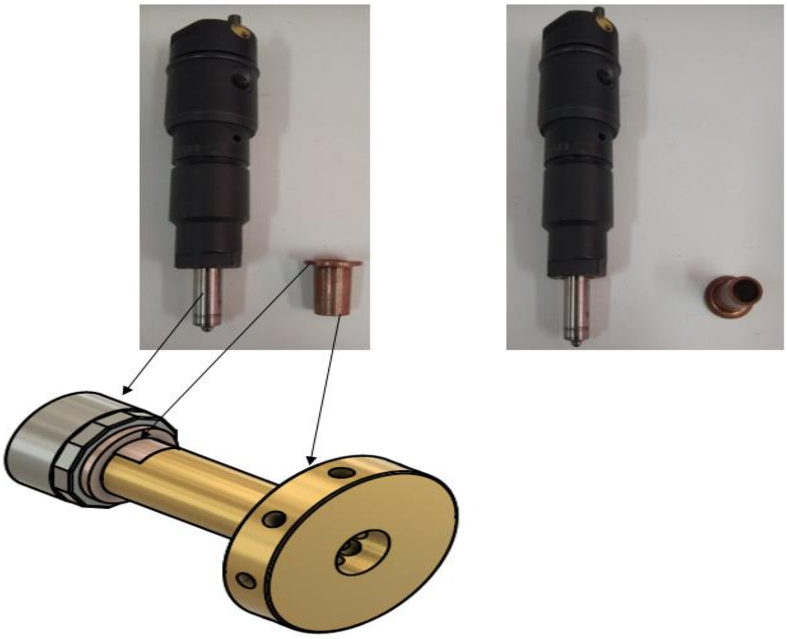

Figure 2 - Prototype from the bronze bushing.

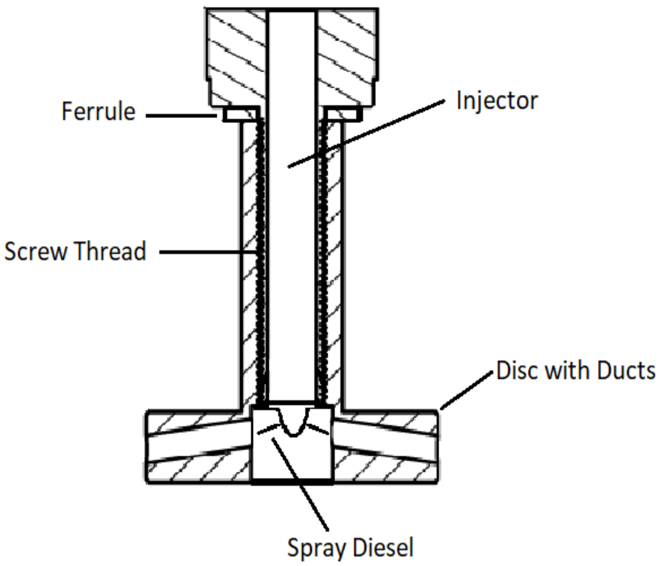

Figure 3 - Section view of the prototype.

2. EXPERIMENTAL CONFIGURATION

The engine used for the development of this work is the AVL 5402, shown in figure 4. It is a mono cylinder engine, where the injector nozzle is mounted on the cylinder head positioned between the three valves being precisely in the center of the piston, this engine also can alter the compression rate using shims in the block. The pressure inside the cylinder was measured using the AVL GU 22C pressure sensor. The fuel injection system is of the common rail type, with a piezoelectric injection nozzle with eight injection holes of 0.122 mm in diameter. The fuel used was commercial S10 diesel. Emissions of carbon monoxide (CO), thermal hydrocarbons (HC), and nitrogen oxides (NOx) were measured by an FTIR gas analyzer MKS Multigas 2030. Soot emissions were measured with the Laser Induced Incandescence (LII-300).

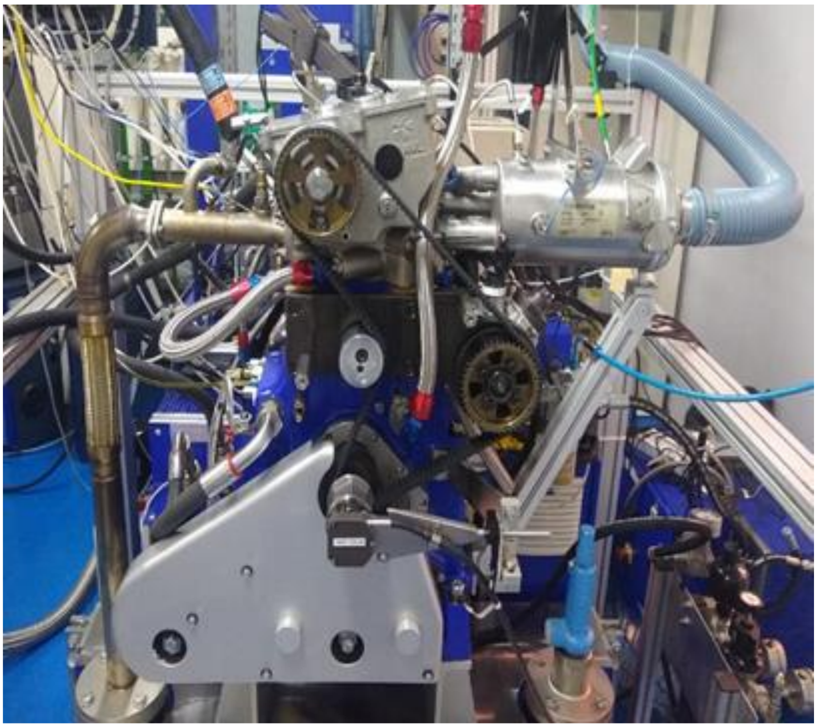

Figure 4. AVL 5402 engine.

3. TEST PROCEDURE

The trade-off between IMEP and emissions is a strategy used in the calibration of engines that in some cases can penalize the IMEP to reach the desired emission levels or vice versa. One of the ways used to achieve this goal is through the timing of the injections, therefore, one way to study how this calibration would happen with the DFI is to change the injection timings, both the main and the pilot, and show how the engine behaves in the DFI mode and free spray mode.

The results of the variation of the PILOT and MAIN injection points will be presented, the compression ratio used was 16.5:1 for the DFI and free spray. Test parameters are shown in table 1.

Table 1 - Test conditions.

Engine speed [rpm]	1200
Duration of injection (DOI) – Main [mg/stroke]	12, 15, and 21
Duration of injection (DOI) – Pilot [mg/stroke]	3
Start of injection (SOI) – Main [°bTDC]	Advance, Base and Delay
Start of injection (SOI) – Pilot [°bTDC]	Advance, Base and Delay
Injection pressure [bar]	1300
Coolant temperature [°C]	60
Injection modes	Free spray, and 3.5 mm stand-off
Compression ratio	16.5:1

Before starting the tests, a survey was made of the injection instant in which the soot would reduce to the maximum table 2. This procedure was done for the advance and for the delay of the pilot and main injections, analyzing only the behavior of the soot. After having the points defined, the tests were started where the other parameters of the engine were analyzed.

Table 8.2 - Advance and delay point for Main and Pilot injection

	DFI					
	SOI Main [°bTDC]			**SOI Pilot [°bTDC]**		
DOI [mg/st]	**Advance**	**Base**	**Delay**	**Advance**	**Base**	**Delay**
12	4.875	2.25	-1.875	18	13.125	8.25
15	4.875	2.25	-1.875	15.375	13.125	10.875
21	4.5	2.25	-1.5	15.75	13.125	10.125
	Free Spray					
	SOI Main [°bTDC]			**SOI Pilot [°bTDC]**		
DOI [mg/st]	**Advance**	**Base**	**Delay**	**Advance**	**Base**	**Delay**
12	4.875	2.25	-1.875	18.375	13.125	10.125
15	4.875	2.25	-1.875	19.125	13.125	10.125
21	4.5	2.25	-1.5	18.375	13.125	10.5

4. RESULTS

Figure 5 shows the AI 50 behavior of the pilot and main injections for DFI and free spray, it can be seen that in the pilot injection of the DFI there was an advance in combustion, both for the advance and for the delay of the injection point in relation to base, the same behavior occurred in the free spray mode, however it is noted that the combustion for the free spray is later in relation to the DFI. For the MAIN injection, the advance in the injection time did not present changes in the combustion for both cases, for the delay in the injection point the AI 50 presented a delay in the combustion for both cases, this in relation to the base.

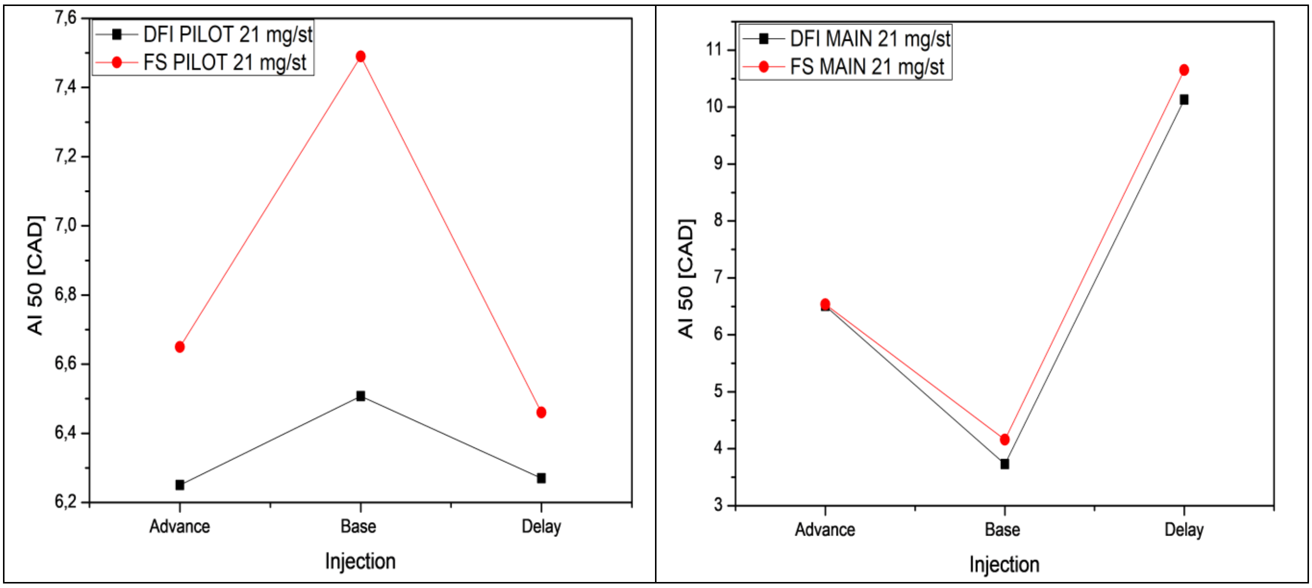

Figure 5 – Value AI 50%.

For a better analysis of the combustion, figure 6 shows the heat release rate - HRR of each injection instant, it is possible to see that in the pilot injection the HRR curves remain very close, but in the heat release of the first pre-fired flame. mixed in the advance injection showed a lower heat release, in the case of the base the heat release was more intense in the first pre-mixed flame and in the delayed injection the heat release was less intense. However, it is possible to see that the rate of heat release in the second pre-mixed flame is more intense in the DFI mode for the three cases studied. In the main injection it is possible to see that the advance to the base and the delay in the injection do not change the first pre-mixed flame, in the second pre-mixed flame it can be seen that the heat release is more intense in the DFI mode in relation to the free spray presenting a displacement in the curves in relation to the base for the delay as for the advance.

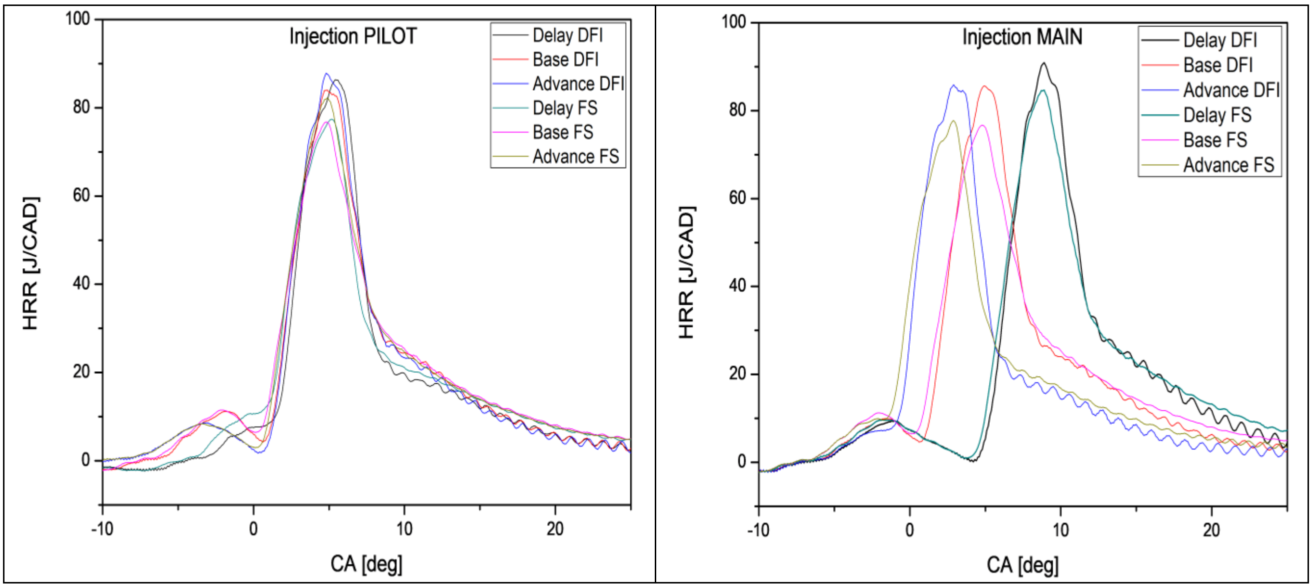

Figure 6 – Heat release rate.

Figure 7 shows the behavior of the IMEP value when advancing and delaying the pilot and main injection for the highest load studied in this work, which is 21 [mg/st] as this is the condition that most promotes soot formation. It was observed that in the pilot injection, both the advance and the delay caused the IMEP value to fall for both the free spray and the DFI, while for the MAIN injection, the IMEP values increased in relation to the baseline, but advancing the injection, the IMEP was greater than the value obtained in the delay. As the injection progresses, the second pre-mixed flame happens earlier, becoming more intense, while the first pre-mixed flame and the diffusive flame become less intense, both for FS and DFI. With combustion happening earlier, the engine is out of phase and the IMEP drops. However, as the DFI already has a greater ignition delay than the FS, the advance of combustion affects less the drop in IMEP. However, previous tests were performed without an imep maximization study with injection adjustment. Which shows that the use of the duct and the load variation requires a more careful calibration work, as the DFI changes the ideal operating point.

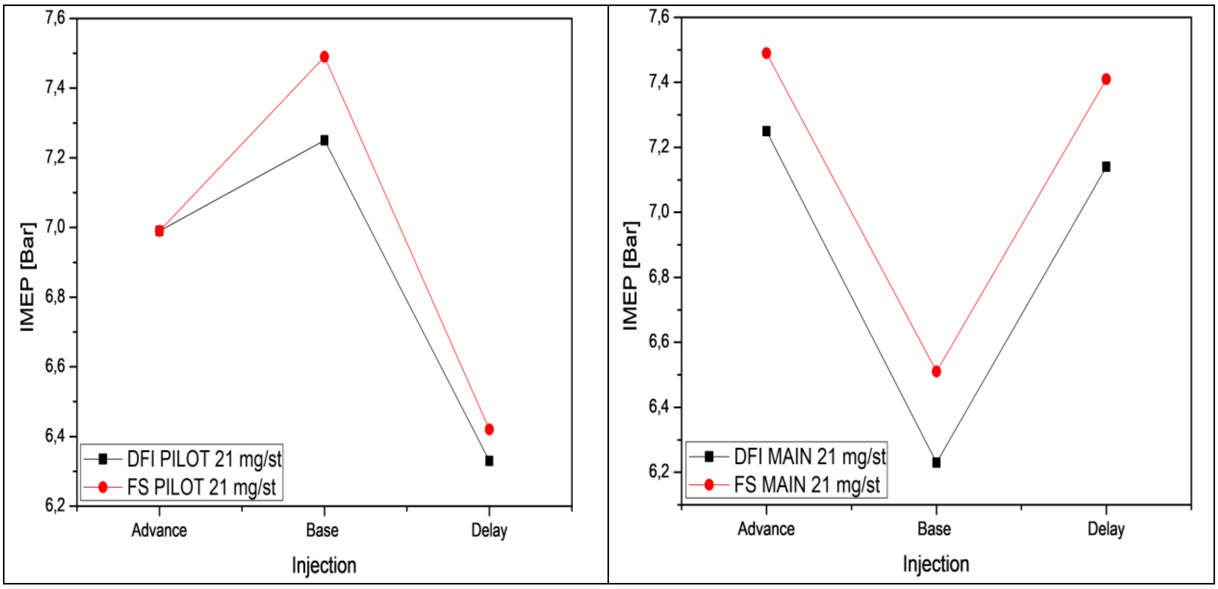

Figure 7 – IMEP values with injection advance and delay.

Figure 8 shows the variation of the cov according to the advance and the delay in the injection, for the pilot and the main one, it can be observed that for both presented an increase in the cov for the DFI mode, however the increase with the advance was noticeably greater than the increase for the delay from the base. As for the free spray, the cov decreased for the variation of the pilot injection for both the advance and for the delay, and only for the delay in the case of the variation of the main injection. The cov presented a small variation, being able to say that the engine remains stable advancing and delaying the injection.

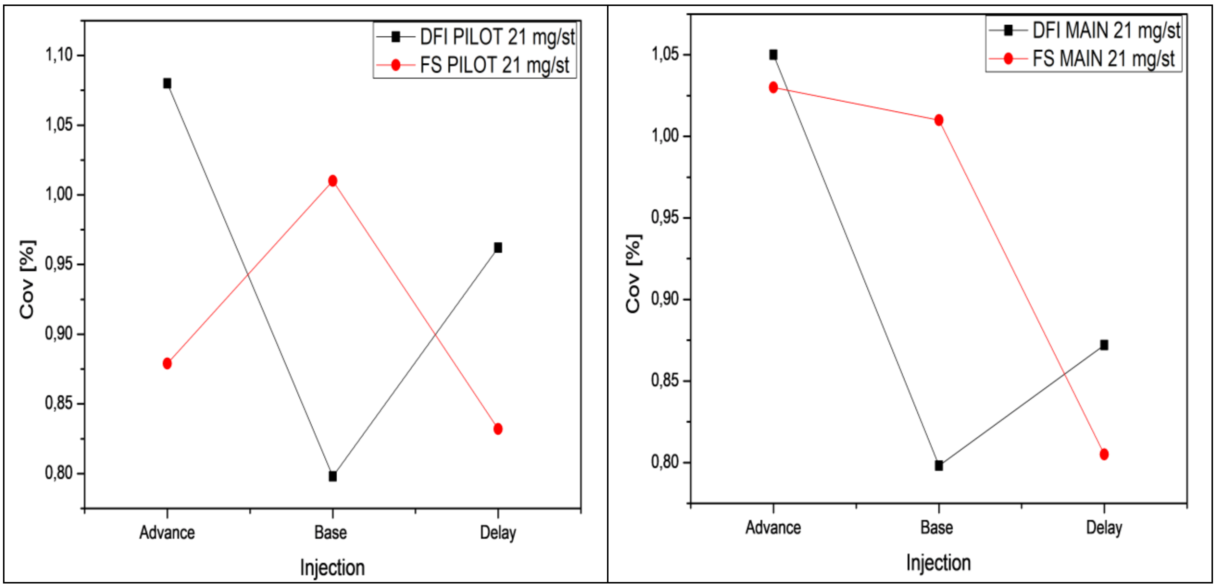

Figure 8 – IMEP Cov for advance and delay injection.

The pilot injection variation reduced free spray soot more significantly than the DFI figure 9. The advance in pilot injection using the DFI showed a 29% increase in soot levels, while the delay provided a 65% reduction in relation to the base. In the case of the main injection, the free spray only presented a reduction of 47% when the injection was delayed, in the DFI the soot reduction was for both injections in the advance it had a reduction of 58% and in the delay 49% of reduction. In the case of the main injection, the free spray only showed a reduction when the injection was delayed, in the DFI the soot reduction was for both injections, and it can be concluded that the main injection is more beneficial than the pilot injection for the DFI, in the case of the main injection. In the case of the main injection, the free spray mode was the opposite, where the pilot injection was more beneficial.

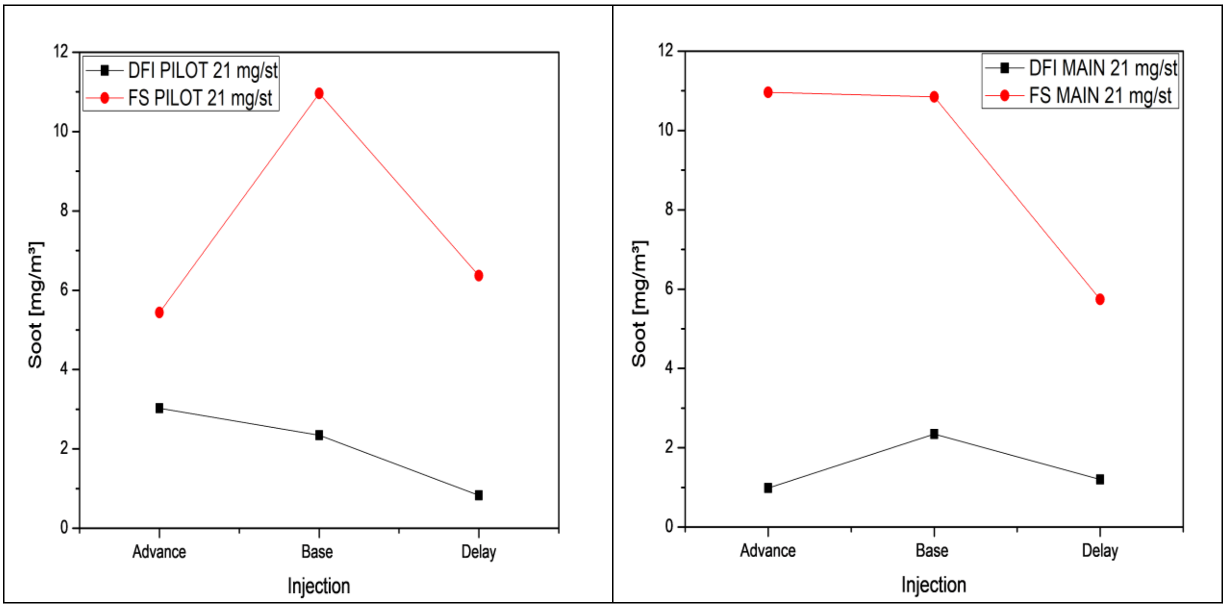

Figure 9 – Soot formation with advance and delay injection.

The NOx formation figure 10 showed an increase when the pilot injection was advanced and delayed for the DFI mode, but even with this increase it remained smaller in relation to the free spray, even for its reduced values found for the delayed and advanced conditions. For the main injection, the delay was beneficial for both the free spray and the DFI, the advance showed an increase for both modes, being higher for the DFI. This is because most of the combustion is taking place in the pre-mixed flame, the temperature is higher and the NOx rises to the DFI. In the case of FS, the HRR peak rises, but it occurs later, which may explain the drop in NOx. At the same time, less diffusive flame results in less particulate formation for the FS.

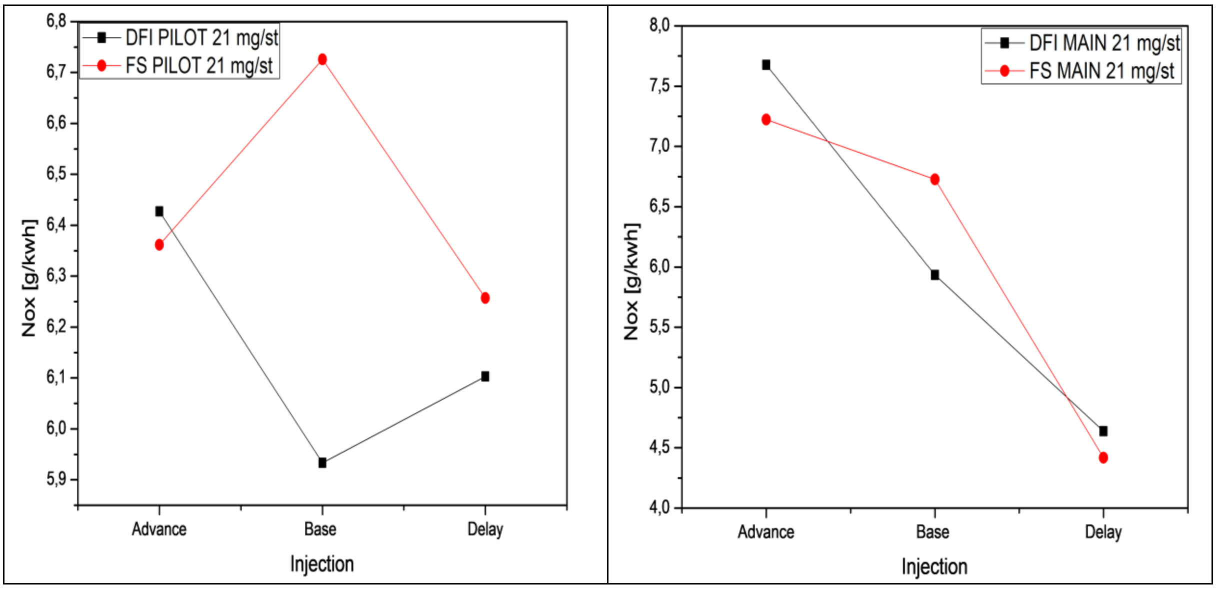

Figure 10 – NOx formation with advance and delay injection.

5. CONCLUSION

Nilsen et.al. (2020) shows that with the advance of the injection, the soot levels increase for the DFI and free spray in relation to the base, in this work this same trend is seen for the main injection, in which it shows that for the DFI mode at high load, the delay in MAIN injection is most beneficial in the cases presented. The NOx emissions in the pilot injection for the free spray showed an inverse trend to the DFI, as advancing or delaying the injection tended to decrease the formation of NOx, while for the DFI the NOx levels increased both in the advance and in the delay of the injection but still they remained below in relation to the free spray. In the main injection, NOx levels attenuated when the injection point was delayed for both DFI and free spray cases agreeing with (Nilsen et al. 2020).

The tests varying the injection point show a calibration strategy where delaying or advancing the pilot injection can bring some thermodynamic or emission penalty. In this work, IMEP was penalized to obtain benefits from emissions. In view of the results obtained, it can be seen that the delay in the main injection brought greater benefits in terms of emissions for the DFI mode, however, as already mentioned, the IMEP had its value attenuated, but it can be observed in the cov that its variation was low, being able to say that the engine remained stable.

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