



ANALYSIS OF THE CONCEPT OF FUEL INJECTION IN DUCTS - DFI WITH DIFFERENT STAND-OFF DISTANCES IN A DIESEL CYCLE RESEARCH ENGINE.

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Abstract. *The present work aimed to investigate applying the concept of fuel injection in ducts (Ducted Fuel Injection - DFI) with different Stand-off distances. The DFI concept consists of making the fuel spray pass through a small cylindrical duct immediately after leaving the nozzle injector injection orifice, thus improving the pre-mixing phase between air/fuel in the fuel auto-ignition zone in comparison to the conventional model, which is called free spray, where it is directly launched into the combustion chamber. This concept shows a significant potential for reducing soot in diesel engines, which is very interesting to meet current emission standards and reduce costs with after-treatment systems. The spacing distance has a significant effect on the results obtained with the installation of the ducts because if the ducts are too far from the injector nozzle, ignition can occur upstream of the chimney, which would cause an increase in soot in the combustion. However, the duct cannot be installed too close to the nozzle, as this would make the mixture very rich due to the deficiency of air inside the chimney, as there would be no space for air to enter the duct to have a good air/fuel mixture increasing soot levels as well.*

Keywords: *Engine, Cycle Diesel, DFI, Stand-off Distance, Soot.*

1. INTRODUCTION

The DFI was based on the Bunsen burner, that 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 allows air to enter the tube (Bunsen, *et. al.* 1857). The high speed of the fuel jet draws air into the tube, and so the air mixes with the fuel along the pipe. The improved entrainment and mixing make combustion more efficient, resulting in low soot. DFI technology can bring several benefits when applied to internal combustion engines. The first is that the flow velocity is zero at each point along the inner diameter of the duct. The presence of the duct can dramatically increase the speed 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 avoid over-mixtures that are poorer in fuel, thereby potentially increasing combustion efficiency by reducing emissions of hydrocarbons and carbon monoxides. The pipeline can also reduce and narrow the distribution of equivalence ratios by reacting during lift-off length. The proximity of the ducts in the intake valve may cause them to be colder than the gases in the cylinder, thus causing the mixture to be more colder inside the duct, allowing the mixture to occur during the ignition delay (Polonowski, *et. al.* 2011). Another benefit of DFI is that it can prevent or delay the dragging of combustion products into the spray upstream of the established lift-off length, thus avoiding the unwanted shortening of the lift-off length, which causes more soot formation. In addition, poorer mixtures may have ignition delays at the outlet of the duct, allowing a longer time for pre-mixing (Curran, *et. al.* 1998). The concept of DFI is presented in Figure 1. Figure 2 shows the essential parameters of DFI.

Previous work explored the effectiveness of DFI versus Free Spray. A variety of designs were tested in a constant volume combustion vessel that influenced designs to test the ducts in internal combustion engines (Mueller, *et. al.* 2017), (Gehmlich, *et. al.* 2018), which is the case with 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 (clearance distance), and H (Lift-off length). These parameters can be seen above in Figure 2. All values are given in millimeters.

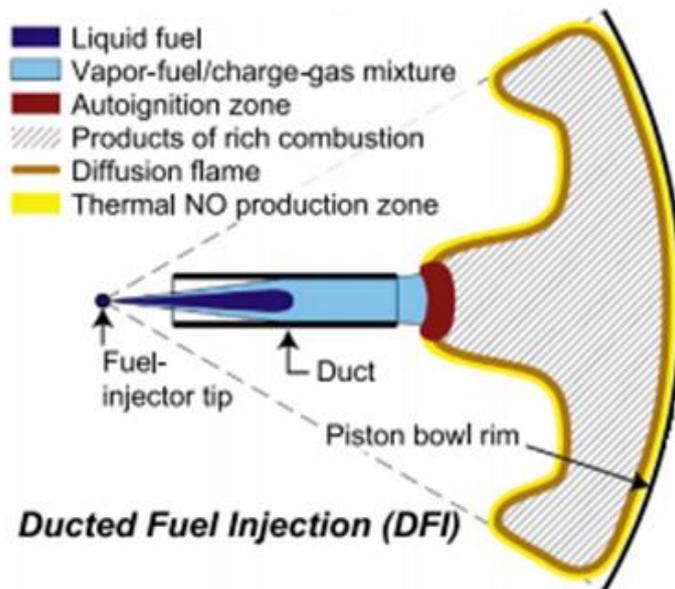


Figure 1. Scheme of the DFI Concept (Mueller, *et. al* 2017).

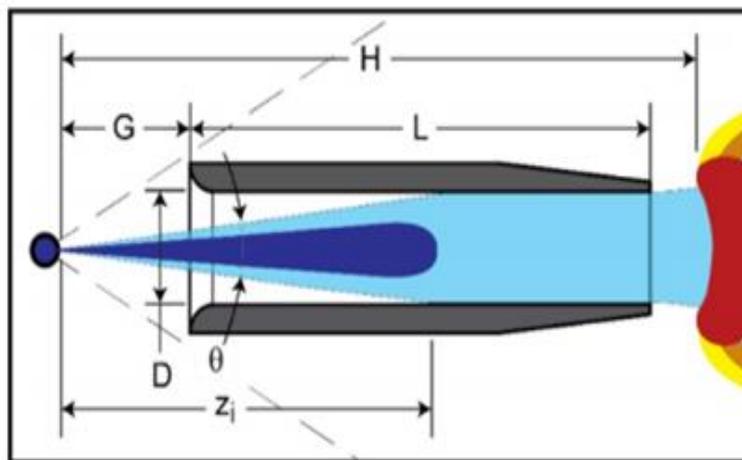


Figure 2. Important DFI parameters, adapted from (Mueller, *et. al* 2017).

2. EXPERIMENTAL CONFIGURATION

The engine used for the development of this work is the AVL 5402, shown in figure 3. 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 shown in figure 4. Soot emissions were measured with the 439 AVL opacimeter. 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. For this work, the fuel injection pressure was varied from 800 to 1300 Bar with an increase of 100. The injection duration, the injection point were kept constant. The tested ducts were D2L7.5G2.5, D2L7G3.0, and D2L6.5G3.5. For all tests, the engine worked with a low load. The ducts were made to these lengths due to a physical limitation since the increase in the size of the ducts would lead to the touch of the valves in the ducts causing damage to the engine. A summary of the test conditions is shown in Table 1.

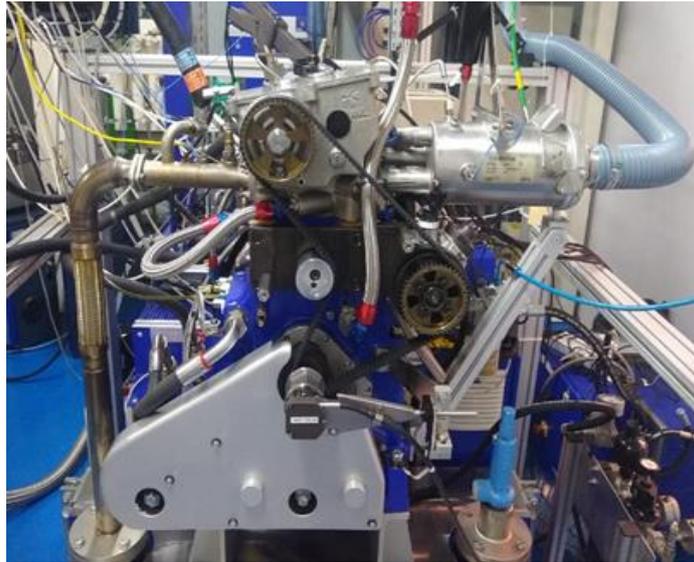


Figure 3. AVL 5402 engine.

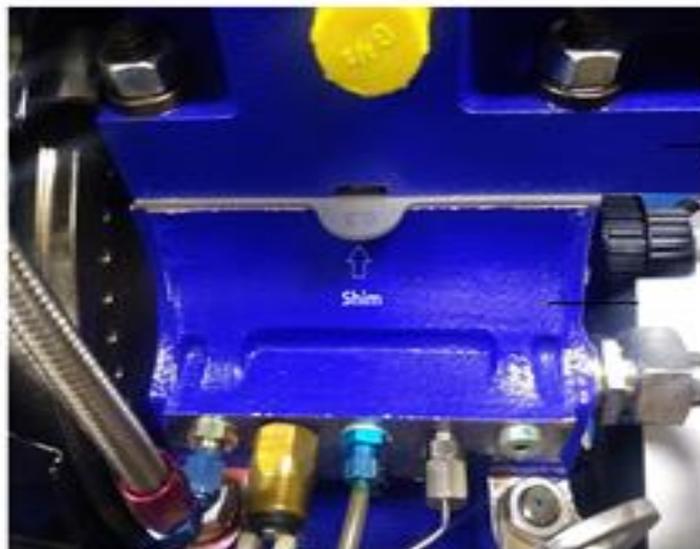


Figure 4. Compression rate adjustment shims.

Table 1 - Test conditions.

Fuel	Diesel S10
Speed	1200 RPM
Displacement	511 cm ³
Duration of Injection (DOI) Main	12 mg/Stroke
Duration of Injection (DOI) Pilot	3 mg/Stroke
Start of Injection (SOI) Main	2.25° BTDC
Start of Injection (SOI) Pilot	13.125° BTDC
Injected Pressure	800, 900, 1000, 1100, 1200, 1300 Bar
Coolant Temperature	60°C
Ducts	D2L7.5G2.5, D2L7G3.0 e D2L6.5G3.5 vs Free Spray

Figure 5 shows the assembly of the ducts in the engine head, in the image the installed duct is the D2L6.5G3.5.

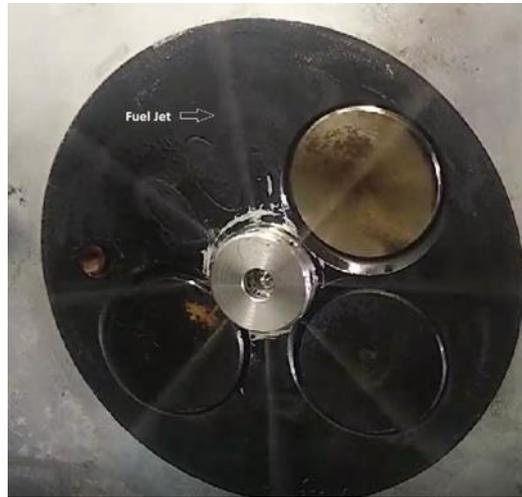


Figure 5. D2L6.5G3.5 duct installed in the head.

3. TEST PROCEDURE

The tests carried out with the free spray were used at a compression ratio of 16.5: 1. For the tests with the ducts, the compression ratio was recalculated considering the volume that the ducts occupy inside the combustion chamber. In this case, the engine was configured with a compression ratio of 16.0: 1. However, the final compression ratio is 16.5: 1 due to the volume of the ducts, so the tests for free spray and with ducts were performed with the same compression ratio, figure 6 shows the free spray pressure curves, and with the ducts, this image confirms that the engine ran with the same compression ratio for all tests, the slight difference between the pressure curves is given due to the delay in the start of combustion, this delay is due to the presence of the ducts. For this work, the COV of IMEP was similar for DFI and Free Spray in approximately 1.68%.

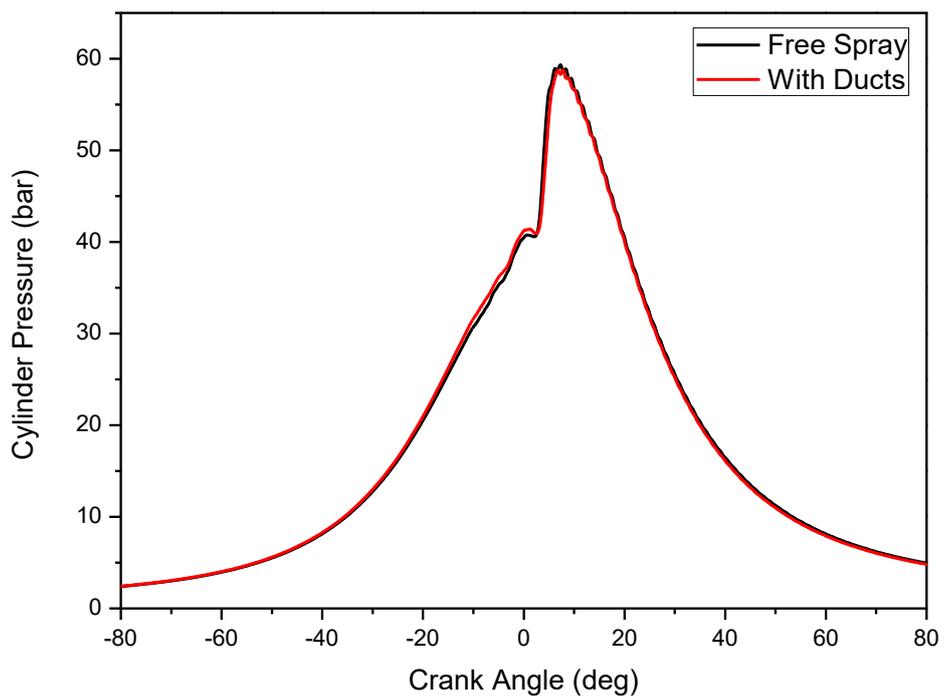


Figure 6. Free Spray and Duct Pressure Curves.

Three tests were carried out for each condition, with an acquisition time of 180 seconds, but the acquisition of the results was only started after the engine stabilized its working temperature. Figure 7 shows the engine temperature stabilization curve. The procedure performed was as follows: the injection pressure varied from 800 to 1300, 1300 to 800 and, finally, from 800 to 1300 Bar with an increment of 100 Bar. This procedure was used to guarantee the reproducibility of the results.

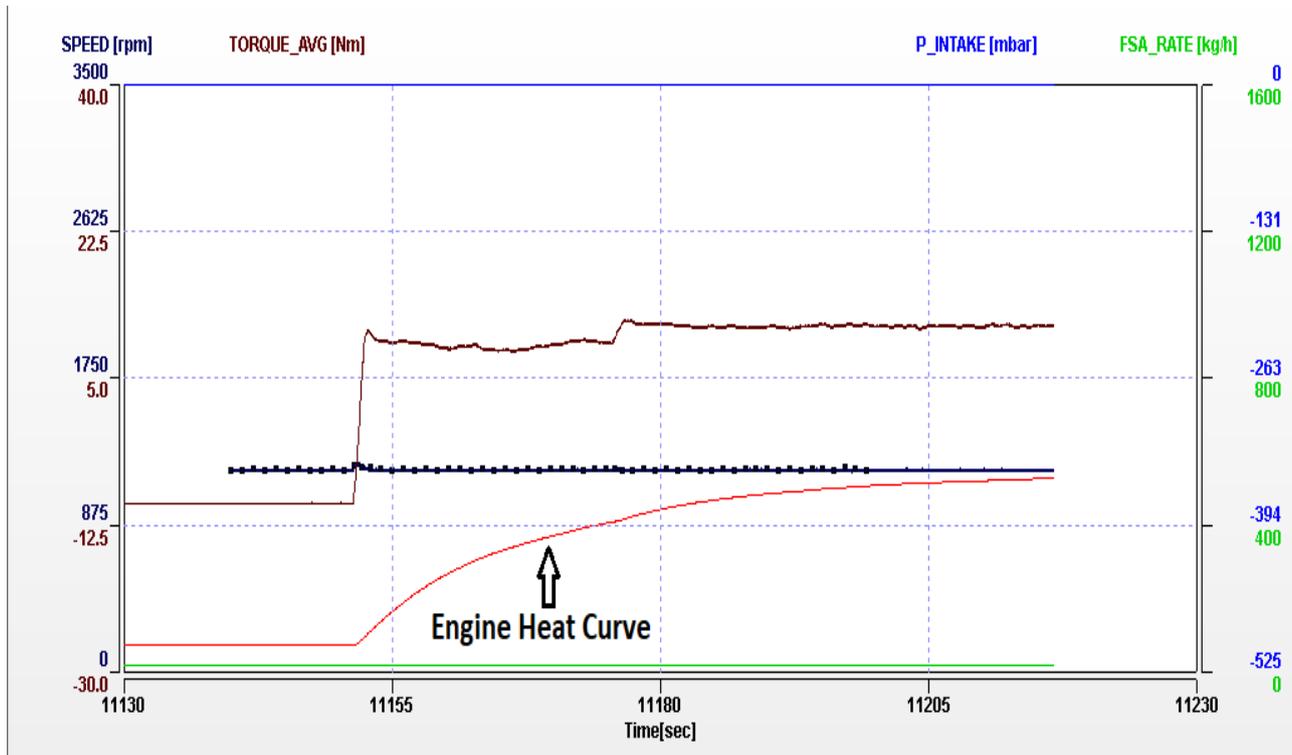


Figure 7. Engine heating curve.

3. RESULTS

Figure 8 shows the AI 50% values, and these values refer to the instant in degrees of the crankshaft when combustion consumes 50% of the fuel injected into the combustion chamber. It is visible that the D2L7.5G2.5 duct had a delay in relation to the other ducts and also to the free spray. Due to the distance being very close to the injector nozzle, this delay can be explained by the fact that the drag of air into the duct is inefficient, impairing the mixture. Thus, the mixture leaves the duct and enters the combustion zone with a very rich mixture, delaying the burning. The D2L6.5G3.5 duct, on the other hand, has a small pressure delay of 1100 Bar in relation to the free spray, so it is understood that the air inlet in the duct was efficiently providing a burn very close to that of the spray free.

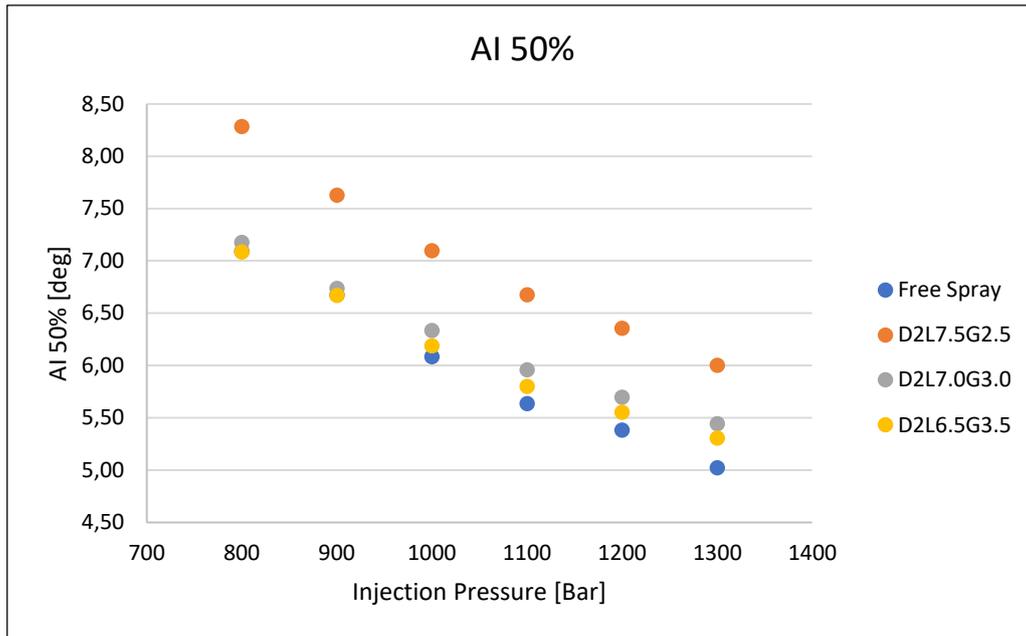


Figure 8 – Value AI 50%.

Figure 9 shows the values of IMEP to the cases tested, it is noted that the value of IMEP for free spray was higher than the three ducts tested. Using the AI 50% graph, it is possible to explain this behavior since the AI 50% of the free spray was more advanced about the ducts. Due to this, the combustion occurred before, thus increasing the indicated average pressure. For the D2L7.5G2.5 pipeline, it can be seen that the IMEP value is lower than the other pipelines and also the free spray. This can also be explained using the AI 50% value, where we can see a delay in the combustion concerning the others. This causes the average pressure indicated to decrease due to the piston traveling through a higher degree of the crankshaft to consume 50% of the fresh mass inside the combustion chamber.

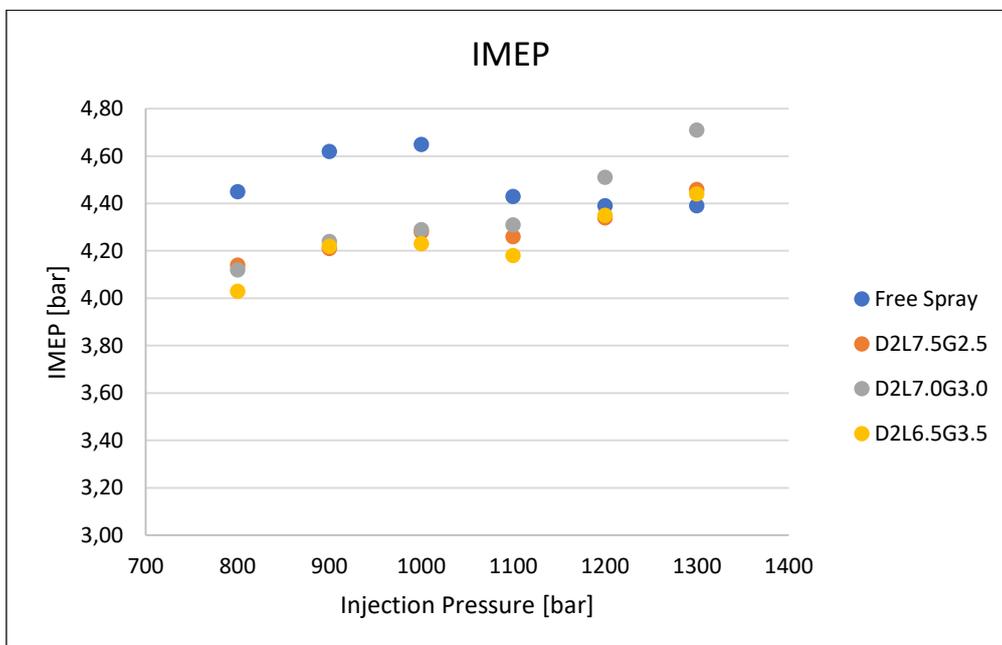


Figure 9 – Values of IMEP results.

Figure 10 shows the temperature values of the exhaust gases for the conditions tested. We know that the higher the temperature of the exhaust gases, the better the burning inside the combustion chamber. However, these values can also respond to the Nox behavior that is shown in figure 11. It is seen that the NOx value for the free spray is higher than the NOx value of the ducts, this is because combustion with free spray had a better burning of the mixture, so the exhaust

temperature graph shows that the temperature in this condition was also higher concerning the others tested, proving the theory. For the D2L7.5G2.5 duct, it can be seen that the NO_x levels are the lowest among all the conditions tested, and it can also be seen in the temperature graph that, for this case, the temperature was also the lowest among all the conditions tested. This same behavior occurs for the D2L7.0G3.0 and D2L6.5G3.5 ducts, which have very close exhaust temperature values, so in the same way, the NO_x levels are also close for these two cases.

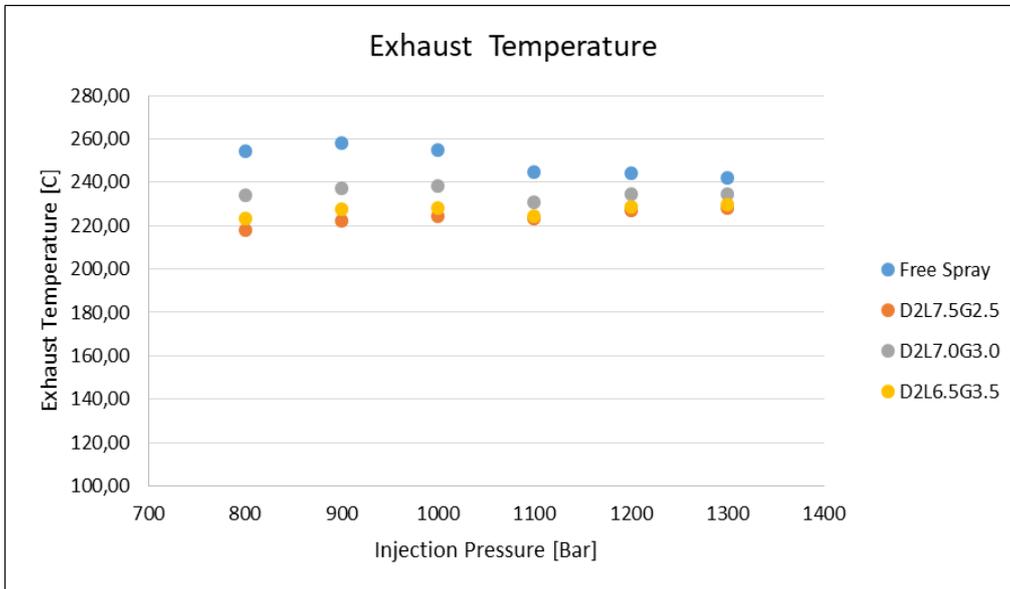


Figure 10 – Exhaust Gas Temperature.

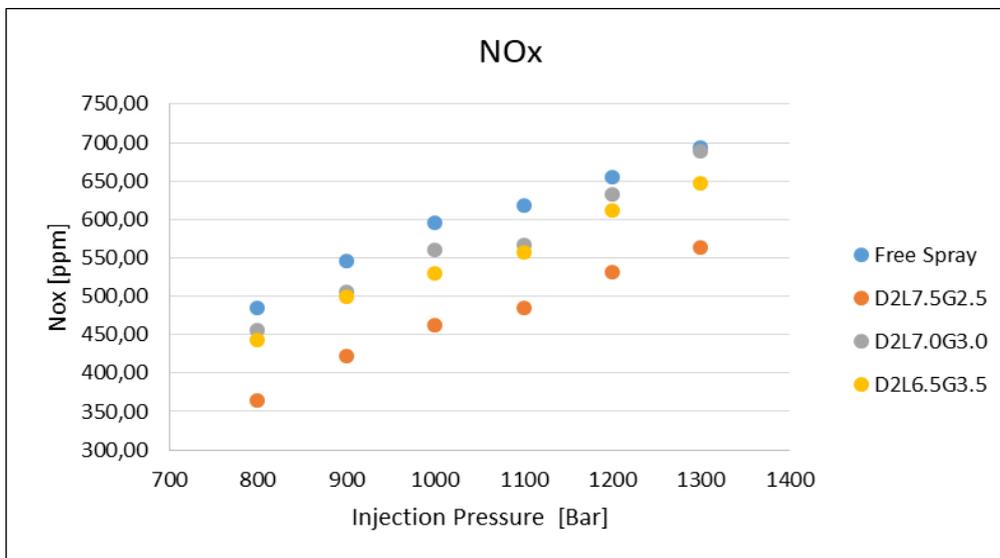


Figure 11 – NO_x levels for the cases tested.

Figure 12 shows the results obtained from soot that are presented as a percentage of opacity. It can be seen in the graph that the D2L6.5G3.5 duct had a better result for all conditions concerning the free spray. This is because the more significant the stand-off distance, the greater the drag of air into the ducts, thus having a better mixture between air and fuel. The same occurs with the D2L7.0G3.0 duct, this is a little less effective concerning the D2L6.5G3.5, but it still exceeds the soot levels of the free spray up to 1200 Bar of injection pressure. The D2L7.5G2.5 duct, on the other hand, had worse behavior concerning the free spray. This is because the air drag into the ducts is deficient due to the small stand-off distance. With the increase in pressure, it is noticed that the soot levels increase even more, this is due to the fuel being very rich in the mixture when it leaves the duct where the combustion begins, causing a fuel-rich burning that generates high levels of soot.

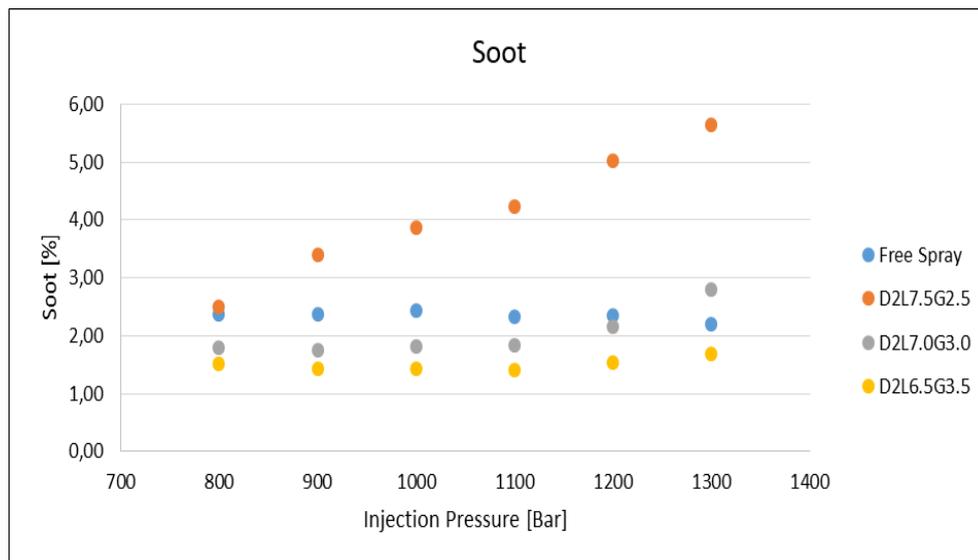


Figure 12 - Results Obtained from Soot.

4. CONCLUSION

Comparing the free spray with different DFI configurations reveals that the presence of the duct can reduce soot. In this case, the duct with the best efficiency was the one with the longest stand-off distance of 3.5 mm. In addition, it was observed that the presence of the duct causes a delay in combustion, as shown in Figure 8. In addition, it is visible that a stand-off distance of 2.5 mm causes a deficiency in the air/fuel mixture within the duct, thus raising the soot levels. The values of IMEP were lower when with the ducts concerning the free spray. This decrease in the values of IMEP was due to the delay in the start of combustion.

The NO_x values released by the combustion proved to be less when with the ducts installed in relation the free spray. As mentioned earlier, the combustion delay makes it impossible to have a complete burning of the existing fuel inside the combustion chamber since the piston is already very close to the PMS when combustion starts. Due to this, we have a lower NO_x value with the ducts in relation the free spray.

The soot values obtained with the D2L6.5G3.5 duct show that the DFI concept does have a possible potential for soot reduction. It is also possible to see that at 1100 Bar of injection pressure, we have the best efficiency for this duct. Therefore, it can be concluded that the DFI has an optimal operating range.

4. REFERENCES

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