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DIAGNOSTIC OF MECHANICAL FUEL INJECTION SYSTEMS OF HEAVY DUTY DIESEL ENGINES BASED ON MEASUREMENT OF FUEL INJECTION PRESSURE

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Abstract. *Heavy duty combustion engines applied in power plants often need maintenance to operate efficiently in terms of break power output and within the allowed limits of emissions. Common malfunctions reported in this type of systems are associated to wear of injector and high-pressure pump components, spring pre-load reductions and others. This work is focused on testing mechanical fuel injection systems, evaluating the performance based on fuel injection pressure and comparing the aged components performances against the results of a reference system. The development of a bespoke rig to test the injection components has been considered, since the rig objective is to test components in the same conditions as operating in the engine. The results give an insight into the injection system behaviour characteristics such as start of injection, injection duration and pressure levels which affects the fuel atomization. The discussion highlights possible indicators to be derived from this diagnostic to assess amount of fuel injected. Also, the learning outcomes of this kind of analysis are of interest to monitor the injection system conditions throughout the life cycle of the components and maintain the engine working optimally.*

Keywords: *Diesel, Heavy duty engine, Fuel injection system, Injection pressure, Malfunctioning components*

1. INTRODUCTION

After several hours of operation, it is expected the components of a reciprocating engine need maintenance to continue working properly. In the case of liquid fuelled combustion engines, the maintenance of fuel injection system components is very relevant for power generation and pollutant emissions as malfunctions of this system result in inefficient combustion. Therefore, it is important to monitor injection system conditions, during the components life cycle, and follow strict maintenance plans to guarantee good engine performance and control emissions.

Some of marine and energy applications rely on large compression ignition engines equipped with fully mechanical injection systems. These systems feature a camshaft driven high-pressure pump responsible for fuelling an injector with calibrated opening pressure according to the injector spring pre-load. Start of injection is determined by increase of fuel pressure on injector needle which overcomes the spring pre-load allowing the fuel to flow through the nozzles to the cylinder of the engine (Kuiken, 2008).

Malfunction of injection system components changes the injection pressure which is the main variable controlling the system response and atomizing the fuel in the engine's cylinder. Modifications in injection pressure affects injection timing, in these particular mechanical injection systems, but also ignition delay and consequently the combustion process in Diesel engines (Heywood, 2018). During early injection time, the fuel enters the engine's cylinder in lower pressure and temperature, delaying the start of combustion and injecting more fuel at the beginning of the process. However, retarding the beginning of the injection event results in lower pressure and temperature during the combustion process, hence reducing NO_x formation but operating out of optimal conditions (Duran et al., 2012). Often malfunctions associated to increase of emissions are the decrease of injector opening pressure and wear of injector and pump components (Grados et al., 2009). The injector opening pressure may be caused by two factors: injector needle seat wear or fatigue of the spring. Both problems reduce the spring pre-load and thus, the start of injection occurs at lower injector opening pressures

(Luoma, 2020), changing the fuel atomization and injection timing. Common issues often found on the high-pressure pump are wear of plunger-cylinder contact, also malfunctions of delivery and constant (relief) pressure valves.

Given this context, the purpose of this work has been to investigate fuel injection systems of a targeted engine and diagnosing possible faulty conditions based on measurements of fuel injection pressure and performance. The results are valuable to monitor the components during their respective life cycles, every scheduled maintenance, and helpful to keep the engine working at the best of its efficiency.

2. METHODOLOGY

The analysis is focused on the Wärtsilä W32 engine family, a compression ignition engine developed for heavy duty applications featuring an injection fuel system per cylinder of the engine. Although the W32 main application is for the marine industry, this work evaluated injection systems of the engine W20V32 which are part of gensets in power plant applications. The engine mostly operates with heavy fuel oil (HFO), but it also burns light fuel oil (LFO) to start operating. This system is fully mechanical and works in accordance to the previous description in the first part of the text. Sketches of the high-pressure pump, showing the parts for thorough understanding about the components subject to malfunctions, may be seen on Figure 1. Both, injector and pump (Figure 2) are manufactured by Woodward L'Orange.

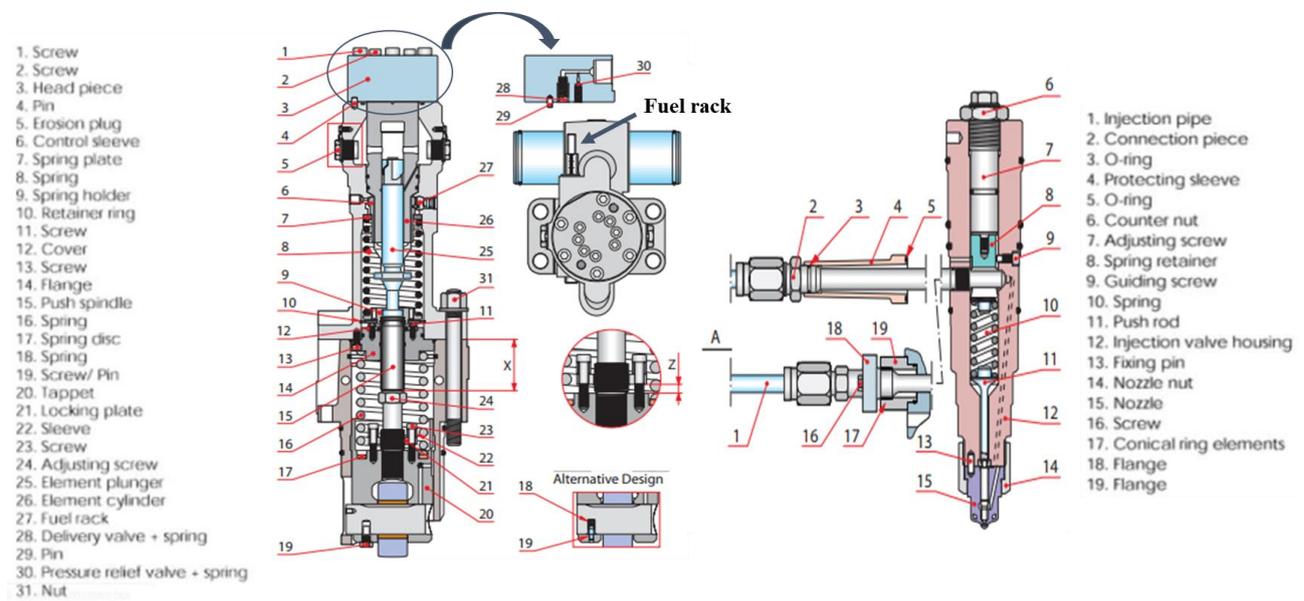


Figure 1 - Injection system components. Left: High-pressure pump, Right: Injector. Adapted from Kaarakainen (2015)



Figure 2 – Testing Components. Left: High-pressure pump, Centre: Injector, Right: Injection system on the test rig

2.1 Test bench

The investigation of the system performance has been conducted in a bespoke rig, specifically developed for this project purpose, aiming fuel pressure measurement along every injection event duration. The test bench concept (Figure 3) sought to mimic the injection system operating conditions, hence the pump tappet has been mounted on the engine's original camshaft to not change the dynamics of the system. The camshaft has been driven by an electric motor and balanced by a flywheel to maintain constant speed while testing. Fuel has been delivered to the high-pressure test pump with a flow rate according to the injection system requirements during engine operation (Wärtsilä, 2014). Though, the amount of fuel injected has been regulated by a linear actuator selected to determine the rack position in the high-pressure pump along with the injection system conditions.

An acquisition system (LabJackT7) programmed using MATLAB collected the fuel injection pressure and angular velocity data with an acquisition frequency of 50 kHz per channel. The pressure has been measured by a Kistler pressure system (Sensor 4067E and Amplifier 4624A), mounted on the high-pressure pipe which connects the pump and injector (Figure 2 – Right), and the angular velocity by a Tecnotron inductive sensor. In addition to acquire data, the system also controlled the speed of the camshaft and monitored the rig throughout the test duration.

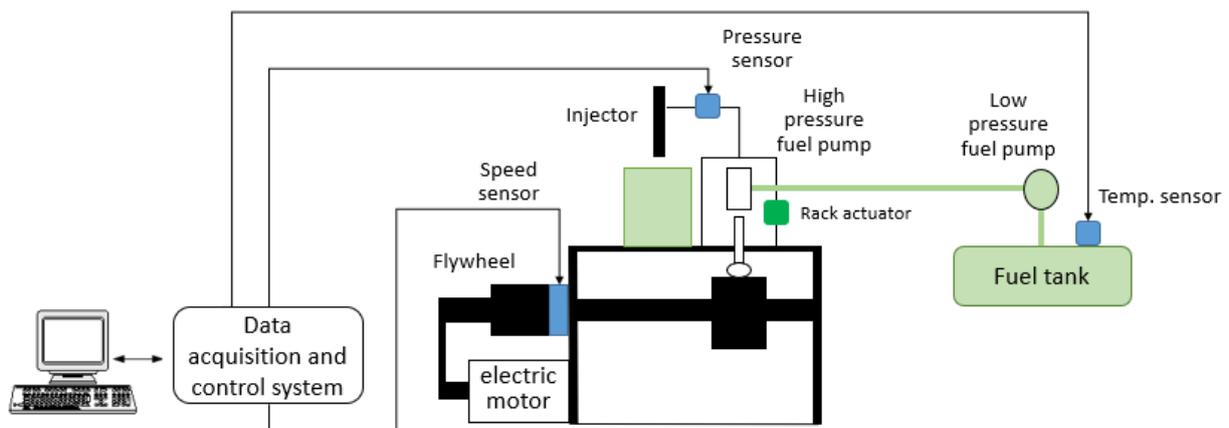


Figure 3 - Test bench concept

2.2 Components and testing conditions

As to selecting the aged components to be tested, the most relevant information taken into consideration has been the quantity of hours the injection systems have been in operation before any maintenance. Therefore, two pairs of injectors and high-pressure pumps have been disassembled from two engines exposed to different aging environments. The number of hours in operation of the components is shown in Table 1.

Table 1 - Testing components aging conditions

Components	Number of hours in operation
Injector A (IA)	1,400
High pressure pump A (HPPA)	4,096
Injector B (IB)	368
High pressure pump B (HPPB)	26,882

In order to evaluate the performance of the tested injection systems, standard procedures have been adopted as a matter of assuring the components would be tested in similar conditions as operating in the engine and avoiding bias towards any malfunctions for fair comparisons against a new injection system (reference) at the end. Thus, the following information have been taken into account for testing procedures:

- The low fuel pressure feed lines supplied the flowrate of 180 litres/hour at 6.5 bar to the tested high-pressure fuel pump;
- After starting the electric motor, the camshaft speed has been monitored until there was very little variations and the average shaft speed was 360 rpm (which is the rotational speed at the usual operating condition at the power plant);
- Same rack position for any high-pressure pump tested;
- For every test run, the acquisition system stored data of 100 injection events;

- Each component testing combination has been repeated three times for statistical analysis.

Since the development of the test rig considered only operation with LFO, the tests have been held with controlled Diesel S10 quality. Also, the aged components have been tested on the rig without any previous maintenance, since they have been removed from the engines, but cleaning, which have been done to prevent the contamination of the testing Diesel with HFO as the engine operates burning this type of fuel.

The tests of the injection system components consisted of three parts for post procedures analysis. First part tested aged injectors (IA and IB) using the reference pump and the second part tested the used high-pressure fuel pumps (HPPA and HPPB) combined with the new injector of the reference system. Last part consisted of testing the worn pairs of injection systems for comparing each respective performance, in terms of fuel injection pressure, against the reference system (new components).

3. RESULTS AND DISCUSSIONS

3.1 Repeatability analysis

The first analysis verified the consistence of pressure data obtained with respect to repeatability. Latter approach focused on plotting the pressure measured during every injection event, calculating the average pressure curve for each test run and all data collected. For the reference injection system tests, the maximum deviation found is 5,37% with respect to the maximum pressure value of the average curve and the results of this repeatability analysis may be seen on Figure 4.

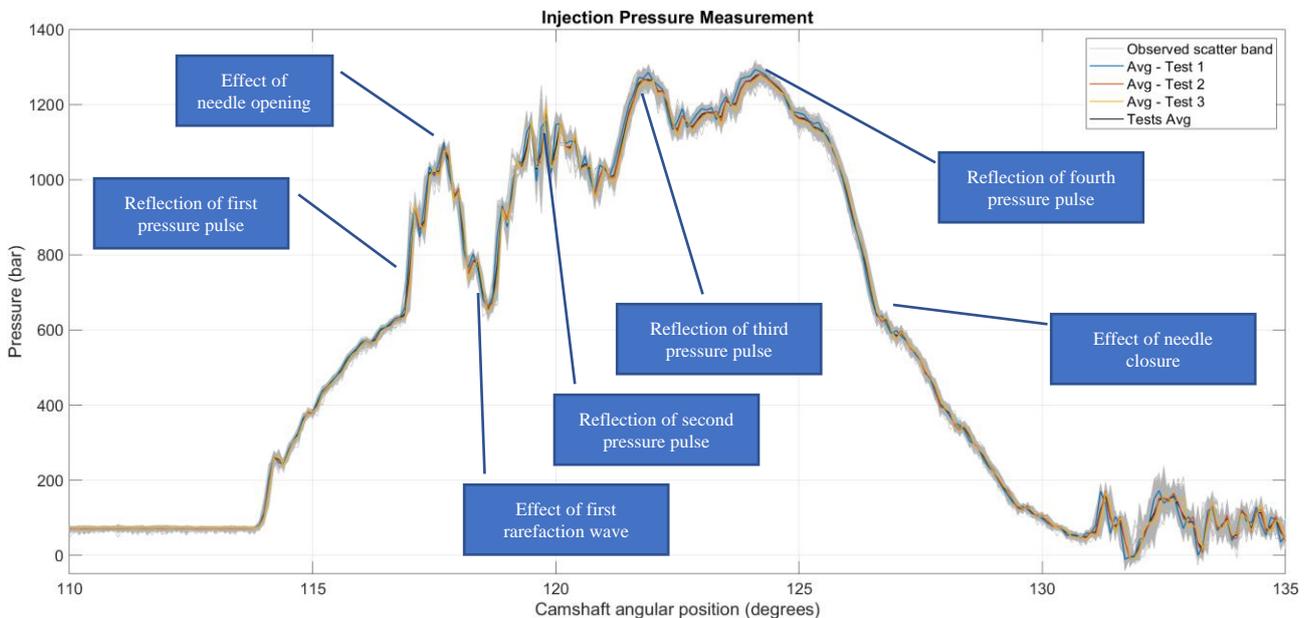


Figure 4 - Injection pressure data for repeatability analysis

As the pressure is measured on the high-pressure pipe (around 230 mm downstream the pump outlet), the plotted data is always a consequence of the events that happened before. So, observing the obtained pressure data, the pressure firstly rises as a consequence of the delivery valve opening that occurred before the 114° of camshaft angular position displayed on the graph. Subsequently, pressure increases steeply until it reaches a peak and suddenly decreases. Former effect is caused by the reflection of the first pressure wave which moves until the injector needle and returns. Likewise, latter represents a rarefaction wave caused by the injector needle opening that flows back towards the pump. Therefore, the first pressure drop observed is an indication of start of fuel injection. Following, measured peaks and spikes on the curve represent the reflection of pressure waves noted by the pressure sensor due to the fluid dynamics response in the high-pressure pipe. At the end of the event (about 126° of camshaft angular), the pressure decreases in a higher rate and then transitioned to a more moderate one. The transition point is an interesting fact as it is caused by the reflection of the injector needle closing which is noted afterwards as well. Finally, the measured pressure starts to oscillate around the same level of pressure, like before the injection event initiated, as reflected pressure waves have not been dissipated yet.

Even though the graphs of each tested component case are not presented, all the collected pressure data demonstrated to be as consistent as the one shown in the previous image with very little variance. Therefore, the forthcoming discussion about the comparison of performance between aged and reference components are supported based on average pressure curves and their respective standard deviations plotted in specific points.

3.2 Injector performance

With the aim of analysing the injector performance separately, the reference pump has been used to pressurize the fuel into the tested injectors. The pressure measurement results for this tests are shown on Figure 5 as well as their respective standard deviation calculated at 2.5° interval highlighting small differences between curves.

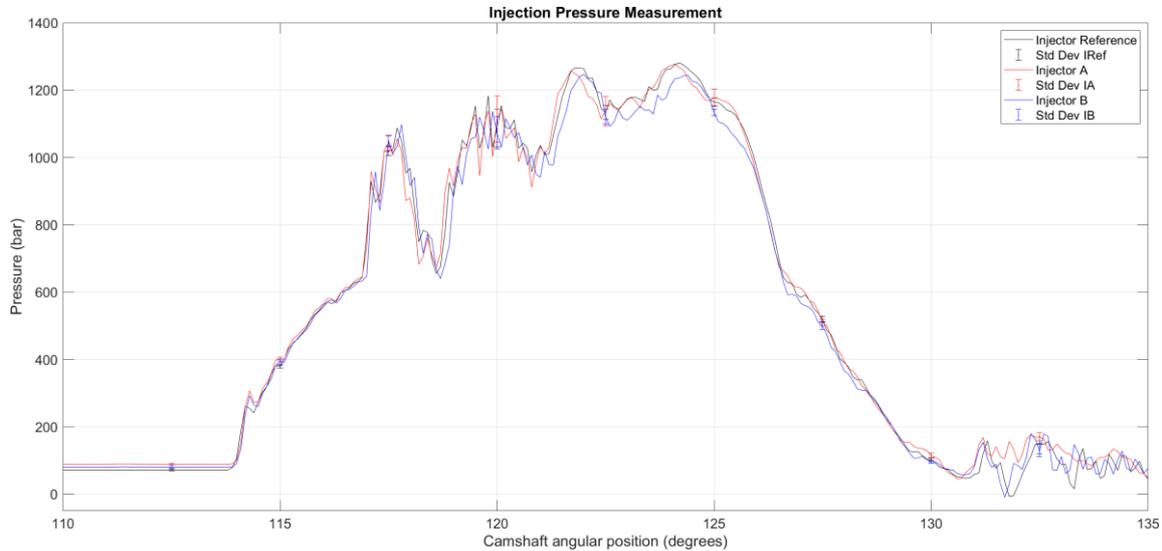


Figure 5 - Injector performance results

During the pressure increase phase – while the needle is expected to be closed, both aged injectors performed very similar to the reference one. After the start of injection, which is considered by the local minimum (approximately 119° - camshaft position), injector B demonstrated a small difference in performance as its pressure curve seems delayed and achieving lower pressure levels in a few occasions and a slightly early end of injection, since the pressure decreased before than other tested injectors. Latter could indicate the total amount of fuel delivered by injector B is marginally less than the amount delivered by other injectors. Though, it is very hard to consider this as a faulty condition diagnostic without measuring the quantity of fuel injected which is planned for future improvements of the test bench.

3.3 High-pressure pump performance

Likewise the investigation for the injectors, the aged high-pressure pumps have been tested in combination with the reference injector. This test sought to understand the influence of the pump components regardless of the respective aged injectors performance. The measured injection pressure of this analysis is displayed on the following graph (Figure 6).

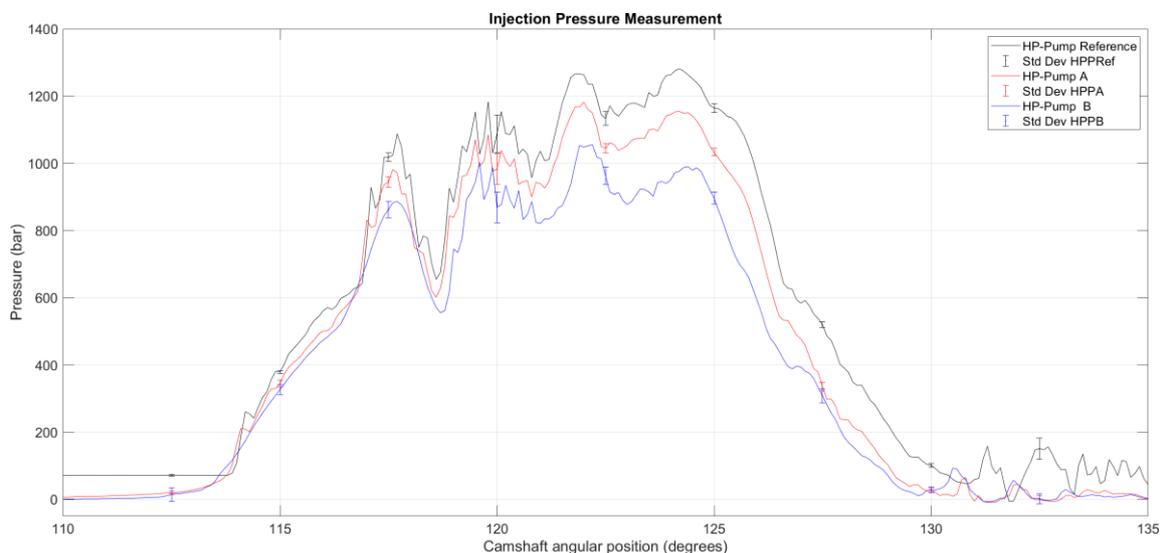


Figure 6 - High pressure pump performance results

In contrast to the injector test outcomes, the results obtained from the aged high-pressure pump test are interesting due to the extent possibility of faulty conditions. Firstly, the low pressure level measured within the period the pump is not pressurising the fuel is an indicator of constant pressure valve malfunctions (Figure 1 - Left). This valve is designed to allow fuel flow from the high pressure pipe, which connects pump and injector, back to the pump chamber for pressure differences of approximately 130 bar, preventing cavitation in this part of the injection system and undesired additional injection events after the main one. Another relevant fact to observe is the difference in injection periods. The higher the number of hours the pump has been in operation, the shorter the injection time duration. Hence, considering that overall pressure levels are lower in conjunction with the smaller duration, one can expect quite different amounts of fuel delivered.

Despite of not showing any delay to start increasing the fuel pressure, both aged pump pressure curves seem to have a less steeper slope in comparison to the reference pump. This may be caused by deficiencies in the delivery valve working dynamics. Apart from that, the performances of the aged components throughout the injection event are clearly poor as the pressure levels are lower than the reference pump (HPPA about 7% lower and HPPB about 20% lower). Besides, since the injection event started (curve minimum after first peak), HPPB is shifted by 0.2° (camshaft position) in comparison to the reference pump.

In addition to the previous causes, the main reason to the lower levels of pressure measured may be wearing on the plunger-cylinder contact. This type of injection pump does not feature any sealing between the components, but the micrometric manufacturing tolerances. The lack of sealing parts is intention of design, hence some leakage is expect. But, once the surface contact wears off, fuel excessively leaks from the top of the plunger decreasing the fuel pressure and amount of fuel injected. The excessive leakage has been observed in both aged pumps tested. Further investigation needs the disassembling of the pump components, though.

3.4 Aged injection system performance

Following the methodology, the aged high pressure pumps have been tested combined with each injector respectively in order to compare the entirely injection systems performances (Injection System A – ISA and Injection System B – ISB) against the reference one (Injection System Reference – ISRef). The pressure results are shown in Figure 7.

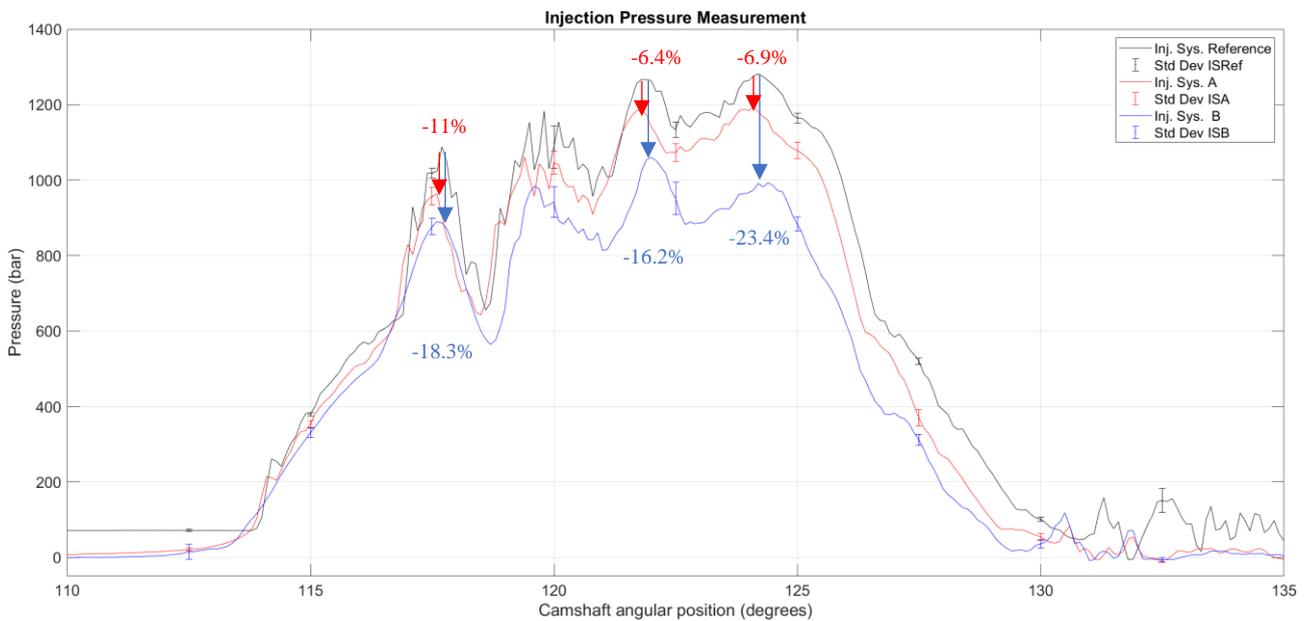


Figure 7 - Comparison of aged injection systems performances

Although the performances of the aged injection system are mostly dominated by the high-pressure pump and not by the injector performance, there is some overlay of effects. After the start of injection, the pressure decreases and suddenly increases back again (around 118° position). For this particular period, the injection system B results show a small delay due to the performance of the injector, while the injection system A performance response is very similar to the one characterised during the injector tests.

As a consequence of the degraded level of pressure throughout the injection event and the differences in injection time duration, the aged injection systems will certainly deliver less quantity of fuel even if the rack position is the same for all of the high-pressure pumps tested. Therefore, rack position adjustments must be considered to balance the delivered amount of fuel, should the aged systems continue in operation. Also, the reduced pressure levels must be taken into consideration when balancing the quantity of fuel injected, as they are probably caused by fuel leakage.

Not only do the lower pressure levels penalise the amount of fuel delivered, but they also influence the spray formation and fuel atomization. None of these spray effects may be assessed using the pressure diagnostic proposed, but the test responsible may report the low pressure level as an indicator for possible atomization issues. Next steps of this project will focus on characterising the spray formation and droplet sizes with the intentions of understanding changes in fuel atomization and spray behaviour.

4. CONCLUSIONS

A method of analysing possible faulty conditions within the injection system has been presented. The advantages of using such procedures is the ease of testing, since the injection system is disassembled from the engine and tested on the rig. Also, the pressure measurement diagnostic provides indications of possible components operating in faulty conditions without any previous intervention. On the other hand, it does not ensure any specific part malfunction and there are needs for issue confirmation. In addition, the diagnostic does not evaluate the spray conditions in terms of fuel atomization.

Based on the observations of this investigation, the following outcomes are listed as per below.

- The injector performance seems to play a small role on the overall performance of the injection system, at least for the injector's wear conditions analysed. Although the results obtained show lower levels of pressure and slightly early end of injection (injector B), the information is not enough to support whether there are relevant differences in quantity of fuel delivered by the aged injectors.
- Inversely, the performance of the high-pressure pump strongly affects the performance of the injection system. The diagnostic of the lower levels of pressure are supported by the leakage noted during the tests and firmly suggest the plunger-cylinder contact may be worn allowing fuel to be wasted rather than delivered to the injector. Adding to the wasted fuel problem, the injection period is also reduced considerably and thus, the quantity of fuel injected is clearly less in comparison the reference system standards. The integral of the pressure curve may become an indicator for fuel delivery comparison amongst tested injection system components.
- Other possible faulty components in the aged pumps are the delivery and constant pressure valves. Former may be diagnosed from the slope when the injection pressure starts to increase and latter, from analysing the pressure level between injection events. These conclusions are derived from the high-pressure pump tests, but they may also be seen on the injection system results as the injector does not influenced these diagnostics.
- Overall injection system pressure performance is reduced mainly by 7%, after 4,000 hours in operation. While an older system, which has been operating for nearly 27,000 hours, may have the pressure level degraded up to more than 20%.

After measuring the injection pressure on the rig, one will be able to further investigate and execute the required maintenance of the suggested mis performing components. Hence, enhancing the aged injection system performance to keep the engine working efficiently. Furthermore, in order to evaluate the impact of the faulty injection system while operating in the engine, additional information such as in cylinder pressure, fuel consumption and others, are of interest to support the investigation. This should be done using all injection systems with similar pressure performance, thus avoiding the usage of systems with differences in dynamic response biasing the investigation results.

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