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Testing high-pressure pumps on the BOSCH test bench

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ABSTRACT

This paper presents the procedure for testing high-pressure inline pumps for special-purpose engine in laboratory conditions. The original methodology and procedure for determining the injection pressure at the beginning and end of the high-pressure pipe, as well as the needle lift of the injector elements for a given number of camshaft pump rotations, are described. The injection parameter trends for three pump elements are also shown. The aim of the paper is to describe in detail the developed methods and acquired experiences in order to standardize them, making them permanently available to researchers dealing with this issue.

KEYWORDS

High-pressure pump, Engine, Camshaft, Injector needle, Injection pressure, BOSCH test bench.

1. INTRODUCTION

The procedures described in this paper were carried out on the BOSCH test bench for adjusting and testing high-pressure inline pumps up to twelve (12) elements. Over decades of development and improvement of special-purpose engines, original methods have been developed for adjusting, testing, and verifying the functionality of various types of high-pressure inline pumps installed on these engines [1]. The test bench is used for adjusting and testing newly developed or existing high-pressure inline pumps.

The developed methodology for testing pumps is based on the theoretical foundations of internal combustion engine processes [2-5], confirmed using advanced simulation software [6]. It is used in the development of domestic high-pressure inline pumps of the P500 family, intended for special-purpose engines with higher power levels, as well as for testing and adjusting high-pressure pumps from the renowned manufacturer BOSCH (high-pressure pump P10 for special-purpose diesel engines up to 1000 KS and high-pressure pump for the Mercedes Benz OM 403 engine used in special-purpose vehicles). It has been used for further research and scientific papers in the field of diesel engine processes [7]. Similar procedures of experimental determination of injection parameters, due to their crucial influence on working processes in engine cylinders, were also applied by other researchers [8-16]. Comparative experimental results of in-cylinder pressure flow and injection parameters in direct injection diesel engines are shown in [8], where standard diesel fuel and emulsion of water and diesel fuel are used. Numerous advantages of the second type of fuel have been noted (faster increase in cylinder pressure, higher pressure values during the expansion stroke, lower NOx emissions, etc.). Experimental determination of injection parameters confirmed that rapeseed oil, as an alternative to

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petroleum diesel fuel, can be successfully used if the pre-injection angle and the geometry of the flow part of the injector are optimized, with two-phase injection of a mixture of rapeseed oil and classic diesel fuel [9]. Considerations of the influence of parameters of injection (such as: pre-injection angle, injection duration, injection rate and number of ports at injectors), on the performance and emission characteristics of a common-rail heavy-duty diesel engine injection system, enabled the development of a quasi-dimensional model [10], with which it was possible to optimize the whole system. The effect of experimentally determined injection pressures on performance, power and fuel consumption in direct injection diesel engines is discussed in detail in [11], [13] and [15]. Calculated process parameters of the injection of a medium-speed diesel engine using a computer program developed for this purpose successfully corresponded to the measured [12], and in [14] it was experimentally proven that oils obtained from waste plastic may have similar injection characteristics to petroleum-based diesel fuel. By experimental determination of the pilot injection times, main injection quantities and times, combined with mathematical models of fuel dispersion, combustion and exhaust emissions, it was possible to determine the influence of the mentioned parameters on performance, noise and exhaust emissions of diesel engines [16]. Before testing, the high-pressure pumps are adjusted. Adjustments include activities such as determining the pre-lift of the pump element, phase (angular) adjustment of the start of injection of the high-pressure pump elements according to the specified fuel delivery sequence, adjustment of the speed regulator, and balancing the fuel cycle quantities per pump elements.

2. TESTING PROCEDURE

After the high-pressure pumps have been adjusted, they are placed on the test bench.

2.1. Placing the high-pressure pump on the BOSCH test bench and checking the tightening torques of individual pump components

The pump is secured to the test bench using two or three mounts, depending on the type of pump. The mounts are specially designed for each type of high-pressure pump being tested. They can be moved (slid) along a fixed rail, according to the specified clamping principle. For each type of pump, appropriate flanges and adapter elements on the pump drive and/or the drive shaft of the test bench must be provided to connect the pump camshaft to the test bench drive shaft. Before finally securing the pump to the mounts, coaxial alignment between the pump camshaft and the test bench drive shaft must be ensured. Figure 1 shows the drive elements used in testing high-pressure pumps from the P500 family. The test bench drive shaft has a cylindrical flywheel with engraved angular division around the circumference of the front base circle and holes on the casing into which a rod of circular cross-section can be inserted for manual driving, or rotation, of the pump camshaft. Thanks to these features, it is possible to perform the necessary adjustments of the pre-lift and phase (angular) adjustment of the start of injection of the high-pressure pump elements according to the specified fuel delivery sequence by precisely and lightly rotating the flywheel.

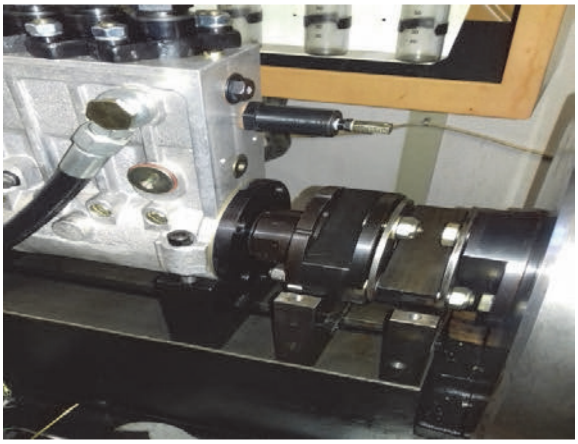

Figure 1: Elements of the drive of high-pressure pumps from the P500 family

Depending on the type of pump being tested, the following configurations of laboratory pipes and nozzles are available within the test bench:

- pipes Ø4 x Ø8 x 1000 and nozzles marked 1 688 911 019,
- pipes Ø3 x Ø6 x 1000 and nozzles marked 0 681 343 009.

By using specially designed adapters and nuts with a right-hand thread at one end and a left-hand thread at the other end (Figure 2), it is possible to overcome the problem of different thread diameters on the quick-connect nuts of the high-pressure laboratory pipes, allowing pipes Ø4 x Ø8 x 1000 and nozzles marked 1 688 911 019 to be used on high-pressure pumps designed for pipes Ø3 x Ø6 x 1000 and nozzles marked 0 681 343 009. Special high-pressure pipes with the ability to use original engine nozzles have been made for high-pressure pumps from the P500 family (Figures 3 and 4).

Figure 2: Specially designed adapters and nuts that have injectors a right-hand thread on one end and a left-hand thread on the other end

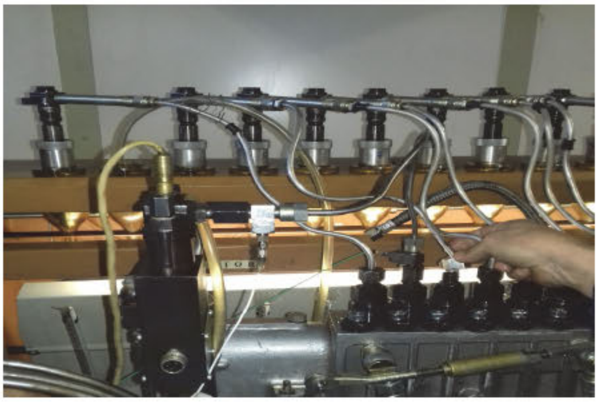

Figure 3: High pressure pipes with original engine and a special assembly (indicated by an arrow) for measuring the stroke of the injector needle

Additionally, for special measurements on high-pressure pumps from the P500 family, when it is necessary to determine the needle lift of the injector in relation to the angle of rotation of the pump camshaft, a specially designed assembly can be used, which includes the original injector, with the injector needle connected to an inductive position sensor (indicated by an arrow in Figure 3). All components of the pump being tested must be tightened with the tightening torques defined in the appropriate design or technical documentation. Tightening torques for pumps of the P500 family are specified on the main assembly drawings of the pumps. It is necessary to connect two pipelines for supplying working fluid to the pump (position 1 in Figure 4) and a pipeline for draining (overflow) the working fluid (position 2 in Figure 4). A special lever assembly is used to regulate the injected amount of working fluid, the tension of which can be adjusted via a hexagonal bar with threads at both ends (position 3, Figure 4). The measuring assembly for determining the pre-lift of the pump is shown in Figure 5.

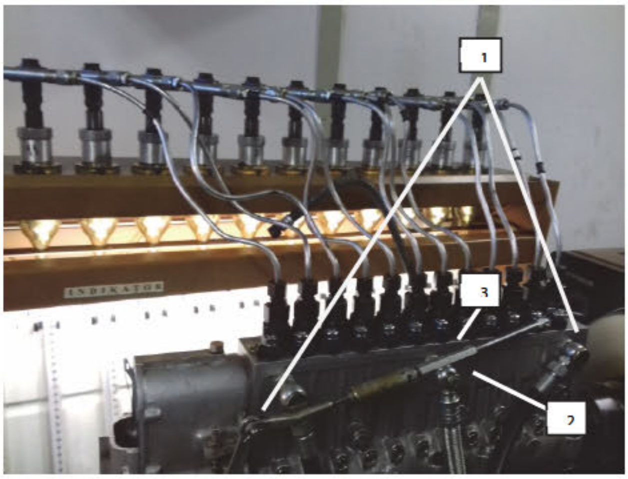

Figure 4: Inlet and outlet of working fluid and lever assembly for regulating the injected fuel quantity

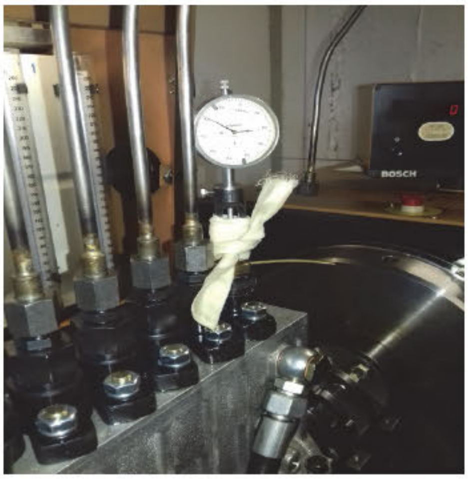

Figure 5: Measuring assembly for determining the pre-lift of the element for P500 family pumps

2.2. Procedure for determining the injection pressure and needle lift of the injector elements for a given number of camshaft pump revolutions

The procedure will be explained using the example of testing the P505 pump family. For this procedure, a measuring system schematically shown in Figure 6 is used, which allows for the measurement of three very important parameters for the qualitative assessment of the pump elements' operation as a function of the camshaft pump rotation angle (marked as UBv in Figure 6) with a camshaft pump resolution of 0.1 degree:

- needle lift (marked as Hi in Figure 6),
- pressure at the beginning of the high-pressure pipe (marked as Pv in Figure 6), and
- pressure at the end of the high-pressure pipe (marked as Pb in Figure 6).

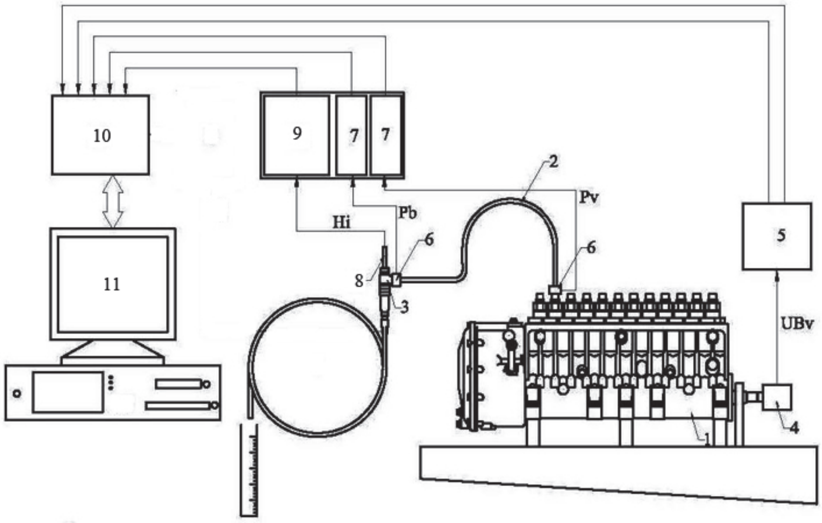

Figure 6: Schematic representation of the measuring system for testing pumps of the P500 family

Positions in Figure 6 indicate: 1 - high-pressure pump P505, 2 - high-pressure pipe, 3 - serial injector with an inductive needle stroke converter, 4 - rotary incremental camshaft rotation angle transducer generating reference mark signals (one signal) and angular divisions (3,600 signals) at the output, 5 - power supply unit for the incremental transducer, 6 - quartz piezoelectric pressure transducers AVL 5QP installed at the beginning and end of the high-pressure pipe, 7 - AVL 3056-A01 charge amplifiers for quartz piezoelectric pressure transducers, 8 - needle lift transducer (custom-made inductive half-bridge), 9 - AVL 3076-A01 bearing frequency measuring bridge for the needle lift transducer, 10 - National Instruments acquisition system (USB 6210 or Compact DAQ), 11 - PC computer.

By using this measuring system, the specified injection parameters of each pump element (Figures 7 to 15) can be tested, followed by various types of analysis of parameters important for assessing the characteristics and quality of the pump being tested (Figures 16 to 24). An important advantage of the described measuring system is that, by using a serial injector, real operating conditions of the pump on the engine are simulated instead of laboratory conditions. The following will show the injection parameter flows discussed here for three P505 pump elements (10, 11, and 12) unchanged for a special-purpose diesel engine with a power level of 840 KS. Each measurement set contained ten (10) consecutive cycles at camshaft pump rotation speeds (referred to as BV) of 650, 800, and 1000 rpm, followed by signal processing consisting of averaging, determining the "zero" line, and multiplying by appropriate proportion factors to convert the measured electrical voltage values into corresponding physical quantities (bar and mm). The following diagrams show the pressure flow charts at the beginning and end of the high-pressure pipe, as well as the needle lift for the following cases: Element 10 at a BV pump speed of 650 min^{-1} (Figure 7), Element 10 at a BV pump speed of 800 min^{-1} (Figure 8), Element 10 at a BV pump speed of 1000 min^{-1} (Figure 9), Element 11 at a BV pump speed of 1000 min^{-1} (Figure 10), Element 11 at a BV pump speed of 1000 min^{-1} (Figure 11), Element 11 at a BV pump speed of 1000 min^{-1} (Figure 12), Element 12 at a BV pump speed of 1000 min^{-1} (Figure 13), Element 12 at a BV pump speed of 1000 min^{-1} (Figure 14), and Element 12 at a BV pump speed of 1000 min^{-1} (Figure 15).

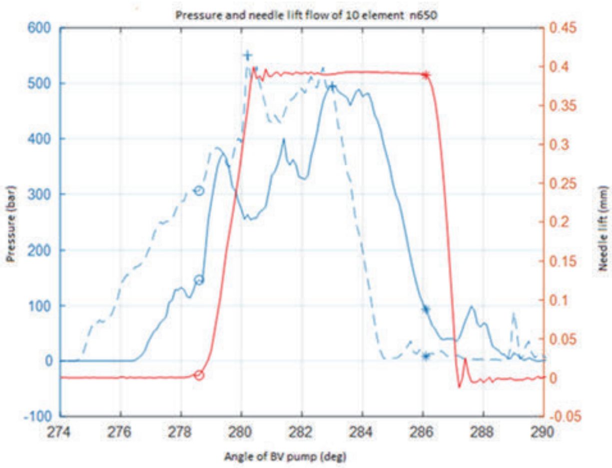

Figure 7: Pressure and needle lift flow diagram of element 10 at a BV pump speed of 650 min^{-1}

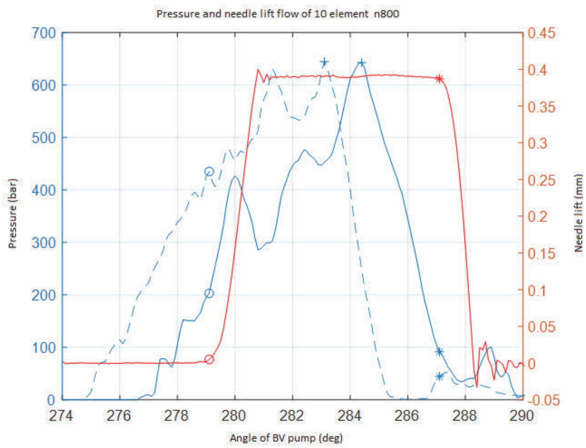

Figure 8: Pressure and needle lift flow diagram of element 10 at a BV pump speed of 800 min^{-1}

On the diagrams shown (Figures 7 to 15), the dashed line represents the pressure at the beginning of the pipe, while the solid line represents the pressure at the end of the high-pressure pipe. The needle lift is represented by the red line, with the ordinate on the right side of the diagram.

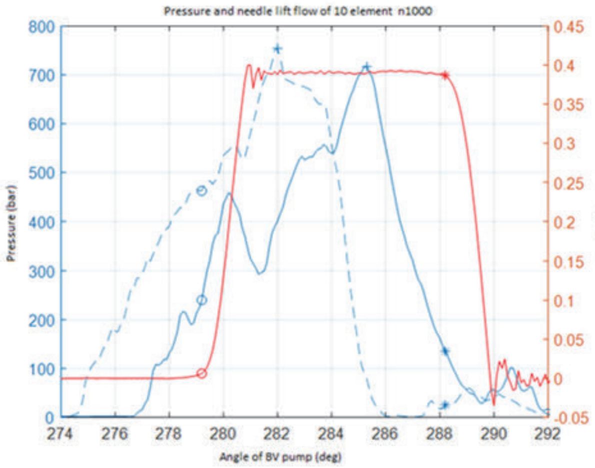

Figure 9: Pressure and needle lift flow diagram of element 10 at a BV pump speed of 1000 min^{-1}

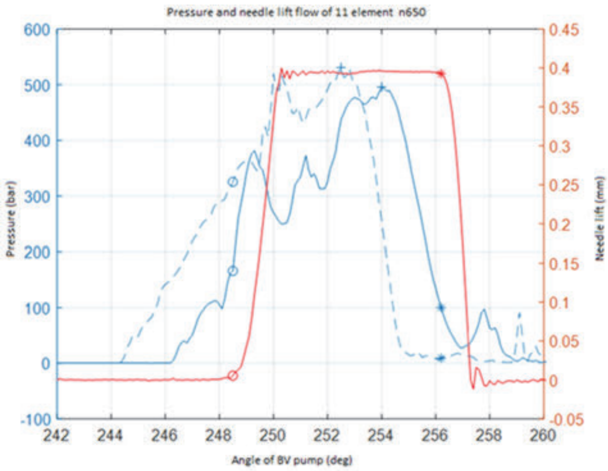

Figure 10: Pressure and needle lift flow diagram of element 11 at a BV pump speed of 650 min^{-1}

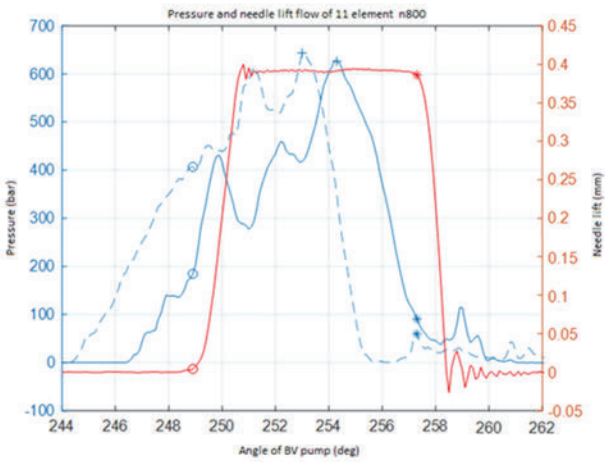

Figure 11: Pressure and needle lift flow diagram of element 11 at a BV pump speed of 800 min^{-1}

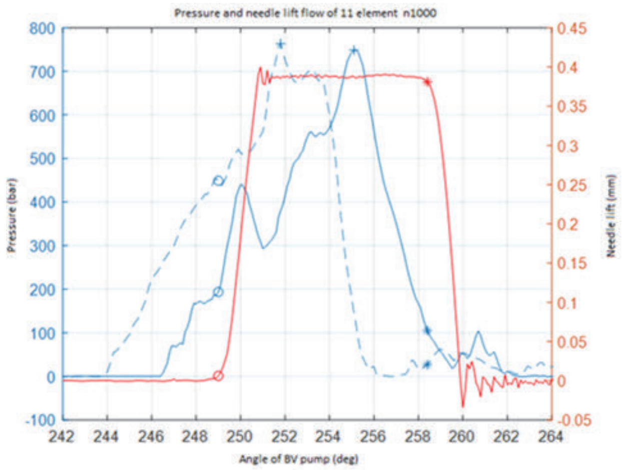

Figure 12: Pressure and needle lift flow diagram of element 11 at a BV pump speed of 1000 min^{-1}

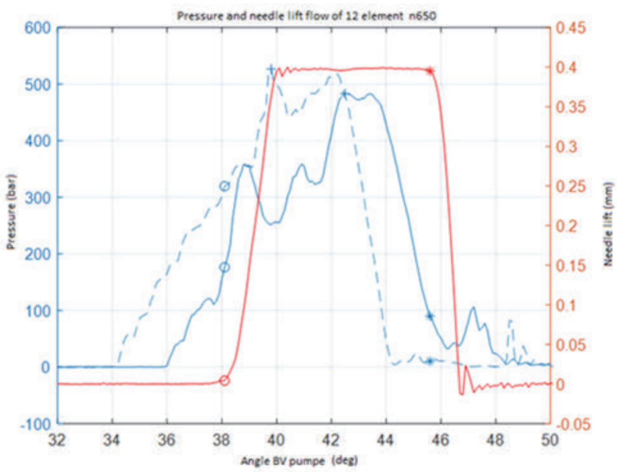

Figure 13: Pressure and needle lift flow diagram of element 12 at a BV pump speed of 650 min^{-}

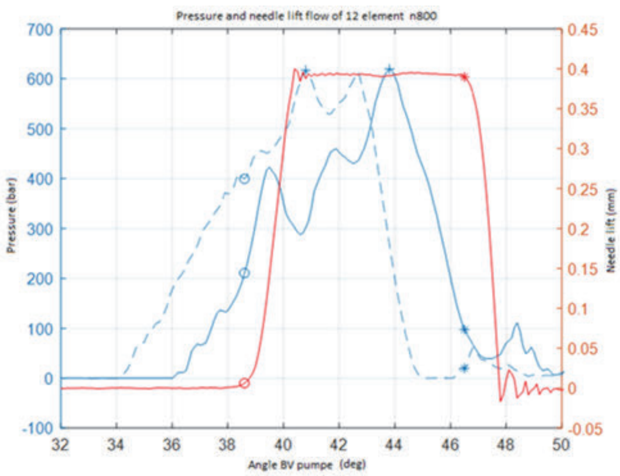

Figure 14: Pressure and needle lift flow diagram of element 12 at a BV pump speed of 800 min^{-1}

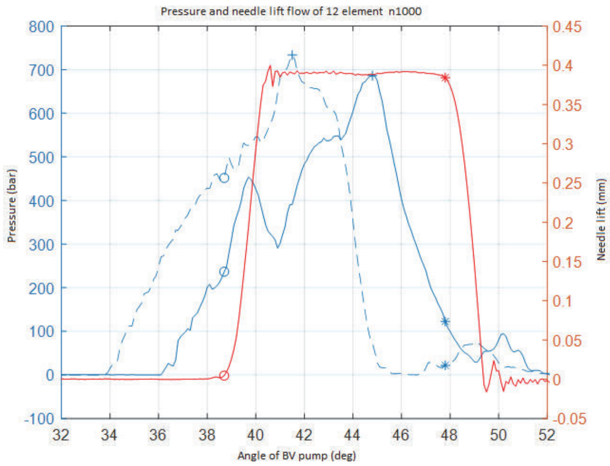

Figure 15: Pressure and needle lift flow diagram of element 12 at a BV pump speed of 1000 min-

The start of injection is determined by the moment when the needle stroke signal reaches a value greater than 0.01 and is indicated by a circle. The end of injection is determined similarly, at the BV angle when the needle lift gradient reaches a value less than -0.01, and is marked with an asterisk. These values are used to calculate the duration of injection in the angular domain. In the pressure diagrams, the circles represent the pressure values at the beginning, and the asterisks represent the pressure values at the end of the injection process, while the maximum pressure values are marked with a plus sign. To compare the operating processes of the PVP elements, all flows are reduced to the same angular domain, where one element remains in its angular domain, and the others are translated along the abscissa by the phase angle difference in the injection of the elements.

Diagrams 16 to 23 show "overlapped" flow diagrams of pressures at the beginning and end of the pipe and needle lift for all three elements, where the curves obtained for element 11 are shifted to the left by 210°, and for element 10 by 240° (according to the injection order of that pump). Following this, it is possible to verify whether the injectors have the prescribed phase difference determined by the injection order, by comparing the flows of the measured pressures and their maximum values, injection duration, etc.

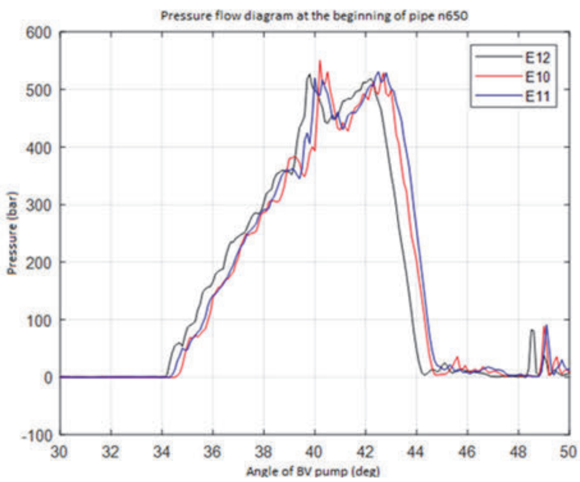

Figure 16: Pressure flow diagram at the beginning of pipe at a BV pump speed of 650 min^{-1}

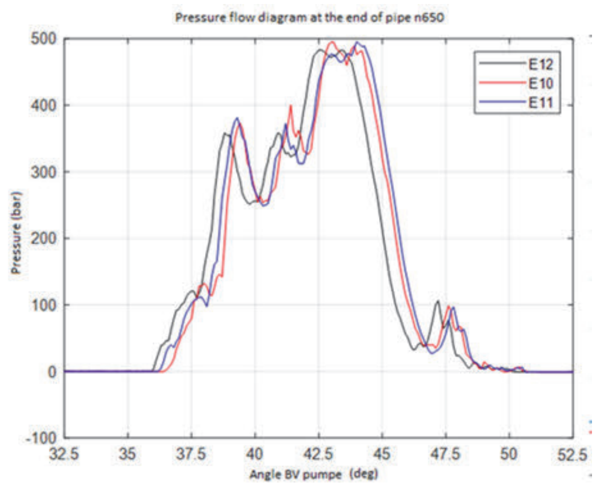

Figure 17: Pressure flow diagram at the end of pipe at a BV pump speed of 650 min^{-1}

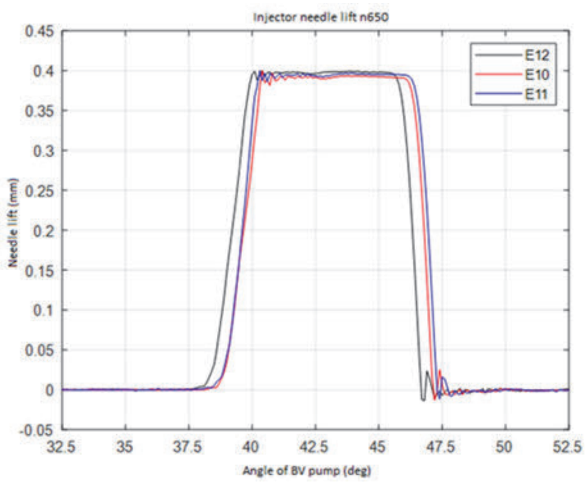

Figure 18: Injector needle lift diagrams at a BV pump speed of 650 min^{-1}

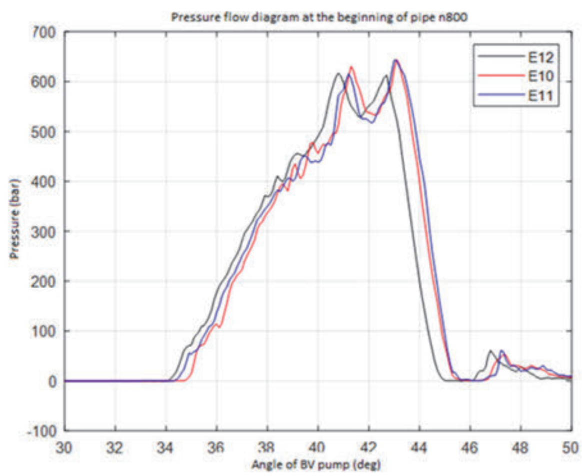

Figure 19: Pressure flow diagram at the beginning of pipe at a BV pump speed of 800 min^{-1}

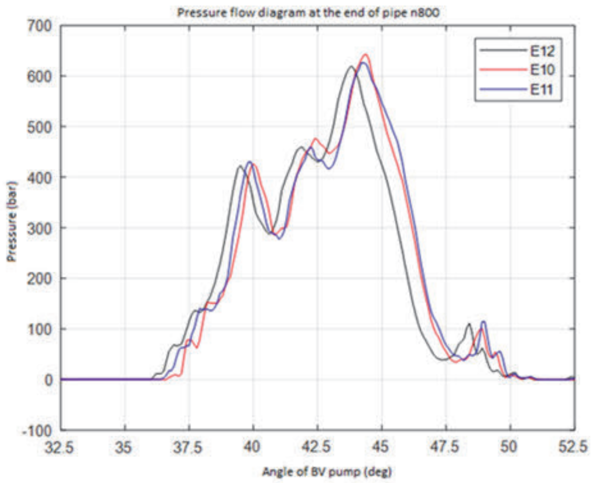

Figure 20: Pressure flow diagram at the end of pipe at a BV pump speed of 800 min^{-1}

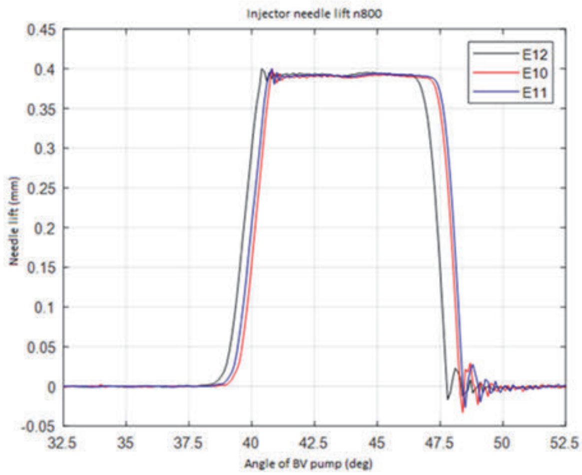

Figure 21: Injector needle lift diagrams at a BV pump speed of 800 min^{-1}

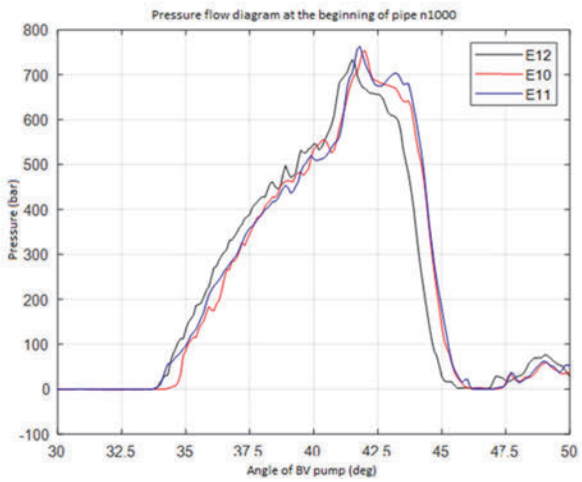

Figure 22: Pressure flow diagram at the beginning of pipe at a BV pump speed of 1000 min^{-1}

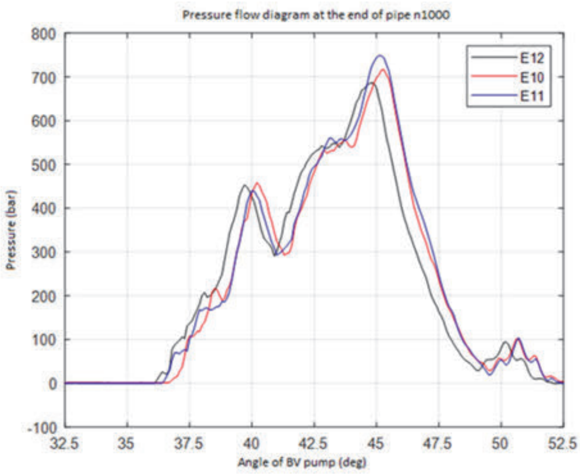

Figure 23: Pressure flow diagram at the end of pipe at a BV pump speed of 1000 min^{-1}

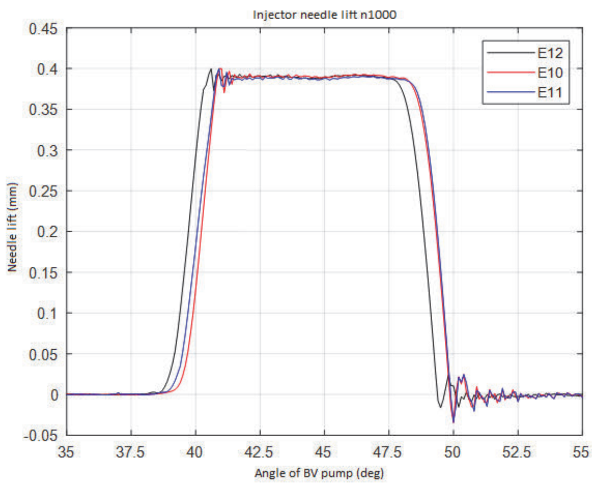

Figure 24: Injector needle lift diagrams at a BV pump speed of 1000 min^{-1}

In Figures 18, 21, and 24, it can be observed that elements 10 and 11 are well phased (fuel injection begins with the specified phase difference), and the injection lasts approximately the same, calculated in the angular domain. Element 12 starts injection slightly earlier, by 0.5° of camshaft rotation angle at 650 min^{-1}, while at 800 and 1000 min^{-1}, this angular deviation is even smaller, at 0.3°. Deviation to this extent is within the permissible limits. It is particularly important that the start of injection be synchronized with the specified phase difference, and the duration of injection depends on the required amount of fuel that a given element needs to inject into the cylinder.

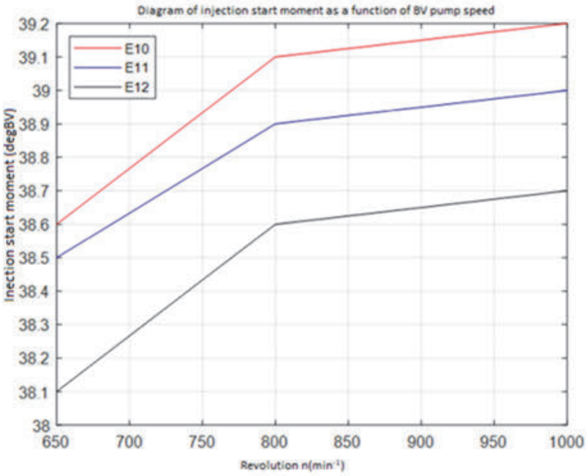

Figure 25: Diagram of injection start moment as a function of BV pump speed

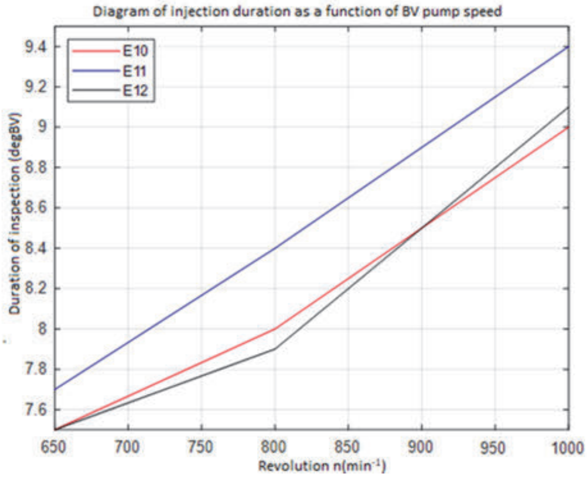

Figure 26: Diagram of injection duration as a function of BV pump speed

Figures 25 and 26 show diagrams of the moment of the start and duration of injection as a function of the BV pump rotation angle. Figure 25 shows that the injection duration of element 11 lasts slightly longer compared to elements 10 and 12. This is in line with the fact that the odd elements of the P505 pump are adjusted to inject 3 to 4% more fuel than the even ones, which corresponds to the difference in volumes between the left and right cylinders of the diesel engine with a complex piston mechanism for which the piston pump use is intended. Maximum pressures at the beginning and end of the high-pressure pipe are shown in the Figures 27 and 28.

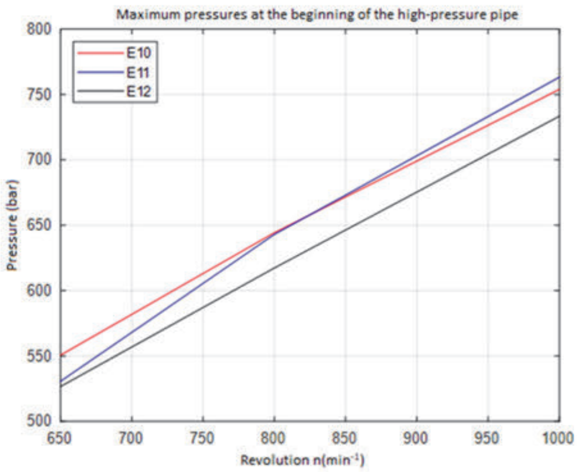

Figure 27: Diagram of the maximum pressures at the beginning of the pipe as a function of the BV pump rotation

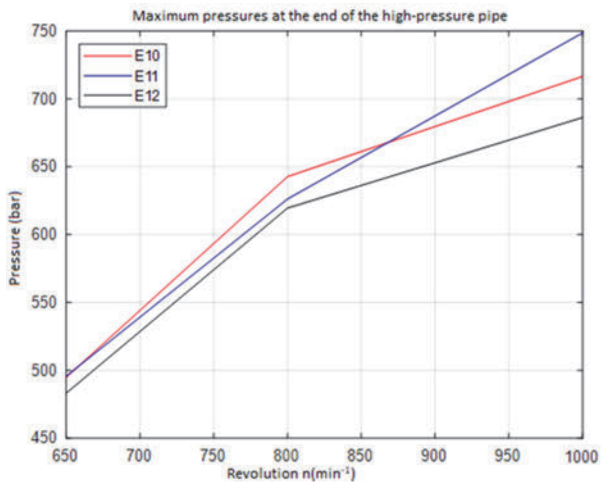

Figure 28: Diagram of the maximum pressures at the end of the pipe as a function of the BV pump rotation

3. CONCLUSION

The procedure for determining injection parameters (pressures at the beginning and at the end of the high-pressure pipe and needle lift) on a high-pressure pump of the P500 family intended for a high-power special-purpose diesel engine is presented in this paper. The procedure is original and can be applied to most high-pressure inline pumps. In support of the validation of the applied testing and adjustment method for high-pressure pumps, it is worth noting that significant results were achieved during the multi-year development and testing of improved variants of special-purpose engines, as well as in increasing the nominal power of the Mercedes Benz OM 403 engine. These results have been verified through the operation of the assets into which these engines have been installed.

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