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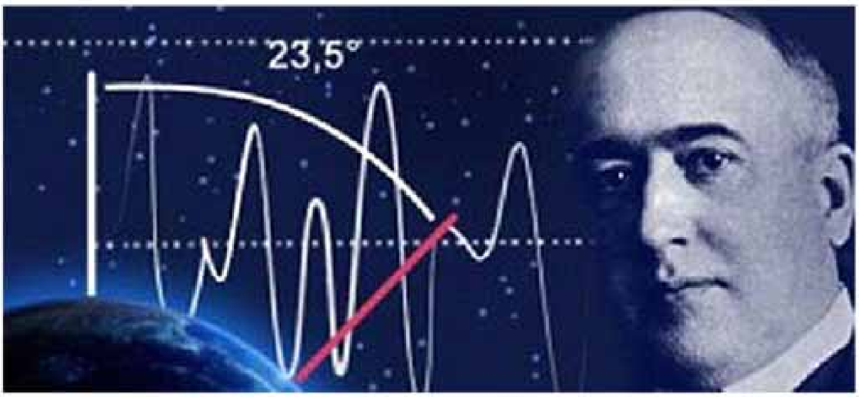

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PROBLEMS AND ACQUIRED EXPERIENCE IN THE DEVELOPMENT OF DOMESTIC HIGH-PRESSURE PUMPS

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Abstract: *The paper presents the applied methods of testing, observations, problems and experiences gained during the development of a domestic high pressure pump at the Military Technical Institute, which can be of interest and benefit to the wider professional public. The pumps are intended and specially designed for diesel engines, with the nominal power of up to 1000 hp, and are produced in many varieties, in our country and abroad, in large number. The development of this pump proved to be very important, as the foreign business partner cancelled the contracted cooperation in the production and delivery of serial engines high-pressure pumps. Problems got even more complicated when the domestic manufacturer, after the ownership transformation, gave up the further cooperation on the almost agreed production of the domestic pump. In the last five years, efforts have been made to enable a domestic manufacturer to produce the pumps. Although it is a company that has never previously dealt with the development and production of such mechanical and hydraulic systems, the achieved results in production and the experience gained so far give real hope that the mutual efforts will reach the required quality and create a competitive product.*

Keywords: *diesel engine, high pressure pump, development*

1. INTRODUCTION

Development and production of domestic high pressure P505 pumps for special purpose engines with the nominal power of 1000 hp is a very demanding process which the Military Technical Institute (VTI hereinafter) has been dealing with for many years.The reactivation of the P505 pump production in 2014. with the manufacturer PPT Namenska a.d. Trstenik (hereinafter PPT), after the previous manufacturer, IPM Belgrade (hereinafter IPM), had given up the high-pressure pumps production.The P505 pump, as a result of domestic development, is a replacement for the imported P10 pump of the German manufacturer BOSCH. The newly acquired P505 pump was made in only one specimen.During the testing of the P505 pump on the BOSCH test bench and ofthe engines with a P505 pump inside, certain defects in the production process, which affect the functionality of the pump, were observed.It should be noted that the pump P505 is still in development, and that the construction and technology documentation developed by the IPM company does not completely match the P505 pumps produced in that company.The new manufacturer, PPT, is expected to raise the level of the production and quality of the rebuilt P505 pump, up to the level of the pump manufactured by IPM, based on its own experience, VTI and the professional IPM company staff consultations, the team that was directly involved in the pump P505 development.

2. Measuring equipment and test methods

The adjustment and the regulation of the high-pressure P505 fuel pump was carried out on the BOSCH test bench (Figure 1) according to the appropriate Instructions for the use of it [1].

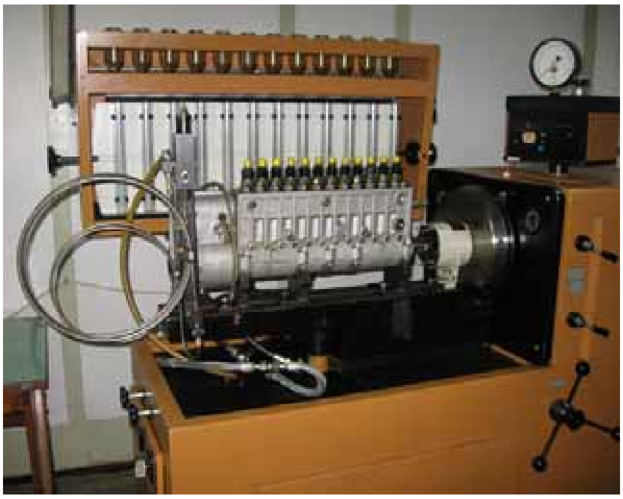

Figure 1. High pressure pump P505 on the BOSCH test bench

In addition, in order to obtain additional useful information on the complex processes in the pump elements, a pressure monitoring system was developed to monitor the pressure at the beginning and the end of the high pressure pipe and the running of the nozzle needle in the function of the camshaft rotation angle as well, shown in Figure 2. This gives the information on [2]:

- The start, end and the duration of the injection, and the possibility an undesireable subsequent injection;
- Maximum and average values of the injection pressure, which directly influence the quality of the work of the engine on which the pump is installed.

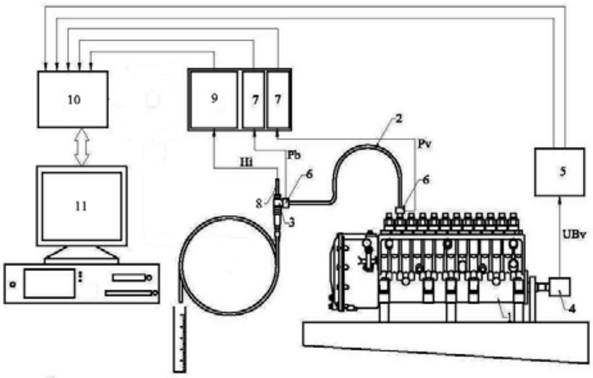

Figure 2. Scheme of the installation for the injection system testing

Positions in Figure 2: 1 - High-pressure P505 pump, 2 - High-pressure tube, 3 - injector, 4 - Rotary incremental transducer of the angle that gives the reference mark and the angular mark 5- power supply of the incremental transducer device, 6 -quartz piezo-electric fuel pressure transducers at the beginning and the end of the AVL 5QP fuel pipe, 7 - Charge boosters for piezo-electric AVL 3056-A01 transducers, 8 - Injector needle walk transducer, 9 - Measuring amplifier withthe AVL 3076- A01 frequency, 10 - National Instruments Acquisition System (USB 6210 or CompactDAQ), 11 - PC, Ubv - camshaft angle, Pv - pressure at the beginning of high pressure pipe, Pb - pressure at the end of the high pressure pipe, Hi - injector needle walk.

3. FAULTS DETECTED AT THE REMANUFACTURED HIGH PRESSURE P505 PUMP

The observed faults are described chronologically, from its delivery to VTI in 2014, until the end of March 2018, when an internal, laboratory, twenty-hour testing of the engines with the rebuilt P505 pump was done.

During the 154-hour functional testing of the pump at the BOSCH test bench in VTI (May - June 2014), the following problems were noted:

1) A fuel control rack manufacture fault. The problem was solved after the P505 was returned to the PPT and the new one was manufactured and and installed.

2) Wider edges of one of the elements(the fourth one) in relation to other elements for 1 - 1.5 mm, which limits the range of the fuel amount regulation when regulating the cycle quantity of this pump element.

3) Leakage at the joint of the body of the pump and the certain elements (cylinders). The problem was solved by replacing all the elements with the existing rubber seals with rubber rings of the corresponding dimensions from the BOSCH production program.

4) The radial bore of the sealing washers under the relief valve on the fifth pump element, resulting in a lower cyclical amount of fuel by 15 to 20% compared to the other pump elements.Replacing this washbasin with the BOSCH one, this problem was solved. By analyzing the BOSCH washbasin material in the VTI Materials Department, it was found that the material was very close to the DC03 steel, i.e. Č.0147 according to the old JUS C.B4.016 standard [3]. IPM spotted this deficiency, and therefore, the material for the washers declared on the drawing was not used on the P505 pumps that were produced at the time, but did not describe this change in the documentation. By analyzing their washers, it was found that the applied material was very close to steel DC04 steel, i.e. Č.0148 according to the old JUS C.B4.016 standard [4]. The influence of this malfunction on the pressure flow measured at the beginning of the pipe is shown in Figure 3.

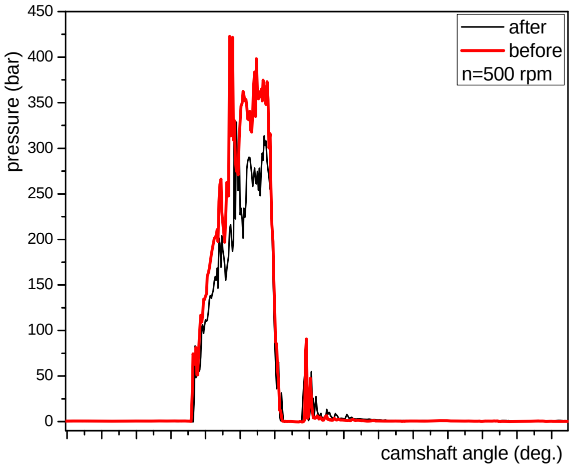

Figure 3. Pressure at the beginning of the high pressure pipebefore and after the replacement, madebecause of the sealable washer defect under the relief valve of the fifthpump element, n = 500 rpm

5) In the 95thhour of the test, the piston in the cylinderpinchedat the seventh element. In the PTT, the 7th element of the pump was replaced and the dimensional control and microscopic examination of the sliding surfaces of the pump elements were made. A mild ovalization of the circuits, approaching the limit, permitted tolerances was observed.

The pump is then adjusted at the BOSCH test bench, in order to provide the predicted cycle quantities of fuel at a nominal power (2000 rpm of the motor) and the maximum torque (1300 to 1400 rpm of motor) [5], after which it was built in the engine. The power, torque and the specific fuel consumption for the range of 1600 to 2000 rpm was recorded at the test bench for testing the engine, and a comparison of the power and the specific effective consumption was made with the results obtained earlier with the pump produced in IPM (Figure 4).

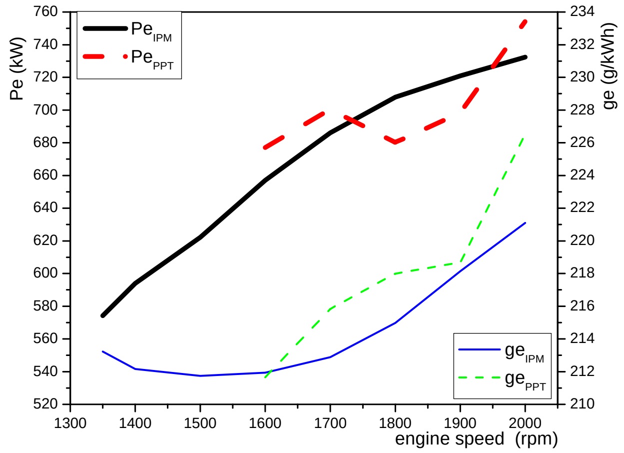

Figure 4. Power (Pe) and specific effective consumption (ge) of engines with high-pressure P505 pumps produced in IPM and PPT

Based on the diagram in Figure 4, it is noted:

– The newly acquired P505 (PPT) pump is satisfactory in terms of nominal engine power (Pe), since the rated power is greater than the required 735^{-30} kW.

– The specific effective fuel consumption at the rated power is significantly higher with the remanufactured P505 (PPT) pump, comparing to the P505 pump produced in IPM. Still, it is still slightly better than the P10 German BOSCH pump.

– Power curves and specific effective fuel consumption with the P505 pump are extremely irregular, at engine speeds of around 1800 rpm. Such a curve is unsuitable for an engine, and is not recorded with the pump produced in the IPM.

This engine testing was stopped in January 2015 due to the breakage of the first left-hand cylinder connecting rod and general engine break-down.The new engine was acquired at the end of 2017. Before building it in the engine, the P505 pump was placed onto the BOSCH test bench (January 2018) again, in order to determine the causes leading to the condition shown in Figure 4 and the new pump setting. On this occasion, the following was established:

6) The piston valves of the pump on the 12th element of the pump, as well as on the 11th, have inadmissibly round edges, which differs from the project documentation (Figure 5, items a and b). In Figure 5 (items c and d), the release valves made in IPM are shown, and they do not have rounded edges. Therefore, all the release valves from the new P505 (PPT) pump were removed and replaced with 100 mm^3 release valves, which were made in the IPM.

Extremely complex hydrodynamic processes take placein the mechanical, pump-pipe-injector systems, where the generated pressure pulses are transferred through the high-pressure pipe in accordance with the wave motion laws. The primary function of the releaqse valves is to eliminate the risk of unwanted subsequent injection, so that the short-term pressure increase due to the incoming wave pressure can not cause the needle lifting [5]. On the other hand, the constriction and the release volume of the release valves significantly influence these complex waves [5], therefore, the choice of the project solution and the construction, must be made with special care.

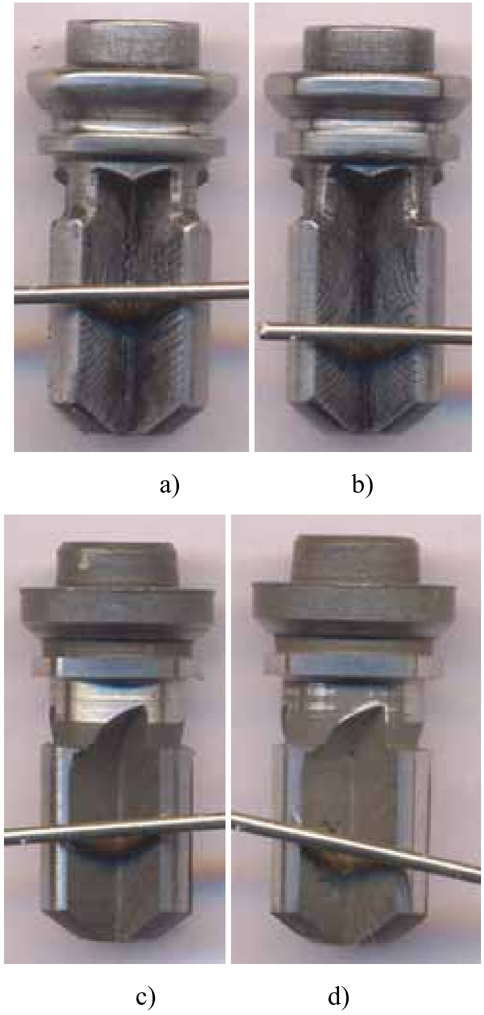

Figure 5. Rejector valve pistons on 12th (a) and 11th (b) P505 (PPT) recharge pump element, and the same elements (c and d) outputted by IPM

The development of the P505 pump and the choice of the optimal solution involves the production of release valves with a wider range of reservoir voltages (80, 90, 100, 110, 120 mm^3), which is achieved by varying the height of the cylindrical part on the piston. Meeting technical requirements of the release valve construction drawingimplies the production of the components (pistons and bodies) in a number far greater than the number of P505 pumps planned to produce, in order to successfully perform the distribution and the pairing of parts.

7) The springs above the release valve piston, on all the elements of the P505 pump, are made with sloping (not parallel) nasal surfaces, and are partially curved (Figure 6). Therefore, the springs do not achieve the prescribed elastic forces for different deformation values. Also, the unnatural position of the springs in the conditions of their complex deformations, which are now not only linear, can cause a breakdown in high- cyclic loads.

8) On the front of the release valve assembly, on which the reservoir body is located, in the 9th element of the P505 pump, a recess with the diameter of approximately 1.5 mm (see Figure 7) is noticed. This circuit was replaced with a set produced in IPM.

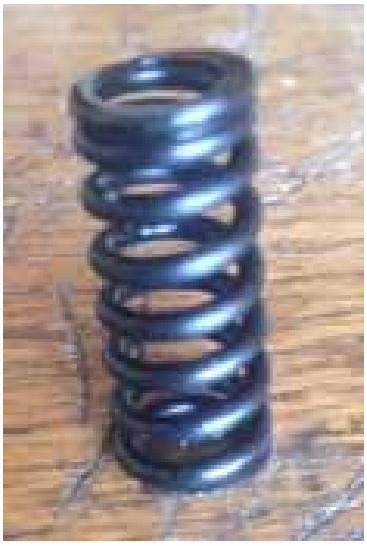

Figure 6. Spring above the piston valve with sloping (not parallel) surfaces

Figure 7. A recess of approximately 1.5 mm in diameter on the front surface of the release valve assembly

9) Bearing in mind negative experiences in the former P505 pump regulation and the problems observed during the testing of the engine with the P505 pump (Figure 4), a detailed and extensive testing and adjustment of the cycle volumes of each pump element P505 was carried out on the BOSCH test table. In order to get closer to the real exploitation conditions,an "engine" injector adapted to the laboratory conditions was usedinstead of the laboratory injectorsof the BOSCH test bench, with a spray (nozzle) used on the engine. With this injector, and the P505 pump, a control was gained which is shown in Figure 8 for the three key camshaft pump revolutions per minute (700, 900 and 1000 rpm). The measured quantities of the fuel shown in Figure 8. were obtained for the 500 revolutions of the P505 pump. The offset in the amount of fuel between the evens and the odds of the rebuilt pump is made to meet the requirement [6] that the cylinders of the right-hand side of the engine (odd pumping elements), due to the higher volume, receive 5 to 6% more fuel than the cylinders on the left side of the engine (even pump elements). The problem arose in the regulation of the second (2) pump element that has a specific, almost linear dependence of the fuel amount on the rpm of the pump camshaft, in relation to all other elements (Figure 8).

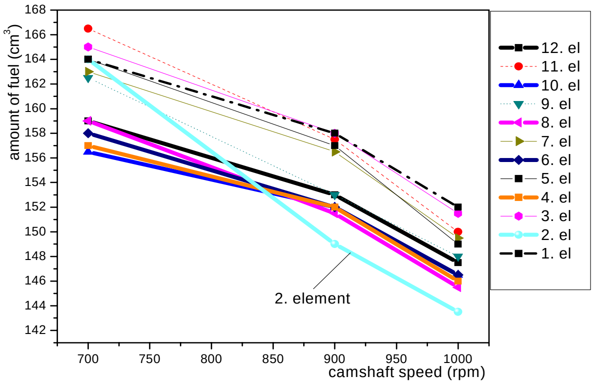

Figure 8. Control of the cyclefuel amounts of the P505 pump elements pump at the BOSCH test table using an "engine" injector

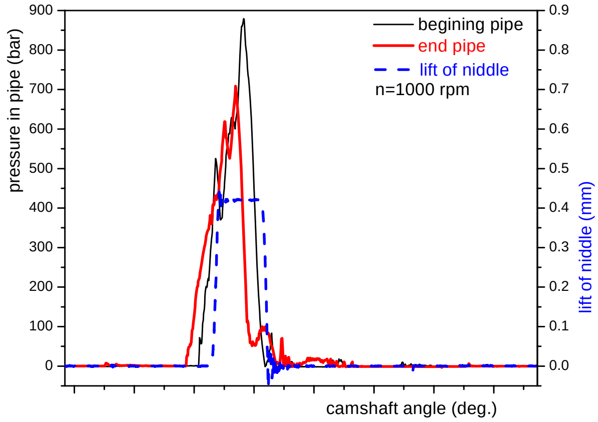

Figure 9. Pressure flow at the beginning and the end of the high pressure pipe and the needle walk of the second pump element (n = 1000 rpm)

As Figure 8 shows, the cyclical amount of fuel of the second element at 700 rpm of the pump camshaft is in the zone of the odd elements, and at 900 rpm and 1000 rpm below all the evenpump elements. All the attempts to bring the general flow of this curve closer to the flows of other elements did not give the expected result. When explaining this phenomenon, it should be noted that the drop in the injected fuel quantity is normal and expected, when increasing the speed of the pump camshaft. Namely, there is a clearance (gap) between the piston and the cylinder which allows the fuel leakage through itduring the suppression of fuel, and that is the case withall the elements of the pump, except for the second one. By increasing the speed of the pump camshaft, this leakage increases too, for several reasons, and the fall in the amount of fuel with the increase in the camshaft speed of the pump is not linear. With the second element of the pump, minimal gaps between the piston and the cylinder are achieved, so the leak is minimal too. This resulted in the "ideal", linear dependence of the cyclical amount of fuel on the number of rpm. Pressure flows at the beginning and end of the high pressure pipe, as well as the needle walk of the 2. pump element are shown in Figure 9 and they correspond to the desired values.

10) When dismantling and checking the pump after the completion of the testing, be sure to check the status of the tiles between the lift and the piston of the element. The IPM

pump that was on a long-term test of 1000 hours suffered fracture of these tiles on all the elements, which could be the consequence of eitheran inadequate thermal treatment or the wrong selection of the material. Since the pump tiles produced in PPT were made according to the same documentation, it has to be determined whether they suffered the same damage.

After these tests and adjustments, the pump was installed on the engine, and in March 2018 an internal, laboratory, twenty-hour engine test was done. Recorded external speed characteristics of the engine, along with the curves obtained earlier with the P505 pump produced in the IPM company, are shown in Figure 10.

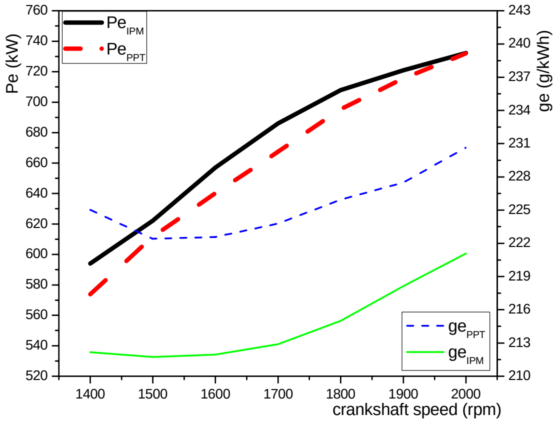

Figure 10. Power (Pe) and specific effective consumption (ge) of engines with high-pressure P505 pumps produced in IPM and PPT

From the diagram in Figure 10, the following can be observed:

– The P505 (PPT) pump meets the nominal engine power (Pe), since the rated power is within the limits of 735^{-30} kW.

– The specific effective consumption (ge) at the nominal power (2000 rpm) is still significantly higher with the P505 (PPT) pump, comparing to the P505 pump produced in IPM. However, this is still at the level of the P10 import pump of the German manufacturer BOSCH.

– The power curves and the specific effective consumption of the engine, are regularwith the P505 pump, and the engine power curve can approach the IPM pump power curve by varying the reledase volumes of the release valves, which, according to the submitted documentation, with the elimination of the noted defects, will be produced by PPT.

4. PROBLEMS IN REACTIVATION OF P505 (PTT) PUMP PRODUCTION THAT HAVE NOT BEEN SOLVED SO FAR

The problems of the new P505 pump production that have not been solved so far, are:

1) Finding a solution for the camshaft production. In doing so, it is considered that the problem of the camshaft shafts production can be solved, since the VTI has the tool, and the former contractor kept the entire production programafter privatization. In the P505 pump (PPT), a camshaft produced in IPM was built in. VTI has a "master" cam with a 2: 1 ratio profile.

2) Conquering the production of the pump body and the regulator housing by casting from Al alloys. For the (PPT) pump, the pump body was poured in a foundry that went bankrupt, and improved in the IPM. At the P505 pump, the entire regulator was built from the license, Russian NK12, but PPT successfully won the production of all its components, except for the case.

3) With the injector production,the nozzle and the nozzle needlecould be demandingproblems. Winning the production of this assembly, PPT would round up the production of the vital parts of the engine injection system.

5. CONCLUSION

This report presents the methods, procedures and test results, as well as the notation of the problems and defects recorded in the high pressure P505 pump at its re-introduction in PPT production. The presented information was collected during the testing of the P505 pump on the BOSCH test bench and the engine tests with the pump built in the engine. In addition, there are problems that have not been solved so far, but the production relied on the pump parts made from the period when the P505 pump was produced in IPM production of P505 pumps.

It can be concluded that the P505 pump output characteristics are slightly worse than those of the pump acquired in the IPM aqt the time, but that it is at the level of the P10 imported pump of the foreign manufacturer BOSCH. Bearing in mind that PPT has never been involved in the production of similar assemblies before, despite all the noted deficiencies, a huge progress has been made, which implies that the new complete production of the P505 pump will be successful.

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