ANALYSIS OF PROPOSED DESIGN CHANGES FOR DIESEL INJECTION NOZZLE USED IN AFTERMARKET APPLICATIONS

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ABSTRACT

Diesel injection systems are widely used in commercial vehicle applications. One of the main components of this system is the injection nozzle, which is responsible for injecting pressurized fuel, spraying it into the combustion chamber. In this study, design modifications of a current injection nozzle used in aftermarket applications are proposed. Objective of the design changes is the increase of the compatibility with other products, thus minimizing the complexity in the manufacturing process and, consequently, saving production costs. For the evaluation of the feasibility of the proposed design under a fatigue endurance point of view, Finite Element Method (FEM) based analyses are performed. In addition, functional tests are done in order to assure the new nozzle's function neutrality and avoid any negative influence in its performance and reliability. Results pointed to the positive technical feasibility of the design changes.

1. INTRODUCTION

Maintaining Bosch' spare parts competitive on Independent Aftermarket (IAM) is one of the key factors for the future of the company. To reduce production costs, the reengineering of components is an alternative to ensure business sustainability.

Given the aforementioned scenario, the scope of this study is to evaluate the technical feasibility of proposed modifications in a nozzle body (Figure 1) supplied for the IAM. The proposed changes include:

i) Alterations in design of needle guide and nozzle tip;
ii) Modification of spray holes manufacturing process - from drilling to Electrical Discharge Machining (EDM).

Based on the changes, concern points regarding nozzle strength and injection performance were arisen and are validated in this study through computational numerical analyses, measurements and functional tests.

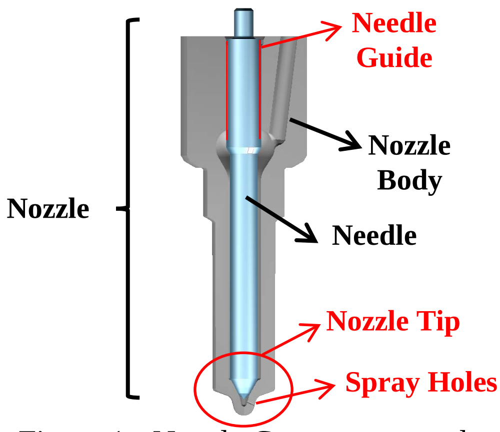

Figure 1 - Nozzle Components and Performed Modifications.

2. METHODOLOGY

Each of the mentioned concern points were evaluated separately according to the most proper technique, as shown in the Table 1.

#	Concern	Evaluation Method
1	Nozzle Strength	FEM simulation to evaluate strength of nozzle body.
		FEMFAT software to verify endurance safety factors.
		CFD analysis in order to verify cavitation possibility at spickel region.
2	Spray Holes Geometries	Measurements in laboratory of format of the holes.
3	Injection Pattern	Comparison of injection map of new proposed and current designs.
		Comparison of pressure oscilogram of both designs.

Table 1. Overview of Strategy used For Evaluation of the Nozzle

A detailed explanation of the evaluation methods can be seen below:

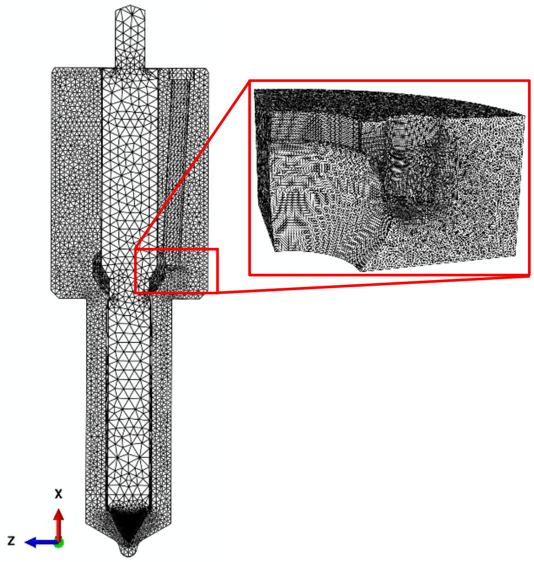

Figure 2. Model Used in the FEM Analyses (Left); Submodel for Spickel Evaluation (Right).

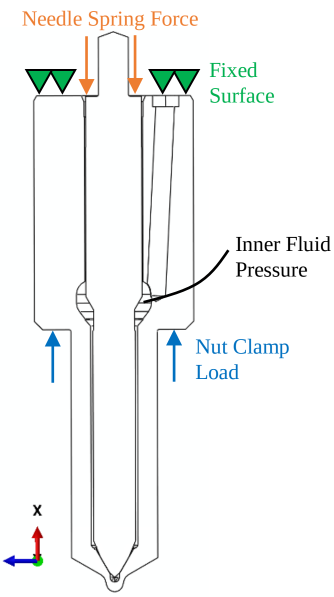

Figure 3. Loads and BC's

2.1 Nozzle Strength - FEM

Finite Element Analyses (FEM) of both spickel (edge of fuel inlet hole, shown in Figures 6 and 7) and nozzle tip regions were performed due to the higher impact of the design changes in this regions. In both evaluations a 180 degrees symmetrical tridimensional numerical model with second-order tetrahedral mesh were used (left side of Figure 2). In the spickel region a submodeling technique was used additionally in order to improve the stress field resolution (through the increase of the number of nodes in the mesh), as seen in the right-side of the Figure 2. The loads and boundary conditions (BC's) are exemplified in Figure 3. The nut clamp load was calculated based on the VDI 2230 [1] and a coulomb friction coefficient of 0,10. The material properties used are shown in Table 2. "Comp" stands for component and "Mat" for material.

Comp.	Mat.	Material Behavior (El./Plast.)	Young's Modulus (GPa)	Poisson's Coefficient (-)
Body	Steel	El.	191	0,31
Needle	Steel	El.	206	0,27

Table 2. Used Material Behaviors.

2.2 Nozzle Strength - FEMFAT

FEMFAT, standing for "Finite Element Method Fatigue", is a software commercialized by Magna which calculates the endurance safety factor of a component previously analyzed through FEM. In fact, for the FEMFAT evaluation, both the meshes and results were imported from the aforementioned FEM simulations. The pulsating load used in the analysis consists of the nozzle assembly loads (nut clamp load + needle force), as the lower stress limit, and assembly loads + internal fluid pressure (IFP) as upper stress limit, as shown in Figure 4.

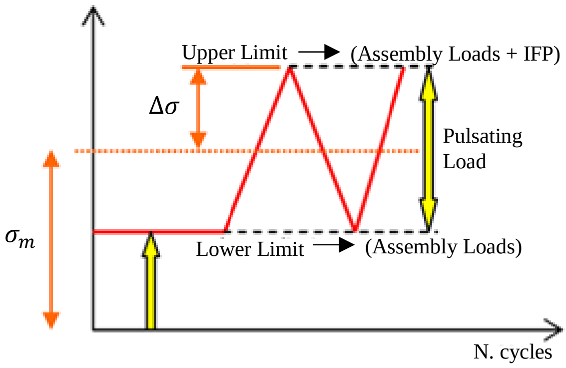

Figure 4. Pulsating Load Used for Fatigue Analysis.

2.3 Nozzle Strength - CFD

The proposed design changes imply in an increase in the spickel radius, therefore changing the flow characteristics in the region. A Computational Fluid Dynamics (CFD) analysis is performed in order to detect the increase/decrease of vapor formation due to the proposed design changes. A turbulent, transient, and multiphasic 180 degrees symmetrical tridimensional model with 880 thousand hexahedral elements was used (see Figure 5). The used turbulence and mass transference models were, respectively, Shear Stress Transport (SST) and Rayleigh Plesset. The two considered phases were compressible diesel and diesel vapor.

2.4 Spray Holes Geometries

Due to the change of the holes manufacturing process (from drilling to EDM) measurements of the diameter of the holes were done in order to see if they remained unchanged.

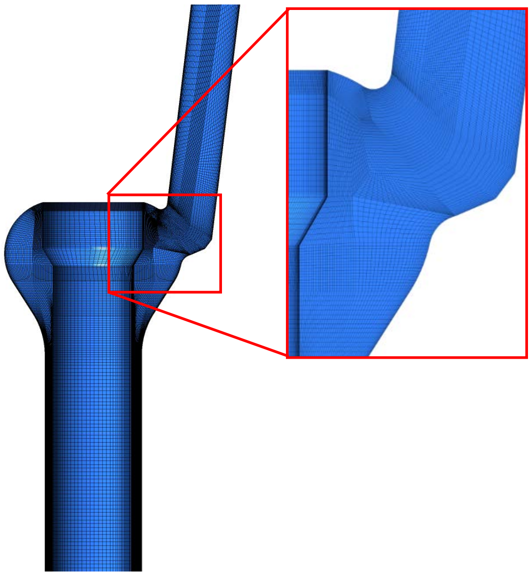

Figure 5. Model Used in the CFD analysis.

2.5 Injection Pattern – Injection Map

An important characteristic of a nozzle is its pressure map, as it correlates, for different values of internal fluid pressure, the injected quantity with the cam speed. Measurements at the engineering lab were performed in order to confirm that the proposed changes do not alter the pressure map of the injector. In this case, three different sample configurations were tested in order to verify the influence of the ECM in the pump injection characteristics:

a) Current nozzle;
b) Proposed nozzle with drilled spray holes;
c) Proposed nozzle with EDM machined spray holes.

2.6 Injection Pattern – Pressure Oscilogram

It is also important that the pressure curves of both nozzles (current and proposed) are similar, as they show the behavior of the pressure in function of cam angle. Thus, tests on the performance test benches were performed in order to register the pressure curves.

3. RESULTS

3.1 Numerical Analyses

Regarding the spickel region, the results of the structural analysis (FEM and FEMFAT) of the current and the new proposed designs, both with assembly and internal fluid pressure loads working (worst condition) can be seen in Figure 6, Figure 7 and in Table 3. The values are shown as percentages, having the current nozzle as reference, due to compliance purposes. $\sigma_{vM,max}$ is the maximal von Mises stress acting in the region; and $s_{f,min}$ is the minimal endurance safety factor.

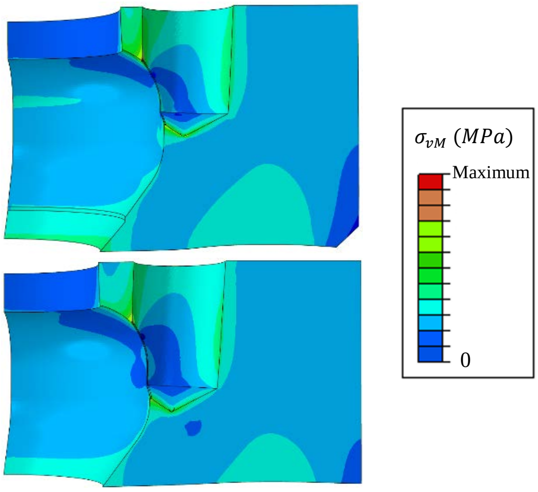

Figure 6. Von Mises Stresses at Spickel Region for Current Design (Top) and New Proposed Design (Bottom).

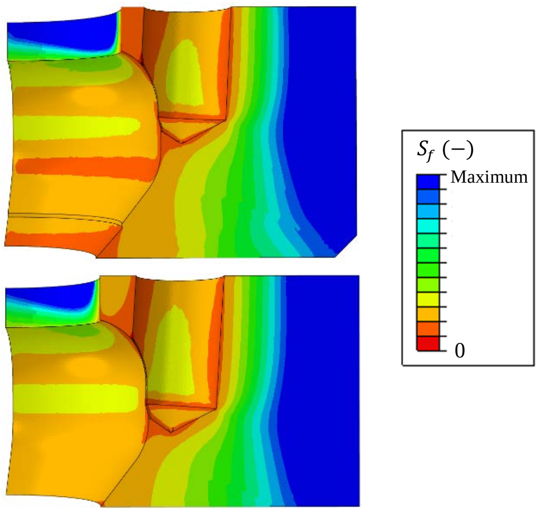

Figure 7. Endurance Safety Factor Spickel Region for Current Design (Top) and New Proposed Design (Bottom).

	$\sigma_{vM,max}$ (MPa)	**$s_{f,min}$ (-)**
New Proposed Design	-19%	+25%

Table 3. Static and Fatigue Results at Spickel Region.

The results related to the tip region with assembly loads and no internal fluid pressure working (worst condition in the contacting region) are summarized in Figure 8 and in Table 5. Similarly, the current design is used as reference for the percentage values.

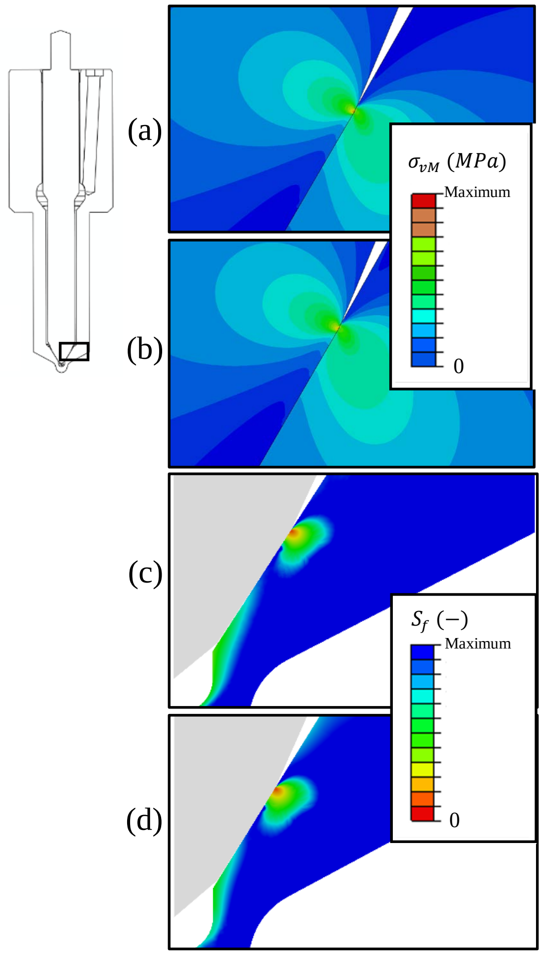

Figure 8. Results at Nozzle Tip Region. (a) σ_{vM} at Current Design; (b) σ_{vM} at New Design; (c) s_f at Current Design; (a) s_f at New Design;

	$\sigma_{vM,max}$ (MPa)	**$s_{f,min}$ (-)**
New Proposed Design	-2%	-3,6%

Table 5. Static and Fatigue at Tip Region

At last, the influence of the increase of the radius at spickel region in the diesel vapor formation is shown in Figure 9.

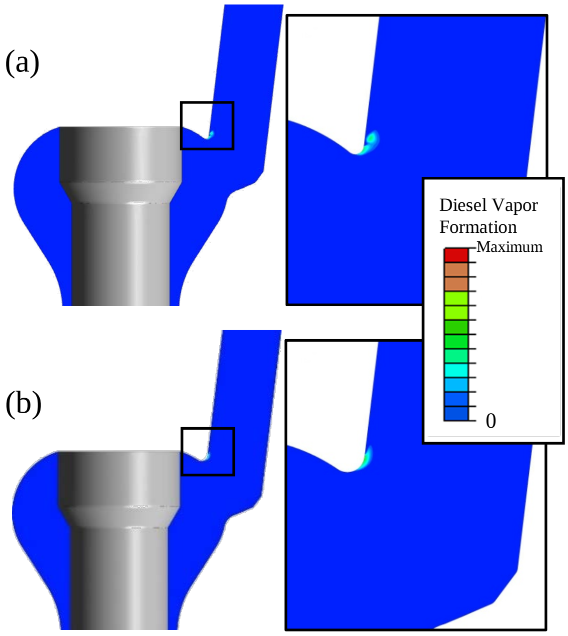

Figure 9. Diesel Vapor Formation at Spickel Region. (a) Current Design and (b) New Design.

3.2 Measurements and Functional Tests

In order to evaluate the EDM process, series nozzles with drilled holes and new proposed design (with EDM holes) had their diameters measured.

Six nozzles were measured in overall, being three of each design. The results are presented below (Table 5) in percentage values. The mean diameter value of the series nozzle holes is taken as reference.

New Nozzle Holes	
Hole Nr.	**Deviation (%)**
1	-2,37
	-1,26
	-0,36
2	-1,08
	-0,17
	0,70
3	-1,44
	-0,17
	1,76
4	-4,10
	-0,89
	2,77
Mean	-0,55

Table 5. Deviation of Holes Diameter

As previously mentioned, the pump injection map describes the injected quantity in function of internal pressure and cam speed. The results for both series design, new proposed design with drilled injection holes and new proposed design with EDM machined holes are shown in Figure 10.

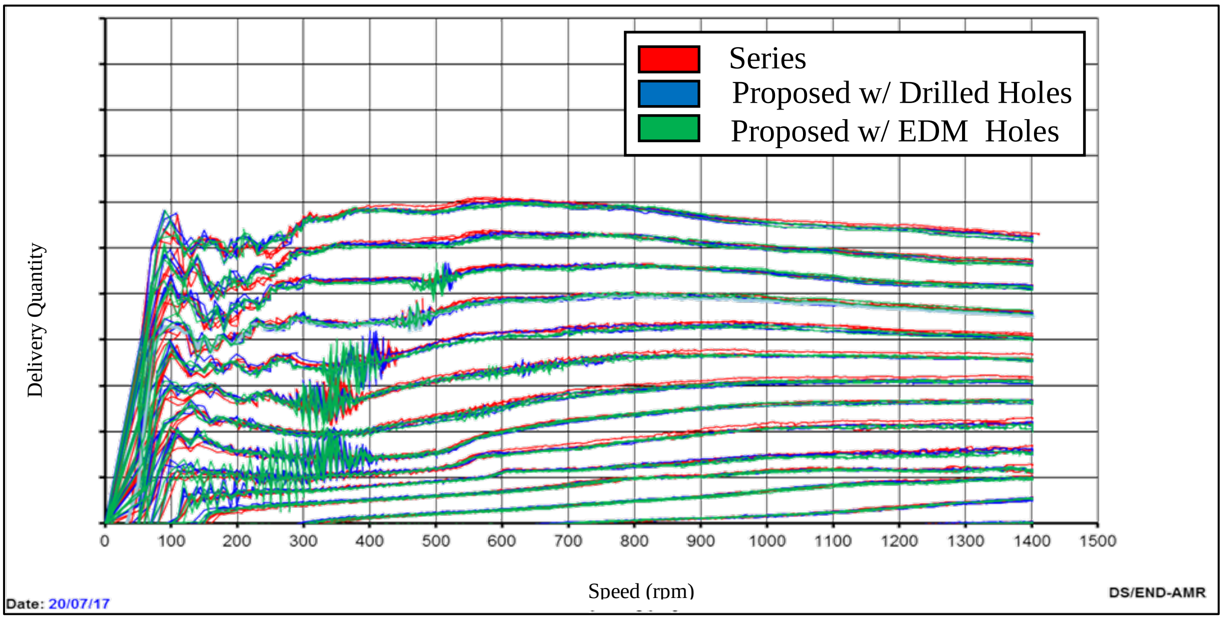

Figure 10. Pressure Map

These three aforementioned design variations were also tested to determine their pressure oscilograms, shown below in Figure 11.

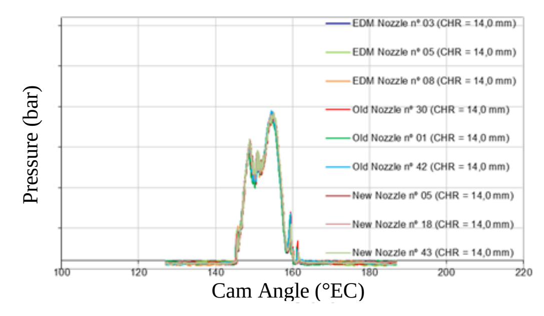

Figure 11. Pressure Oscilograms at 750 Rpm. Current and New Proposed Nozzle (Drilled and EDM Machined Spray Holes) are Plotted.

4. DISCUSSION

According to the numerical analysis results, the proposed design changes are beneficial, in a structural point of view, for the nozzle body. Table 3 shows that the von Mises stresses at the most critical region (spickel) decreases 19% if the design modifications are made. Besides, the minimum endurance safety factor increases in 25%. Regarding the tip region, where the contact between needle and the body takes place, the stresses remain almost the same (see Table 5).

Under a fluid dynamic view, the increase of the radius in the spickel region slightly reduces the vapor formation (see Figure 9), decreasing the erosion through cavitation. The vapor formation occurs due to the increase in the flow velocity that takes place in the region, thus reducing the local fluid static pressure below the vapor pressure.

With regard to the spray hole measurements, the difference between the diameters of the holes manufactured by the two processes (drilled and EDM) is almost inexistent (0,55%). Nevertheless, this was only possible due to the parameters set up for the EDM process. Different parameters will lead to different results.

Both pressure map and pressure oscilograms show no behavioral differences between the series and the new proposed components. Figure 10 shows that, for any given pressures, both nozzles deliver the same quantity of fuel throughout the entire cam speed range. The pressure curves (shown in Figure 11) of both designs showed no expressive difference between the nozzles and no issues were observed from a functional point of view.

5. CONCLUSIONS

Structural and fluid dynamic analyses showed no concerns regarding the proposed changes. The performed measurements and functional tests indicated that the new design is neutral, in terms of functionality and reliability, in comparison to the series one. The proposed changes can be performed without problems and will not impact the injection system in any level.

6. REFERENCES

[1] VDI 2230. Systematic calculation of high duty bolted joints. Joints with one cylindrical bolt. 2003.