# STUDY OF HYDRAULIC BEHAVIOR OF INJECTOR NOZZLES CONSIDERING DIFFERENT DESIGNS

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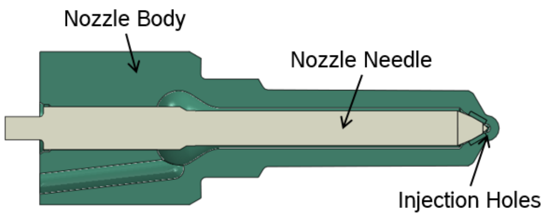
## ABSTRACT

Two different injector nozzle designs are selected to evaluate the hydraulic behavior in the opening phase. Considering the same needle closing force, it was expected that the nozzle with smaller seat diameter open with smaller internal pressure and under same pressure level, it opens faster and inject more fuel. However, opposite behavior is observed at hydraulic and injection test benches. Simulations with Finite Element Method are performed and the same results from analytical calculations are obtained. Thus, Computational Fluid Dynamic simulations are performed in order to understand the difference. It is verified that the behavior occurs due to the higher hydraulic force over needle tip, at beginning of needle opening phase. The hydraulic force is consequence of pressure drop through the seat diameter, which is basically an effect of needle angles. It causes the nozzle opens faster and inject higher fuel quantity, as observed on test bench. Therefore, in order to obtain higher fuel injected quantity, new needle design, with different angles and seat diameter, needs to be used. As example, a new geometry is simulated, showing the gains on injected quantity, and tested at injection test bench, proving the numerical results.

## INTRODUCTION

Injector nozzles have an important function at systems of diesel engines. They connect the fuel injection system to the engine and determine how the fuel is injected into the engine's combustion chamber [1]. The assembly of injector nozzles is composed by the nozzle body, with the injection holes, the nozzle needle, as shown in Picture 1.



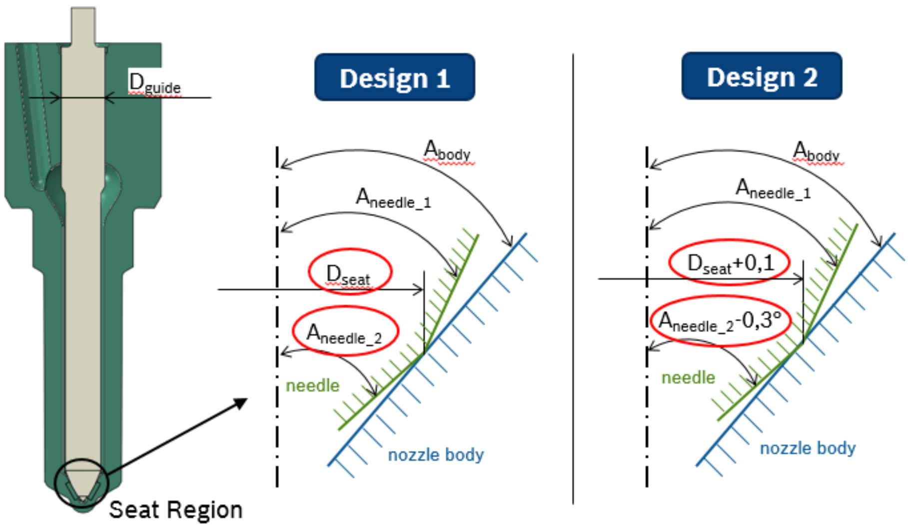

Picture 1 – Injector nozzle assembly.

The quantity, length, diameter and direction of injection holes affect mixture formation, consequently the engine power, fuel consumption and emissions levels, while the hydraulic

behavior is correlated to the needle response, which contributes to achieve the required injection quantity [1].
This works study the hydraulic behavior of some injector nozzle designs due to differences observed at hydraulic and injection test benches. Initially two injector nozzles are tested with different needle designs and an unexpected behavior is observed. Analytical equations and simulations with Finite Element Method (FEM) are used to evaluated this designs and compare with test results. After that, designs are evaluated through simulations with Computational Fluid Dynamic (CFD) in order to understand the needle response. After understanding the factors influencing the needle response, a new geometry is proposed to obtain a faster needle response and to achieve higher fuel injected quantity. Then, this new geometry is tested at injection test bench in order to prove the numerical results and to compare with previous design.

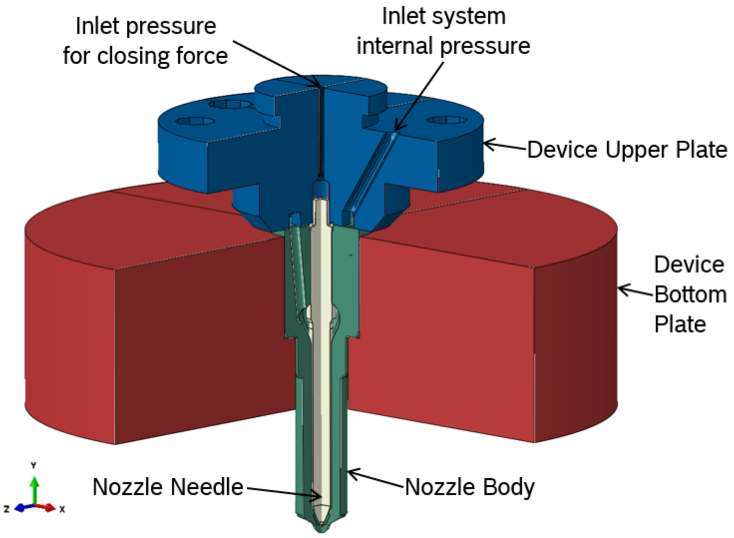
## 1. INITIAL HYDRAULIC TESTS

Two injector nozzle designs with the same seat angle at nozzle body ($A_{body}$) and different needle designs are evaluated at hydraulic test bench. The only differences between both needles are the seat diameter ($D_{seat}$) and needle angle ($A_{needle\_2}$). Picture 2 shows the injector nozzle geometry and the detailed seat dimensions of both evaluated designs.



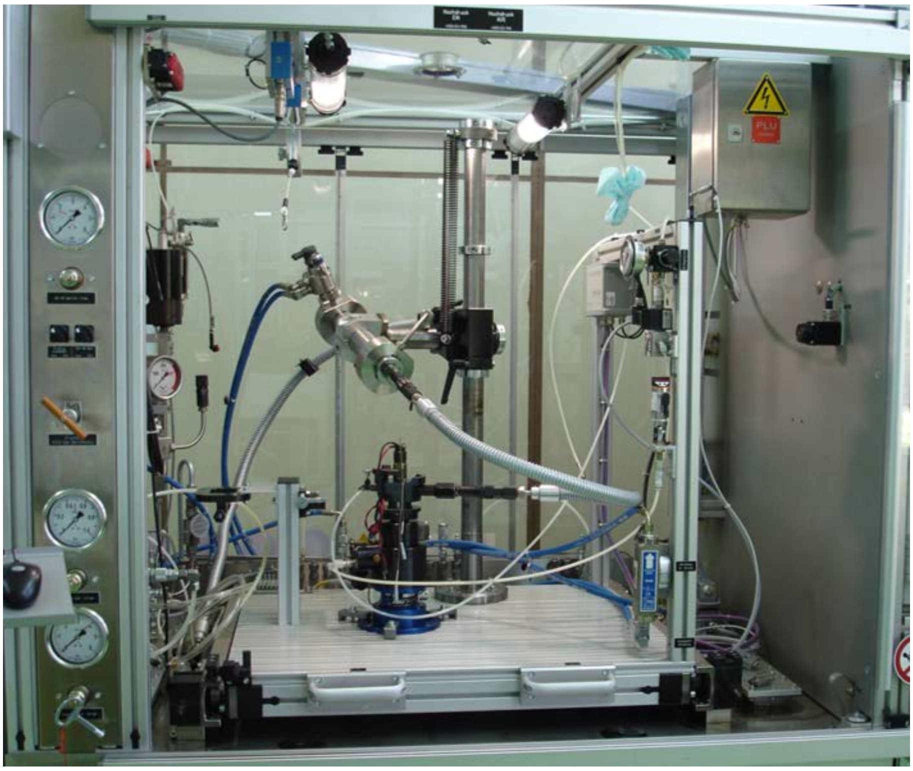
Picture 2 – Injector nozzle geometry and detailed seat dimensions both evaluated designs.

Picture 3 shows schematically the hydraulic test bench used to obtain the opening pressure of each injector nozzle. The device upper plate is fixed at test bench while a pressure is applied at bottom plate to assembly all parts. An inlet pressure of 150 bar is used to generate the closing force of needle and internal pressure is applied up to open the contact at seat region.
Considering the two evaluated designs 1 and 2, opening pressures of 205 bar and 184 bar are obtained respectively. This behavior is not expected, because design 1, with smaller seat diameter, should open with smaller internal pressure, under same closing force, due to higher resultant opening force acting at needle.



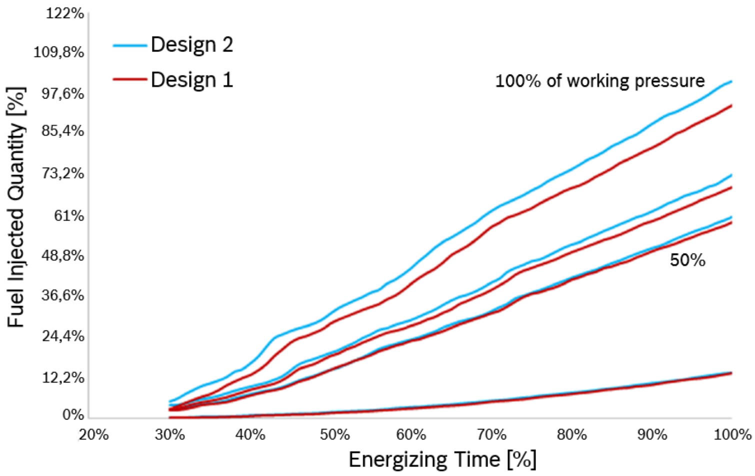

Picture 3 – Schematic assembly of hydraulic test bench.

The injection map of both designs 1 and 2 are also evaluated at injection test bench shown in Picture 4. An original injector is assembly at test bench and only the injector nozzles are replaced. Different rail pressure levels and energizing time of injector are set up in order to create the injection map.



Picture 4 – Injection test bench.

Picture 5 shows the comparison of injection maps of both designs 1 and 2. As design 2 opens faster than design 1, with smaller internal pressure level according to hydraulic tests, higher fuel injected quantity is observed for the same energizing time and pressure level. This behavior is more evident under higher pressures.



Picture 5 – Comparison of injection map of both designs 1 and 2.

Because this difference of hydraulic behavior between both designs 1 and 2, analytical calculations and computational simulations are performed, as shown on next steps of this work.

## 2. ANALYTICAL CALCULATIONS

First of all, theoretical opening pressure is calculated through analytical equations based on nozzle designs and hydraulic test load.

At the hydraulic test bench the closing force ($F_{closing}$) is resultant from the applied pressure. It is calculated, as

$$F_{closing} = P_{closing} * A_{guide} \quad \text{Eq. 1}$$

where $P_{closing}$ is the applied closing pressure of 150 bar and $A_{guide}$ is the guide area at top region of needle, calculated as

$$A_{guide} = \frac{\pi * D_{guide}{}^2}{4} \quad \text{Eq. 2}$$

where $D_{guide}$ is the needle guide diameter.

The estimated opening pressure ($P_{opening}$) can be calculated based on the needle area where the internal pressure acts and the closing force, as

$$P_{opening} = \frac{F_{closing}}{A_{needle}} \quad \text{Eq. 3}$$

where $A_{needle}$ is the needle area, calculated as

$$A_{needle} = \frac{\pi * (D_{guide}{}^2 - D_{seat}{}^2)}{4} \quad \text{Eq. 4}$$

where $D_{seat}$ is the needle seat diameter.

Table 1 shows the parameters for analytical calculations and the estimated opening pressure for both nozzle designs, comparing with opening pressure values from hydraulic tests.

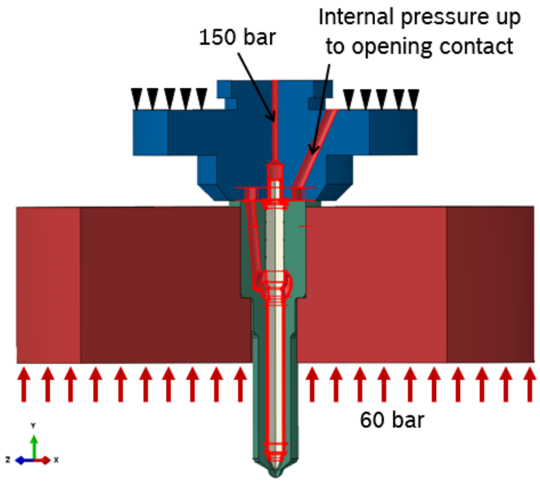
Table 1 – Analytical calculation and comparison with hydraulic test results.

| Nozzle Design | $P_{closing}$ [bar] | $D_{guide}$ | $D_{seat}$ | $A_{guide}$ | $A_{needle}$ | $F_{closing}$ | $P_{opening}$ [bar] | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Analytical | Test | Dif. |
| 1 | 150 | Ref. | Ref. | Ref. | Ref. | Ref. | 207 | 205 | 1% |
| 2 | 150 | Ref. | Ref.+0,1 | Ref. | Ref.-0,3 | Ref. | 215 | 184 | 17% |

As expected, analytical calculations shows that the nozzle with smaller seat diameter needs smaller internal pressure to open contact at seat region, when the same closing force is applied. Compared with test results, the calculated opening pressure of design 1 is very similar while for design 2 a difference of 17% is observed.

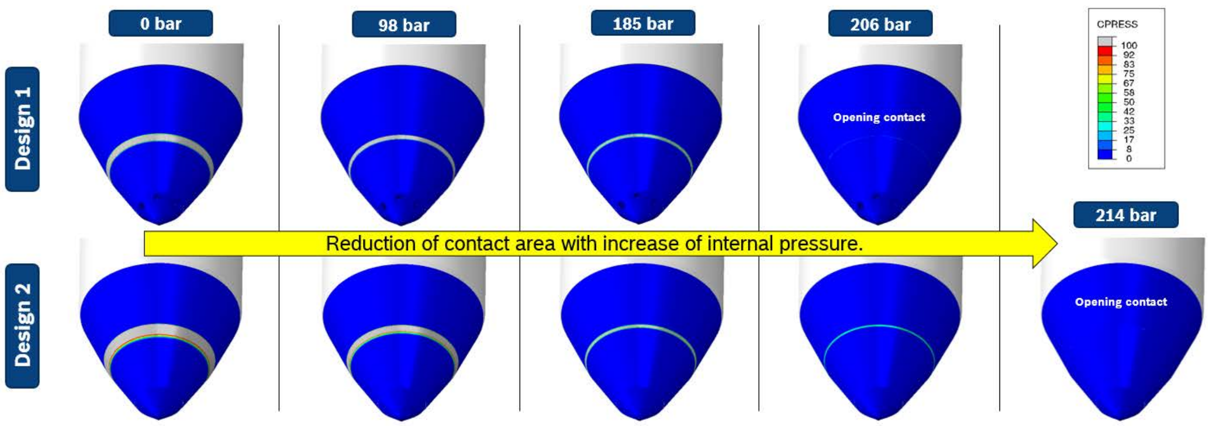
## 3. FEM SIMULATIONS

In order to understand why opposite behavior is observed at hydraulic tests and to compare with analytical results, static FEM simulations are performed considering the same geometries, boundary conditions and loads from hydraulic test, as shown in Picture 6.




Picture 6 – FEM simulation: model, boundary conditions and loads.

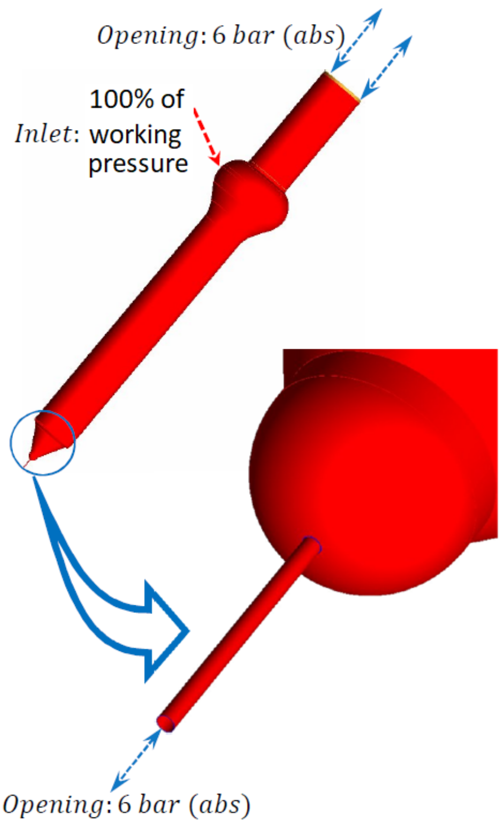
Picture 7 shows contact pressure distribution at needle seat of both designs 1 and 2 under different internal pressure levels up to open the contact at seat region. Full contact ring is observed at needle seat surface at both designs because no deviation is take into account, that means nozzle needle and body are perfect aligned at simulation model. Opening pressures of 206 bar and 214 bar are obtained for design 1 and 2 respectively. These results are very similar to values calculated analytically, with differences smaller than 0,5%. However, for design 2 it is still different from hydraulic test.




Picture 7 – Contact pressure at needle seat under different internal pressure levels for both designs 1 and 2.

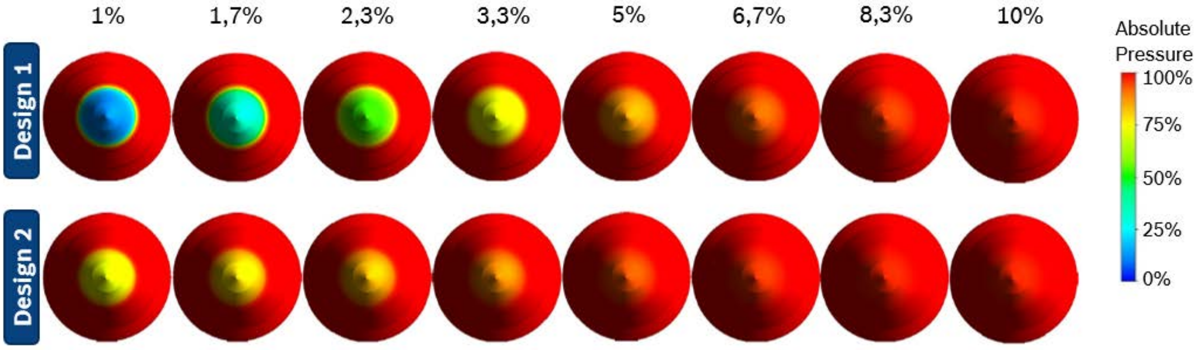
## 4. CFD SIMULATIONS

As analytical calculations and FEM simulations does not show the same behavior observed on hydraulic tests, CFD simulations are performed to study the magnitude of hydraulic forces acting at needle in order to understand why design 2 open faster than design 1, with smaller internal pressure level, as observed on tests.
Both designs 1 and 2 are evaluate through a 2 degree section model with single center injection hole, instead of the radial injection holes of real nozzle body design. These simplifications are used in order to speed up calculation times and reduce convergence issues. Internal pressure of 100% of working pressure is considered in order to compare results with the highest evaluated internal pressure at injection tests. Picture 8 shows geometry, boundary conditions and loads used for CFD simulations.

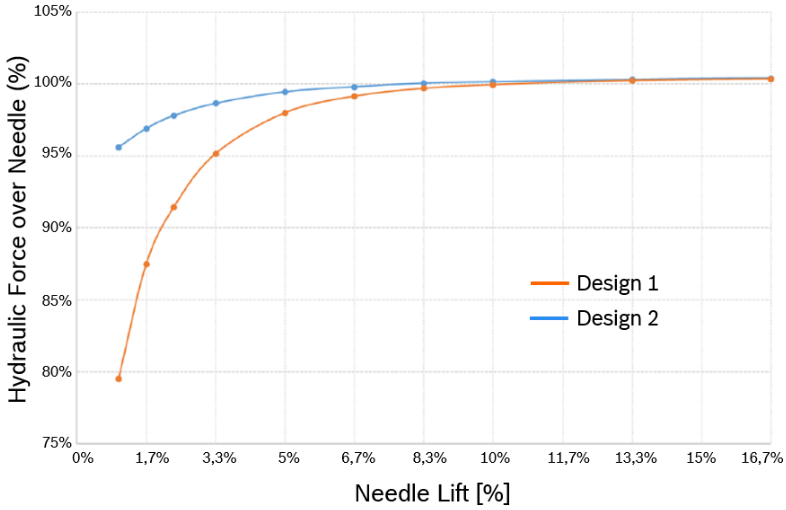



Picture 8 – CFD simulation: model, boundary conditions and loads.

It is observed that the absolute pressure distribution over needle tip is higher at design 2 than design 1 with smaller needle lifts, as shown in Picture 9. This means that pressure drop is smaller at design 2 on opening phase of needle. As consequence, higher hydraulic force acts at needle tip on opening phase, as shown in Picture 10. With lifts higher than 10% of total lift the pressure over the needle tip, and consequently the hydraulic force, stabilizes and similar needle response occurs at both designs 1 and 2.

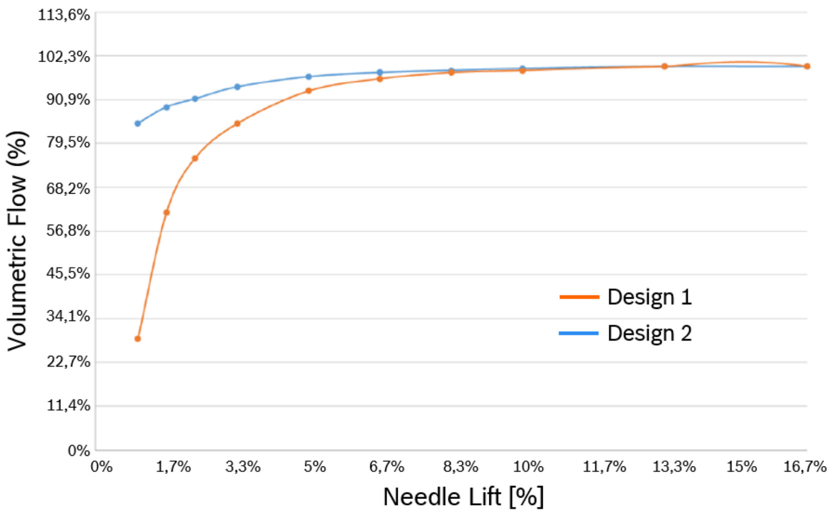



Picture 9 – Absolute pressure distribution over needle tip for both designs 1 and 2.



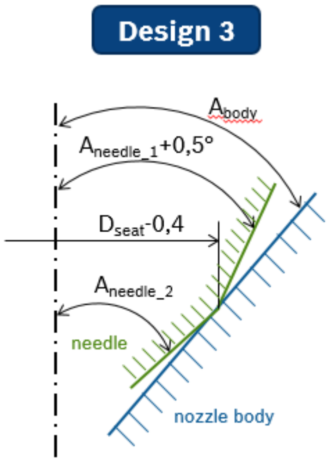

Picture 10 – Hydraulic force over needle tip for both designs 1 and 2.

Picture 11 shows the volumetric flow through the injection hole. Design 2 shows higher volumetric flow up to needle lift of approximately 8,3% of total lift, which means this design has higher fuel injected quantity per stroke, as observed at injection test bench results.



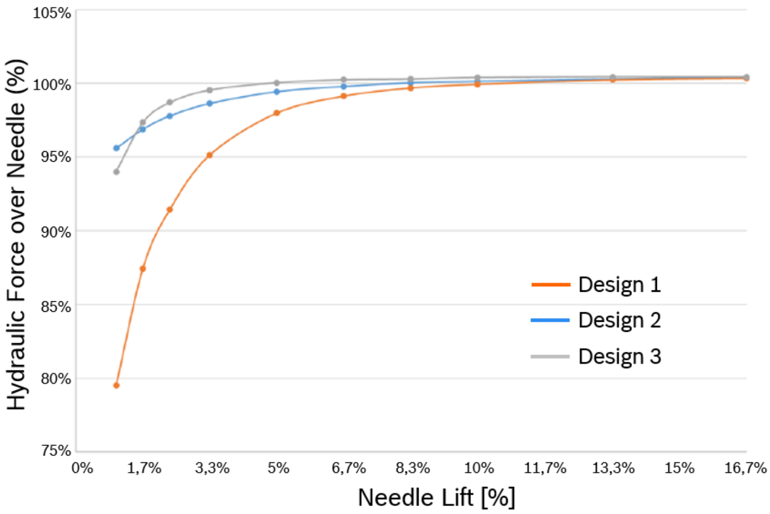

Picture 11 – Volumetric flow though injection hole for both designs 1 and 2.

From these results, it is concluded that the needle hydraulic response is an effect of the needle angles. In order to verify this statement, a new design is proposed considering a smaller seat diameter and different needle angles in order to achieve similar results from design 2, even with smaller seat diameter. The detailed dimensions at seat region of the proposed design 3 is shown in Picture 12.

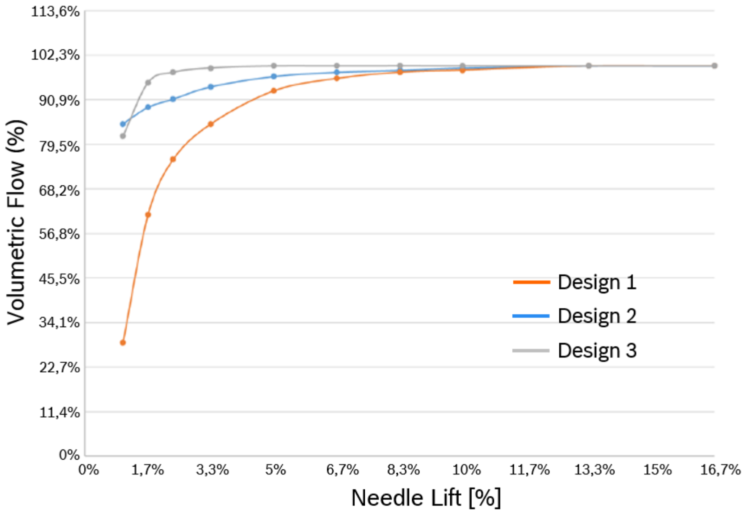



Picture 12 – Detailed dimensions at seat region of design 3.

The same results of hydraulic force over needle tip and volumetric flow through injection hole are evaluated for design 3 and compared with previous designs 1 and 2, as shown in Picture 13 and Picture 14 respectively. Proposed design 3 shows similar, or slightly faster, needle response than design 2, showing similar hydraulic force and volumetric flow curves.



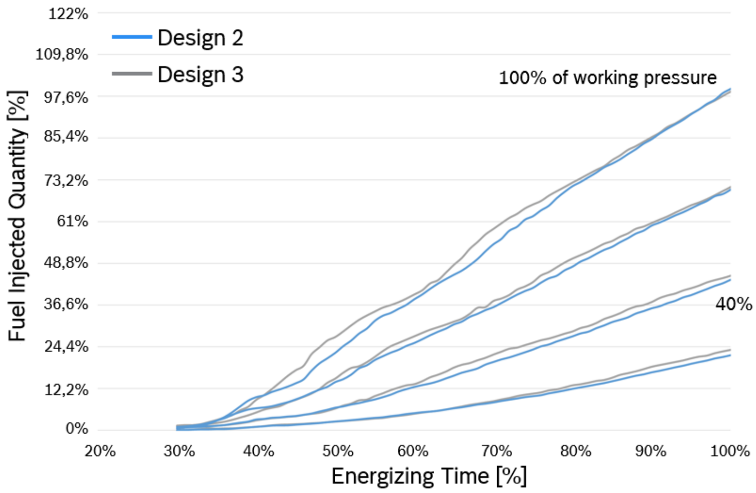

Picture 13 – Comparison of hydraulic force over needle tip at designs 1, 2 and 3.



Picture 14 – Comparison of volumetric flow though injection hole at designs 1, 2 and 3.

## 5. VALIDATION TESTS

In order to validate the results and statements from CFD simulations, tests at injection test bench are performed comparing both designs 2 and 3. Picture 15 shows the injection maps of both designs with similar results, or slightly faster the design 3, proving numerical results.



Picture 15 – Comparison of injection maps of designs 2 and 3.

## CONCLUSIONS

Results of opening pressure of both designs 1 and 2 from analytical calculations and static FEM simulations are similar, but they does not match with those found at hydraulic and injection tests.

Through CFD simulations, it is verified that design 2 has higher fuel injected quantities per stroke than design 1, as observed on injection tests, due to the different pressure drop at needle tip at opening phase. Higher pressure and consequently higher hydraulic force acts at needle tip at opening phase and because this the needle response at design 2 is faster than at design 1. Needle angles are the main contributor for these behaviors.

Design 3 with different needle angles and smaller seat diameter shows similar injection map than design 2, proving the numerical results.
In order to obtain higher fuel injected quantities and different needle hydraulic responses, new needle designs with different angles and seat diameters need to be used.

## REFERENCES

[1] © Robert Bosch GmbH. **Automotive Handbook 7th Edition**. Germany. July 2007.