

# Experimental Characterization of the Geometrical Shape of *ks-hole* and Comparison of its Fluid Dynamic Performance Respect to Cylindrical and *k-hole* Layouts

Federico Brusiani and Gian Marco Bianchi  
University of Bologna

Rita Di Gioia  
Magnet Marelli Powertrain SPA

## ABSTRACT

Diesel engine performances are strictly correlated to the fluid dynamic characteristics of the injection system. Actual Diesel engines employ injector characterized by micro-orifices operating at injection pressure till 20MPa. These main injection characteristics resulted in the critical relation between engine performance and injector hole shape.

In the present study, the authors' attention was focused on the hole geometry influence on the main injector fluid dynamic characteristics. At this purpose, three different nozzle hole shapes were considered: cylindrical, *k*, and *ks* nozzle shapes.

Because of the lack of information available about *ks-hole* real geometry, firstly it was completely characterized by the combined use of two non-destructive techniques. Secondly, all the three nozzle layouts were characterized from the fluid dynamic point of view by a fully transient CFD multiphase simulation methodology previously validated by the authors against experimental results. The experimental characterization of the *ks-hole* geometry was a mandatory task to assure a good numerical simulation accuracy.

From the fluid dynamic point of view, the three nozzle layouts were compared by the average fluid dynamic conditions recorded on the nozzle hole outlet sections and by the cavitating flow evolution inside the injector hole themselves.

**CITATION:** Brusiani, F., Bianchi, G., and Di Gioia, R., "Experimental Characterization of the Geometrical Shape of *ks-hole* and Comparison of its Fluid Dynamic Performance Respect to Cylindrical and *k-hole* Layouts," *SAE Int. J. Engines* 6(3): 2013, doi:10.4271/2013-24-0008.

## INTRODUCTION

In modern Diesel engines, fuel efficiency and exhaust emissions are mainly governed by the spray characteristics and fuel atomization which, in turn, are strongly influenced by the flow conditions developed within the micro-orifice injector nozzle [1].

Because of the importance of spray behavior on combustion efficiency, many researchers have focused their attention on how to improve stability and control of the main spray characteristics (penetration, droplet diameter distribution, etc.). By a literature overview it is possible to find out many studies regarding the influence of injector operating conditions [2, 3, 4, 5, 6] and injector geometric

layouts [7, 8, 9] on Diesel engine combustion efficiency and global spray behavior.

Focusing the attention on the injector geometric layout, recently one of the most interesting research field has regarded the analysis of the injector hole shape evolution from the classic cylindrical shape (Figure 1-a) to the so called *k-hole* layout (Figure 1-b). The *k-hole* layout is characterized by a progressively reduction of the hole cross-sectional area passing from the inlet to the outlet orifice sections. This hole shape layout is usually manufactured by the Electronic Discharge Machine (EDM) and is classified by the so called *k-factor* parameter defined as:

$$k - factor = \frac{d_{in} - d_{out}}{10} \quad [\mu m]$$

where  $d_{in}$  and  $d_{out}$  are inlet and outlet hole diameters respectively. For automotive applications, the  $k$ -factor is usually bounded between 1.1 and 2.

With respect to the cylindrical injector hole, the spray generated from a  $k$ -hole is characterized by:

- Small spray cone angles, especially near the nozzle.
- Large penetration.
- Reduced injection rate (smaller exit area).
- More stable and repeatable spray characteristics.

Regarding the spray stability, the improvement obtained by using the conical injector hole, can be mainly ascribed to the different cavitation evolution characterizing the cylindrical and  $k$  orifice layouts.

As well known, Common rail (CR) Diesel injectors are often working under cavitating conditions because of the presence of adverse hydraulic flow conditions in conjunction to very high injection pressures (up to 20MPa). It implies the generation of a considerable vapor fraction inside the injector orifice at which the following effects can be associated:

- Positive effects on droplet atomization [10].
- Detrimental effects on spray stability [11] and injector lifetime (cavitation physical erosion) [12].

In the  $k$ -hole, the conicity of the orifice promotes the recondensation of the vapor bubble eventually generated at hole entrance (flow detachment condition) before the hole outlet section. It helps to reduce the stochastic perturbation promoted on the liquid jet surface by the vapor bubble collapse and therefore to improve the spray stability. The tendency of the  $k$ -hole layout in suppressing cavitation over the hole length is well presented by Benajes et al [13] and Payri et al. [14] works. They performed experimental comparison between cylindrical and conical nozzle holes finding a noticeable reduction about the injector cavitation tendency underlined by the proportionality between the injector mass flow rate and the square root of pressure drop over all the injector operating field.

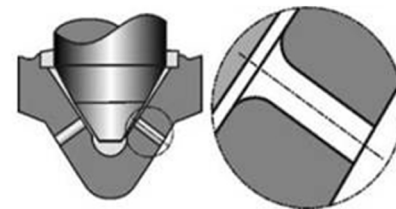
A further evolution of the  $k$ -hole is represented by the  $ks$ -hole (from German “Konisch Strömungsoptimiert”). The  $ks$ -hole is manufactured by the same EDM methodology adopted for the  $k$ -hole at which is associated an optimized Hydro Grading (HG) process to guarantee a defined hole erosion. The result is a  $k$ -hole characterized by a huge rounded edge at hole entrance (Figure 1-c). The target results of a  $ks$ -hole can be summarized as follow:

- To increase the efficiency in transforming the pressure into velocity [10].
- To reduce the flow separation at inlet section and therefore the corresponding vapor bubble generation.
- To improve the  $k$ -hole benefit in reducing the Soot-NO<sub>x</sub> trade-off and the adhesion of the coked matter [1].

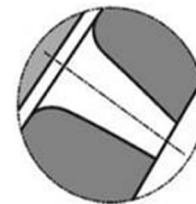
To the best of authors' knowledge, the literature review does not provide significant data about  $ks$ -hole real geometry and its fluid dynamic performance. From these considerations derive the major motivations of the present work:

- To present an experimental characterization of a  $ks$ -hole geometry equipping a CR automotive Diesel engine.
- To reproduce by a multiphase CFD simulation methodology [15] the fluid dynamic behavior of the considered  $ks$ -hole. The results obtained by the  $ks$ -hole numerical analysis are here compared to the fluid dynamic performance guaranteed by other cylindrical and conical injector layouts belonging to the same engine size.

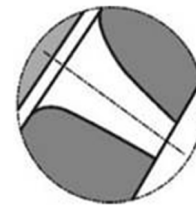
As far as the structure of the paper is concerned, it is divided into three main sections. Firstly, the experimental characterization of the  $ks$ -hole geometry is presented. Secondly, all the injector hole geometries numerically analyzed are presented together with the adopted simulation methodologies. Finally, the numerical results in terms of main fluid dynamic characteristics obtained for each injector are presented and compared each other.



(a). Cylindrical injector nozzle



(b).  $k$ -hole injector nozzle



(c).  $ks$ -hole injector nozzle

Figure 1. Cylindrical,  $k$ , and  $ks$  injector hole layouts.

## KS-HOLE GEOMETRY EXPERIMENTAL CHARACTERIZATION

Usually, to perform a Diesel injector CFD analysis the engine designers start from the information reported in the injector drawings provided by the manufacturers.

Unfortunately, the real shape of the orifice internal shape can significantly differ from the original drawing. It represents a limit to the correct numerical representation of the micro-orifice injector internal flow. This is even more true for the *ks-hole* because it is a quite new injector configuration not yet extensively studied experimentally.

In the present paper, a commercial MJII Common Rail 7-hole *ks* injector geometry was experimentally characterized. The relevant declared data about this injector are summarized in [Table 1](#). To provide to the engine designers a complete geometrical characterization of the considered *ks-hole* geometry, two complementary non-destructive experimental approaches were adopted.

**Table 1. Commercial MJII Common Rail *ks* injector geometrical data extracted from its drawing.**

|                      |                        |        |
|----------------------|------------------------|--------|
| <i>ks</i> parameter  | [-]                    | 1.3    |
| Hole outlet diameter | [mm]                   | 0.121  |
| Hole length          | [mm]                   | 0.75   |
| Flow @ 10MPa         | [cm <sup>3</sup> /30s] | 325*   |
| Cd                   | [-]                    | 0.86** |

\*After HG with needle at 0.25mm

\*\*Flow coefficient calculated out of spray hole outlet diameter and needle at maximum lift.

The first experimental technique was based on the use of the Werth Fiber Probe (WFP) equipment ([Figure 2](#)) by which it is possible to perform measurements of extremely small geometries [16]. The WFP is mainly constituted by a glassfiber with a melted spherical tip as probing element. The sphere (diameter as small as 20μm) is illuminated by a light coming from a LED and travelling down to the glass fiber. The tip is positioned at the focal point of the optical system. When probing the measured object, a CCD camera takes images of the tip. The pictures are subsequently analyzed by an image processor to carry out the probe exact position [17].

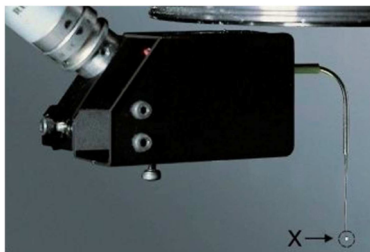


**Figure 2. Werth Fiber Probe (WFP) experimental equipment. The “X” in the picture indicates the position on the spherical probing element.**

The second experimental technique was based on the use of a vinyl-polysiloxane silicone. The silicone is firstly injected inside the *ks* nozzle geometry. Secondly, after the silicone solidification, the mold is pulled out from the nozzle and it is analyzed by a CAD software obtaining detailed information about the injector hole internal geometry. The main drawback of the silicone method is about the risk of

adhesions between the silicon and the injector internal surface. In that case, the mold will be a misrepresentation of the real nozzle internal geometry. Details about this technique can be found in [18].

In the next sections, the results obtained by the combined application of these two analysis techniques on the considered *ks-hole* geometry are presented in detail. The output of this experimental campaign was the definition of the *ks-hole* real CAD model, representing the first step for its subsequent fluid dynamic CFD characterization.

## WFP Technique

By the WFP machine, three measurement sets ( $M_1$ ,  $M_2$ , and  $M_3$ ) were performed to evaluate the axial diameter evolution of one of the *ks* injector holes. Each measurement set started at injector hole outlet section (injector axial coordinate equal to 0). Then the spherical probing element was moved down to the hole toward the inlet section ([Figure 3](#)). The hole diameter was evaluated at seven fixed axial position identified between the inlet and outlet hole sections. [Table 2](#) summarizes the characteristic probe axial positions considered for  $M_1$ ,  $M_2$ , and  $M_3$  measurement series. For each measurement set and for each probe axial position, the hole diameter measurement was repeated seven times at different angular positions ([Figure 3](#)).

[Figure 4](#) shows the hole diameter values extracted by the WFP technique for the  $M_1$  measurement set. At each fixed axial position, the hole diameter values extracted by the seven angular measurements showed a quite small variability around the mean diameter value (<1.2%). Therefore, by experimental results it should be stated as the considered hole was characterized by a good circularity of the cross section over its axial length. [Figure 5](#) shows the mean hole diameter trends found out over the hole axis for the  $M_1$ ,  $M_2$ , and  $M_3$  series. The interpolation between all the mean hole diameter values obtained by the  $M_1$ ,  $M_2$ , and  $M_3$  probing series allowed to exactly define the injector hole internal profile till the inlet rounding edge. From the trends reported in [Figure 5](#), it was possible to observe how from the outlet section to the axial coordinate equal to 0.49mm the variation of the hole diameter was almost linear. Over the axial coordinate equal to 0.49mm, the hole diameter started to increase exponentially over the axial coordinate. It is important to note as this change in rate of the hole diameter over the axial coordinate happened quite before the hole inlet section (hole total length equal to 0.75mm).

Close to the inlet section, the evaluation of the real inlet rounded edge by the WFP machine could be difficult because of its 3D-shape evolution. For this reason, the WFP technique was coupled to the silicone technique whose results are reported in the next section.

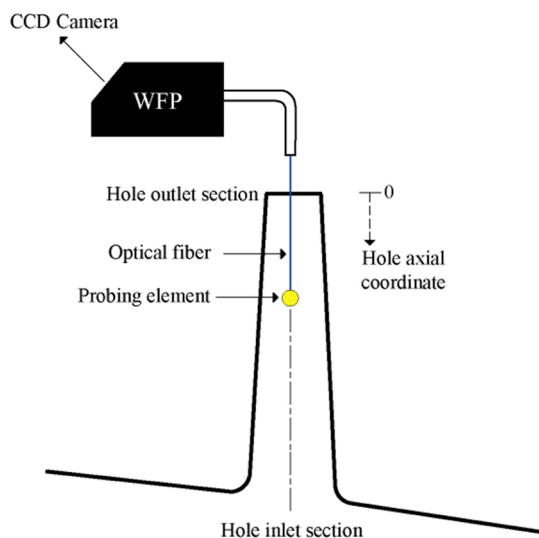


**Figure 3.** Schematic representation of the WFP experimental ring adopted for the injector hole diameter experimental characterization.

**Table 2.** Axial distances (from hole outlet section) at which the hole diameter was evaluated for each measurement set.

| Hole diameter measurement sets |                |                |  |
|--------------------------------|----------------|----------------|--|
| Axial Depth [mm]               |                |                |  |
| M <sub>1</sub>                 | M <sub>2</sub> | M <sub>3</sub> |  |
| 0                              | 0              | 0              |  |
| 0.10                           | 0.10           | 0.10           |  |
| 0.19                           | 0.22           | 0.23           |  |
| 0.28                           | 0.34           | 0.36           |  |
| 0.37                           | 0.46           | 0.49           |  |
| 0.46                           | 0.58           | 0.62           |  |
| 0.55                           | 0.70           | 0.75           |  |

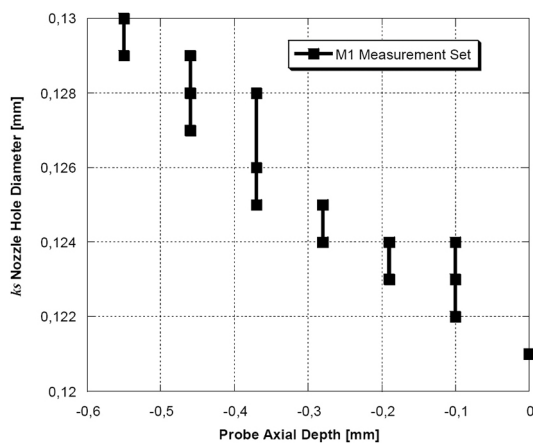


**Figure 4.** M<sub>1</sub> measurement set. Hole diameter values recorded for each probe axial position (seven experimental measures performed for each axial position).

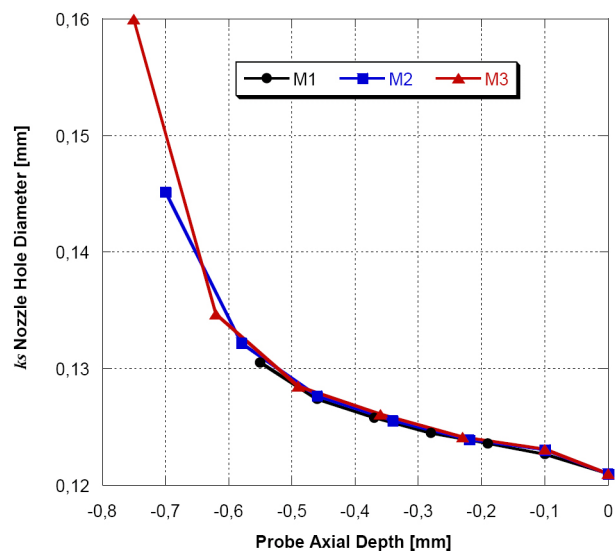


**Figure 5.** M<sub>1</sub>, M<sub>2</sub>, and M<sub>3</sub> measurement sets. Mean hole diameter evolutions recorded over the injector axis.

## Silicone Technique

The silicone technique was adopted to obtain a physical 3D model of the considered *ks-hole* nozzle. Figure 6 shows the obtained nozzle hole mold subsequently analyzed by a CAD software to carry out the spatial evolution of the inlet rounded edge.

As expected, the HG process performed on the injector produced a non-uniform rounded edge at hole entrance. The highest rounding edge value (45μm) was located on the top side of the injector hole, where the highest velocity gradient was located (Figure 6-a). At hole bottom side, the velocity gradient was significantly reduced thanks to the fluid dynamic effect acted by the sac volume. Correspondingly, the physical erosion process was quite reduced and the rounding edge value decreased to 35μm (Figure 6-a). At both injector hole inlet lateral sides, the measured rounded edge was equal to 40μm (Figure 6-b).

By the silicon model showed in Figure 6-b it was possible also to perform a double check on the hole diameter values extracted by the WFP technique at hole exit and just downstream the inlet rounded edge.

Figure 7 shows the final *ks-hole* geometrical shape resulted from the combination of the dimensional data extracted by the WFP and silicone techniques. In Figure 7, the change in rate of the hole diameter over the axial coordinate is clearly visible.