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COMPARISON OF DIFFERENT TECHNIQUES FOR CHARACTERIZING THE DIESEL INJECTOR INTERNAL DIMENSIONS.

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ABSTRACT

The geometry of certain parts of diesel injectors is key to the injection, atomization and fuel-air mixing phenomena. Small variations on the geometrical parameters may have a strong influence on the aforementioned processes. Thus, OEMs need to assess their manufacturing tolerances, whereas researchers in the field (both experimentalists and modelers) rely on the accuracy of a certain metrology technique for their studies.

In the current paper, an investigation of the capability of different experimental techniques to determine the geometry of a modern diesel fuel injector has been performed. For this purpose, three main elements of the injector have been evaluated: the control volume inlet and outlet orifices, together with the nozzle orifices. While the direct observation of the samples through an optical microscope is only possible for the simplest pieces, both Computed Tomography Scanning and the visualization of silicone molds technique have proven their ability to characterize the most complex internal shapes corresponding to the internal injector elements. Indeed, results indicate that the differences observed among these methodologies for the determination of the control volume inlet orifice diameter and the nozzle orifice dimensions are smaller than the uncertainties related to the experimental techniques, showing that they are both equally accurate. This implies that the choice of a given technique for the particular application of determining the geometry of diesel injectors can be done on the basis of availability, intrusion and costs, rather than on its accuracy.

KEYWORDS

Injector, metrology, orifices.

1. INTRODUCTION

The performance, emissions and NVH (Noise, Vibration and Harness) characteristics of direct-injection engines are highly influenced by the characteristics of the fuel injection system [1]–[5]. Thus, many researchers have tried to combine different experimental [6]–[10] and computational tools [11]–[14] to provide a better understanding of the physics behind fuel injection processes. Nevertheless, performing a detailed analysis of these aspects is not simple, due to the combination of small dimensions, high flow velocities and complex physical phenomena (cavitation, atomization, etc). Many of these studies focus on the effects of the injector geometry on the injection system performance [15]–[17]. On the one hand, the dimensions of the injector internal passages, including the control volume orifices, are critical for the injector needle dynamics and consequently the opening and closing slopes of the injection rate profile [18]–[20]. These effects are particularly important when using multiple injection strategies, since the injector acoustics also affect the needle motion [21], [22]. On the other hand, the geometry of the injector nozzle orifices also influence the nozzle outlet conditions and the spray propagation characteristics [23]–[25].

In particular, the authors have investigated the effects of several geometrical and functional injector parameters on the injection process, identifying the diameters of the nozzle and control volume orifices as the most significant ones [26]. The dominating influence of these parameters on the rate of injection means that small variations in their values strongly affect the injector opening, closing and steady-state flow rate capabilities. Thus, knowledge on the internal dimensions of these orifices is vital to both OEMs and researchers in the diesel engine injection field. OEMs, on the one hand, need to accurately determine their manufacturing tolerances in order to assess their impact on the engine performance. On the other hand, both modelers and experimentalist researchers rely on a known geometry for their studies and predictions to have validity.

In order to assess such aspects, it is then clear that it is first necessary to characterize the internal dimensions of the fuel injector in an accurate way. While traditional metrology tools can be used for most of the injector elements, the small dimensions associated to some of them (precisely like the dominating control volume or the nozzle orifices) call for the use of more advanced techniques. Some years ago, Macian et al. [27] developed a silicone molding technique for this purpose. The silicone molds are then analyzed using a Scanning Electron Microscope (SEM) to obtain the internal dimensions of these elements. More recently, high-power Computed Tomography (CT) scanning machines have also being used for the similar purposes [28]–[30]. These CT-scan tools have the advantage that they can be used on the complete injector without any dismounting, but high power (and consequently cost) machines are needed in order to provide high-enough resolution. Regarding the relative accuracy of both techniques, both have been reported to provide an uncertainty around ±2 μm, but no clear comparison between them has been reported yet.

In the current paper, different metrology techniques are employed and compared for the dimensional characterization of different internal elements of a last-generation solenoid injector. First, the diameter of the control volume outlet orifice is measured both by direct observation and the use of CT-scan technique, providing values within 1 μm tolerance. Then, CT-scan and silicone molds are compared for other two critical elements: the control volume inlet and the nozzle orifices. Again, both techniques show practically the same dimensions, confirming the capability of silicone molds technique to accurately determine the injector geometry. Therefore, the selection of a metrology technique for this kind of application could be done depending on the availability of the techniques, the associated costs and the possibility or not to extract the pieces to be characterized from their original assembly.

2. EXPERIMENTAL TECHNIQUES

In the current paper, different experimental techniques have been assessed for the determination of the diameters of the control volume inlet and outlet orifices of a commercial common-rail solenoid diesel injector, together with the nozzle orifices. A schematic view of these elements is provided in Figure 1.

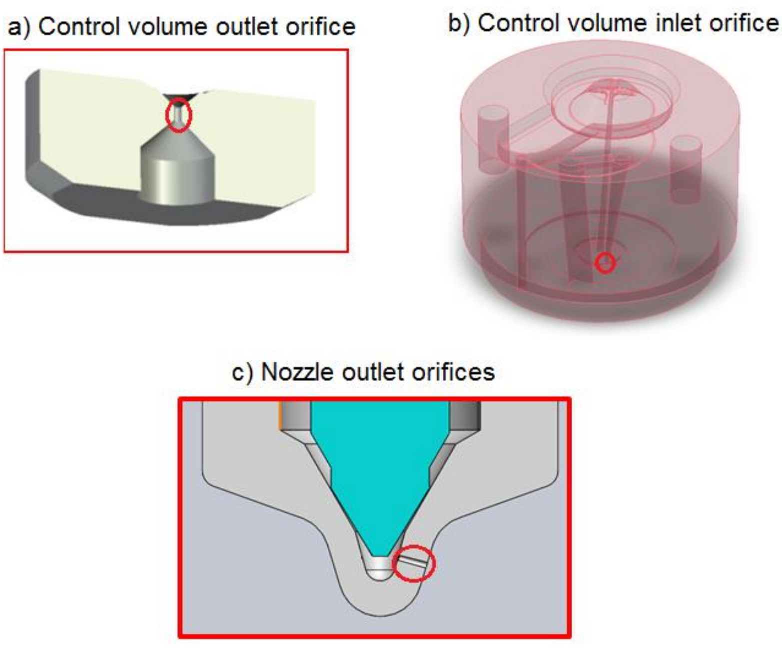

Figure 1. Schematic of the internal injector elements characterized: a) Control volume outlet orifice; b) Control volume inlet orifice; c) Nozzle outlet orifices

2.1. Optical microscope

For some of the internal injector elements, a direct observation through an optical microscope can be used. In particular, a Leica MZ APO system, capable to provide up to 80x magnification, is selected. The system includes a PLANAPO 1.0X objective and a KL1500 Fiber Optic Illuminator.

2.2. Computed Tomography

X-ray computed tomography is performed using a Nikon XT H-160 CT-Scan machine. This installation is able to produce x-ray beams with up to 60W power at a maximum voltage of 60 kV. The images produced have a maximum magnification of 150x, and a resolution in the range of 2-3 µm. The installation includes a 5-axis automated part manipulation in order to properly align the samples to the x-ray beam direction. The actual power and resolution employed for each part has been adapted depending on the particular geometry and the material that the beams had to travel through.

2.3. Silicone molds

For this technique, semi-liquid vinyl-polysiloxane silicone is injected into the orifice using a syringe, until the orifice of study is fully covered. After a few hours, the silicone dries out and hardens, after which it is carefully extracted. The resulting mold can be measured either using the previously defined optical microscope or a Jeol JSM6300 Scanning Electron Microscope (SEM). Such machine operates at 30 kV and proves up to x1000 magnification capabilities. For the SEM, the sample needs to be first covered by a thin layer (in the order of nm) of gold dust, so that it becomes a conductor. The accuracy of this technique has been reported to be around 2% (2-3 µm) in the determination of the nozzle outlet diameter. More details about this technique can be found in [27].

3. RESULTS

3.1. Control volume outlet orifice.

The first geometry examined is the control volume outlet orifice, which is located in the control plate (Figure 1.a). Thanks to its relatively simple geometry, it was possible in this case to assess the orifice diameter using the optical microscope in real magnitude, since the optics could be located perpendicular to the sample. Additionally, the same sample was analyzed using the CT-scan technique. Both results are compared in Figure 2. In the left hand side, an image obtained with the optical microscope is seen. This image has been post-processed using a CAD software to obtain the orifice diameter, resulting in a value of 100.95 (approximately 101) µm. In the right hand side, the image taken with the CT-scan for the same orifice is depicted, resulting in a value of 102 µm (i.e., a difference of approximately 1 µm compared to the direct observation). The images of the CT-scan have been post-processed using an image binarization methodology based on Otsu's algorithm [31] in order to determine the edge of the orifices in a systematic manner.

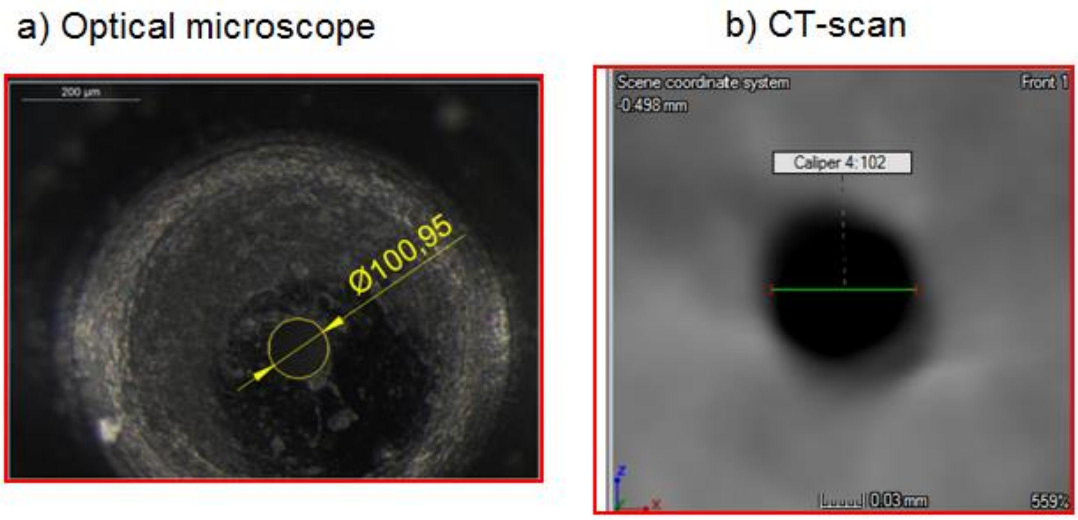

Figure 2. Control volume outlet orifice diameter: a) Optical microscope; b) CT-scan

3.2. Control volume inlet orifice.

In the case of the control volume inlet orifice (Figure 1.b) the characteristics of the piece where it is contained are more complex. Hence, a direct observation using the optical microscope was not attainable. Thus, CT-scan and silicone mold technique have been applied. The results are available in Figure 3. The upper part (a) shows the post-processing of the CT-scan, where an outlet diameter of 198 µm has been determined. It has to be noted that the quality of the image is limited by the amount of power available in the machine used for the experiments, since the material of the plate has relatively low transmittance of the x-ray beams. If more advanced equipment were available, better resolution could have been obtained. In the case of the silicone mold (b), since there was no need for higher magnification, the sample was examined using the optical microscope. The diameter value obtained was 198.8 µm. This confirms the consistency between these techniques, with results that are within 1µm difference (lower than the relative uncertainties in both cases).

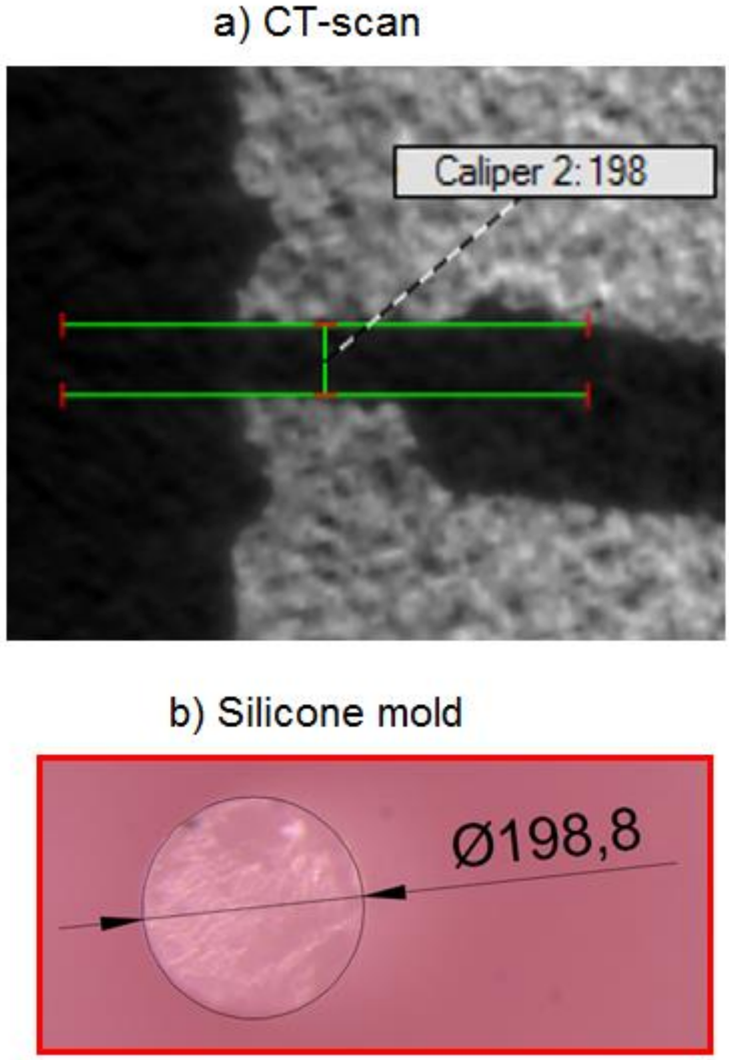

Figure 3. Control volume inlet orifice diameter: a) CT-scan; b) Silicone mold

3.3. Nozzle orifices.

Finally, the nozzle orifices have been also assessed. Again, due to the complexity of the nozzle geometry, only CT-scan and silicone molds techniques could be used. Additionally, the silicone molds in this case were analyzed using the SEM tool. In this case, the CT-scan provides values of 150 µm for one of the inlet diameter of the orifice, and 124 µm for the outlet. For the same nozzle orifice, the silicone mold combined with SEM leads to values of 149 and 126 µm, respectively. As it happened with the control volume inlet orifice, the maximum difference between both techniques (2 µm) is within the uncertainty of both experimental techniques, so they can be judged as equivalent. This fact confirms that the silicone molds technique has state-of-the-art capability to determine the injector internal dimensions.

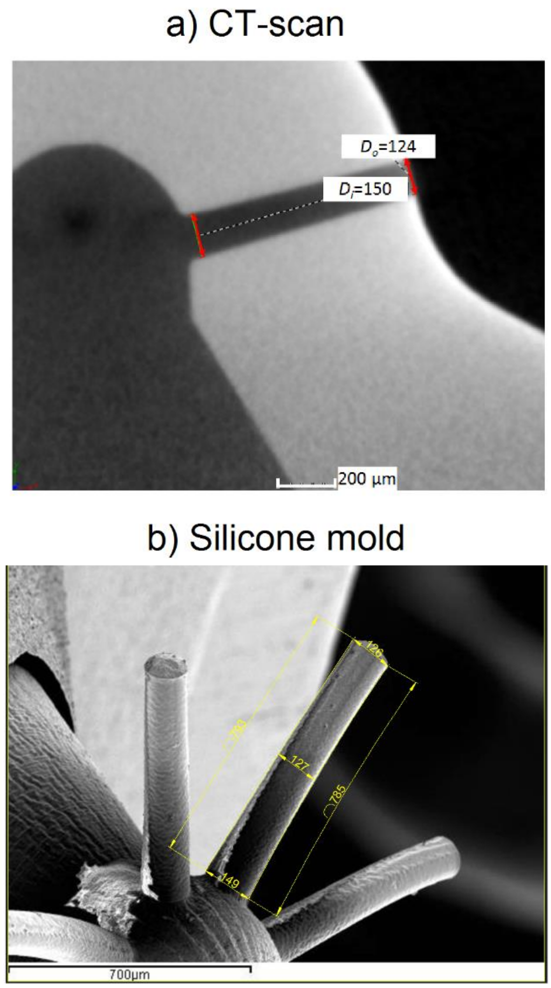

Figure 4. Nozzle orifice inlet and outlet diameters: a) CT-scan; b) Silicone mold

3.4. Summary of measurements

In the previous sections, sample measurements on single images have been presented for the different experimental techniques. Nevertheless, during the activity different measurements have been performed from different planes and orientations of the CT-scan. Additionally, in the case of the nozzle, independent measurements have been done on each of the 8 orifices conforming the nozzle for both techniques. This information is summarized in Table 1. As it can be seen, differences in results between the techniques for each dimension are within the standard deviation of the measurements, indicating that the techniques can be considered equivalent in accuracy for the particular application of study. It has to be considered that the relatively higher standard deviation values observed for the nozzle orifices in both techniques is not only due to the repeatability of the techniques themselves, but also from the slight manufacturing deviation existing between the different orifices.

Table 1. Summary of measurements for each metrology technique

Part	Dimension	Optical microscope		Silicone mold		CT-scan	
		# Meas.	Value [µm]	# Meas.	Value [µm]	# Meas.	Value [µm]
Control volume outlet	**Diameter**	1	100.95	-	-	5	102±1.1
Control volume inlet	**Diameter**	-	-	1	198.8	5	198±1.2
Nozzle	**Inlet diameter**	-	-	16	150±3	24	150±2.5
	Outlet diameter	-	-	16	126±2	24	125±2.1

3.5. Discussion on the applicability of the techniques.

Sections 3.1 to 3.4 compare the three metrology techniques tested in terms of accuracy when determining the geometrical dimensions of the injector internal orifices and ducts. Even though it becomes clear from the results that all techniques can be equally effective to characterize the internal geometry of the injector, each of them has a series of advantages and disadvantages. Thus, the applicability of each technique will depend on other factors, rather than depending on the accuracy of the technique. The present section discusses the applicability of each of the techniques. It is important to note that the following statements could be extrapolated to industrial applications different from the diesel injectors metrology, as long as the dimensions involved were in similar or greater orders of magnitude.

With regard to the direct observation by means of the optical microscope, this technique has the main advantages of simplicity and low cost, while virtually keeping the same accuracy as the other techniques. However, it may be used to characterize simple geometries that can be placed perpendicularly to the microscope optics. This implies that it is only possible to measure the diameter of orifices and ducts, but no information about their lengths can be obtained. Also, the technique is only non-intrusive if the geometry to be measured is external. If information about the internal ducts of the injector is desired, it becomes necessary to dismount the injector.

As far as the CT-scan technique is concerned, its distinctive advantage is the non-intrusiveness. A complete injector may be placed inside the machine without need for disassembling. Nevertheless, the resolution obtained in the pictures to be processed depends on the thickness of the solid material that the x-ray beams need to travel through. Also, these machines are not readily available and the costs of operating them are higher than for the rest of techniques.

Finally, the silicone molds technique proved as accurate as the CT-scan technique, generally coming at a lower cost. Its main drawback is the fact that it is an intrusive technique, since it is necessary to introduce a silicone in the injector. This implies that there is a risk that the silicone may remain inside the injector if the extraction procedure is performed too early. However, when used in combination with the optical microscope this technique allows to overcome the main drawback of the direct observation, since internal ducts may also be characterized. When combined with a SEM, this technique offers the greatest magnification capabilities out of the three ones tested. Thus, it offers versatility as long as the injector can be disassembled.

4. CONCLUSIONS

In the current paper, an investigation of different metrological techniques to determine the internal geometry of a diesel injector has been performed. In particular, direct visualization using an optical microscope, computed tomography scanning and silicone molds were used for this purpose. These techniques were analyzed for the three most significant dimensions influencing the injector hydraulic performance: the control volume inlet and outlet orifices, and the nozzle discharge orifices. The following conclusions have been obtained, in terms of both accuracy and applicability:

- Direct observation through the optical microscope was successfully used for the control plate holding the control volume outlet orifice. Due to the simplicity of the part, it was possible to obtain the orifice diameter in true dimension with acceptable tolerances. However, this technique only allows to characterize external geometries that can be placed perpendicularly to the optics, thus excluding the possibility of measuring the length of internal orifices and ducts.
- CT-scan technique could successfully be used to determine all the dimensions analyzed. For the control volume outlet orifice, the diameter computed from the CT-scan was practically equal to the one achieved with the optical microscope, with a deviation of less than 1 µm, lower than the uncertainty of the technique. Its main advantage is the non-intrusiveness of the measurements, allowing the characterization of the injector internal parts without need for disassembly. However, the applicability of the technique is limited by its availability and costs.
- Silicone molds were obtained for the control volume inlet orifice and the nozzle. The comparison with the CT-scan technique for the same samples shows that the capability to predict the orifices diameters is equivalent, since the differences between both techniques are within the expected uncertainties associated to the measurements. This reinforces the capability of the silicone molds for internal injector geometry determination, at the expense of its intrusiveness, when possible.

The previous conclusions imply that, where more than one technique can be used to characterize a geometry, the selection may be carried out in terms of the applicability and costs of each of them rather than on their accuracy. These conclusions could also be transferred to metrology for industrial applications different from the diesel injection, as long as the dimensions of the samples involved were in similar or greater orders of magnitude.

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