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DIESEL SPRAYS THROUGH MULTI-HOLE MICRO-NOZZLES: SPRAY DYNAMICS AND STRUCTURE

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ABSTRACT The current work attempts to experimentally determine the effects of multi-hole micro-nozzles fabricated using the MEMS-LIGA method. Spray behavior is quantified by SMD measurements using Malvern Spraytec system and cone angle, penetration length through use of a high speed camera imagery.

MEMS-LIGA based method was chosen as the method of fabrication for its ability to fabricate diameters below the EDM capability. The advantage of the LIGA method is quality of the nozzle cross-section and the ability to maintain very close tolerances in diameter and nozzle-to-nozzle distance. A total of 17 planar (2D) and 8 curved (3D) nozzles were tested at different injection pressures (up to 400bar).

The current work uses a HEUI system and documents the effects of Injection (Rail) Pressure, number of micro-nozzles and nozzles' placement. The results suggest that the multi-hole micro nozzle behavior is to some extent similar to that of a single hole nozzle but additional variables like number of nozzles, solid cone angle and placement play a critical role and are specific to the multi-hole behavior.

The current work presents spray tip penetration and cone angle data for both single hole and multi-hole nozzles. The current paper is an extension to our previous paper on spray sizing of multi-hole nozzles[1].

Keywords: Multi-hole Nozzle, Micro-Nozzle, Spray Structure, Penetration, Cone Angle

1. INTRODUCTION

Diesel engines are an efficient alternative to gasoline engines. Over the last decade, especially in Europe, diesels have made impressive gains in what was considered a traditional gasoline market for mid-size automobiles. Inherent issues associated with diesels – NOx, soot emission and noise have precluded its extensive use in North-American automotive market.

One of the alternatives being considered that have the advantages of high efficiency and low emission is the use of Homogenous-Charged-Compression-Ignition (HCCI) engines. Extensive work is underway in the area of combustion, engine control experiments and modeling at University of Wisconsin-Madison [2, 3] as well as other engine research centers [4].

One of the key design parameters to control both emissions and noise is improved spray atomization, since atomization influences fuel-air mixing and fuel vaporization rates. In traditional Diesel engines this has been successfully achieved by using continually higher injection pressures combined with reductions in nozzle diameter [5]. Traditional fuel injection equipment may be ill-suited to HCCI engine requirements. In HCCI engines, injection occurs before the charge is fully compressed and the low cylinder gas density allows current fuel injection sprays to penetrate through the lower density gas to the walls. The resulting wall impingement could result in poor fuel and air mixing. To alleviate this problem, injectors containing many, smaller injection orifices, could be used, providing high-quality atomization without such unacceptable penetration to the combustion chamber wall.

Current manufacturing techniques (e.g., EDM) have inherent limits to reduction in nozzle diameter. The advances in the field of Micro-Electro-Mechanical-Systems (MEMS) offer advantages in reproducibly manufacturing micron-scale nozzle diameters. MEMS are a class of mechanical-electrical devices that have length scales in the order of microns (1-100μm). MEMS devices conventionally used silicon as the working material and used modified Integrated Circuit fabrication techniques. Silicon is a very versatile material but quite brittle. On the other hand, more ductile microstructures can be fabricated from metals via the LIGA process, which is based on deep etch X-ray Lithography, electroplating and molding [6]. The name LIGA originates from the German acronym: Lithographie, Galvanoformung and Abformung. The process involves the use of a thick layer of X-Ray photoresist and high-energy X-Ray radiation exposure and development to achieve a three-dimensional resist structure. Subsequent electro-deposition fills the mold with a metal. After the resist removal by chemical dissolution, the metal structure may be a final product or serve as a mold for subsequent parts molding.

The MEMS injection system demonstrated by University of Wisconsin (UW) researchers is potentially ideal for use in HCCI engine concepts. At low ambient gas pressure, they demonstrated spray-averaged drop sizes of around 17 microns. Their MEMS multi-hole nozzles were quite reproducible and produced good atomization without over-penetration. One of the reasons for increases in the spray SMD might be coalescence of droplets due to the densely placed micron sized nozzles [7,8].

This work was further extended and 3-Dimensional micro-nozzles were fabricated at UW to address the issue of increased SMD for multi-hole nozzles. Initial results at low injection pressures suggested an improvement may be possible using such 3-dimensional micro-nozzles [10,14]. Air-entrainment or the lack of it is a potential contributory factor as the nozzle diameter and injection pressure decreases, thereby reducing spray momentum flux and the interfacial air-fuel shear stress. In addition, for a multi-hole nozzle with "tens" of holes the ability of air to flow into the inner regions of the multi-hole spray could be hampered, thus reducing the effectiveness of multiple holes with small diameters to minimize the droplet diameter and yet deliver the required flow.

The behavior of a single hole nozzle is understood quite well. Empirical relations have been proposed in literatures for the spray parameters. Transient 3D simulations also been successfully attempted not only to explain spray kinematics like penetrations, cone angle but also to understand spray kinetics-Air entrainment, combustion, lift-off length etc. But there is limited published data on behavior of interacting multi-hole nozzles placed in close proximity. The work being done at the University of Wisconsin-Madison [1,6,7,8,10,14,15] suggest that the multi-hole micro nozzle behavior is to some extent similar to that of a single hole nozzle but additional variables like number of nozzles, solid cone angle and placement play a critical role and are specific to the multi-hole behavior.

2. FABRICATION OF 3D MICRO NOZZLE USING THE MODIFIED LIGA TECHNIQUE

The current work is based on mask-making technology of Guckel et al., which uses silicon nitride (SiN) as a mask blank and gold as an absorber [6]. The X-Ray mask fabrication involves many steps and these are discussed in our previous paper [8]. A new substrate fabrication technique was developed to allow for the manufacture of 3-Dimensional micro-nozzles. The process diagram is shown in Figure 1. The process is discussed in detail in our previous paper [10].

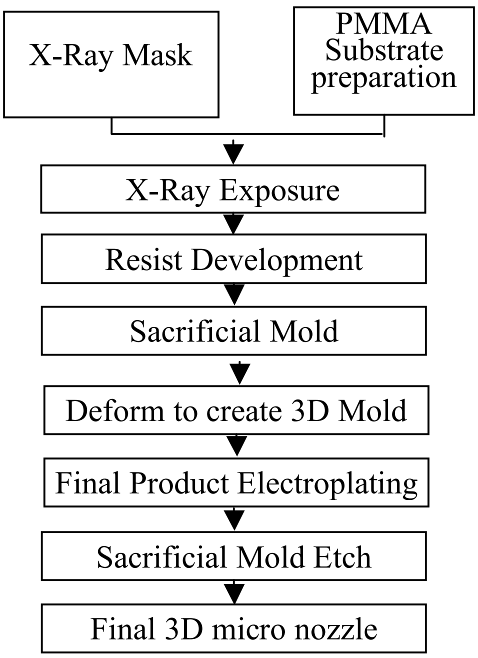

Figure 1 Modified LIGA Process

A total of 17 planar (2D) and 8 curved (3D) nozzles were tested at different injection pressures (up to 400bar). The outer diameter is about 2.5 mm and the thickness varied from 200-300 microns. Table 1 at the end of the paper lists the various nozzles fabricated and the nomenclature of each. Figure 2 shows the SEM of two such nozzles.

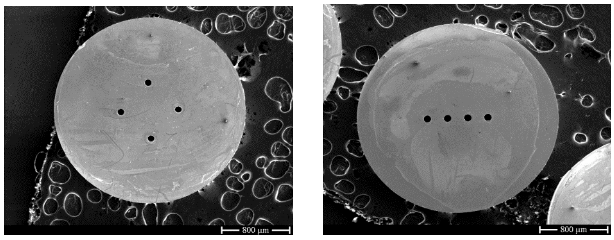

Figure 2 2D 4X80C and 2D 4X80L micro-nozzle

3. EXPERIMENTAL SET-UP

Experiments were carried out at room temperature and under quiescent gas conditions, in a constant volume cylindrical chamber (185 mm inner diameter and 185 mm long) equipped with two quartz windows with field of view 101 mm in diameter. Nitrogen gas was used to pressurize the chamber and the gas density inside the chamber was 11.85 kg/m^3. Measurements were performed on single shot diesel sprays produced by Caterpillar HEUI fuel-injection system. A high pressure oil pump was procured and assembled to drive the HEUI system.

The end of the HEUI nozzle was cut and the micro-nozzle was attached using a test mechanical clamp [14]. Laser diffraction-based commercial system from Malvern/Insitec, was used to measure the Sauter Mean Diameter (SMD). The receiver focal length was 200 mm and the laser beam diameter was 3 mm. The Malvern system was setup so that the detector could be easily moved in and out when required. The SMD values were measured at an axial distance of 25mm from the nozzle. The results from the Droplet sizing exercise is presented in a previous paper [1]

The optical system used for high speed movies was based partly on the 4.25 inch Schlieren system marketed by Edmund Optics. A fiber optic light source was used to obtain a variable light intensity. A 50 mm focal length convex lens along with an iris was used to provide the diverging rays of light to the spherical mirror (focal length =4.25 inch) procured from Edmund optics. The collimated beam was allowed to pass through the bomb. The scattered image of spray was focused through a Tamaron zoom lens and it was possible to capture the spray without the Malvern detector in the view.

A high speed digital camera procured from Vision Research Inc was used for high speed movies. The camera was controlled through the control software, Phantom 6.06 [16]. The camera linked to the control computer through Ethernet. The HEUI was also controlled from the same computer. The camera was triggered by the HEUI ECM with a falling TTL pulse. The exposure, frame rate etc could be controlled through Phantom. The camera had 1024 Megabyte integral image memory. This camera was used to capture images with frame rates from 7200 fps (full field) to 55000 fps (near nozzle) based on the parameter of interest. Most of the images were taken at 15000 fps at 256 X 512 pixel resolution. The schematic of the experimental setup is described in more detail in [1].

Multiple sprays were observed to ensure constant injection duration, the solenoid current duration was adjusted till the duration (as determined by the total number of frames where the spray was visible) was approximately 1.5 ms. Once the duration stayed constant for a fixed solenoid current duration, a single injection event was recorded. The bomb was purged off the Nitrogen and a fresh charge was filled to get the desired back pressure. The Malvern Detector was slid back into its locating plates and finer adjustments if needed were done based on the background scatter signature. For a fixed Rail Pressure, Multiple spray events were measured for duration of 3ms. The SMD values were measured at an axial distance of 25mm from the nozzle.

The data was saved in its raw form and as ensemble average values. These data files were used for result analysis and to draw conclusions. A few measurements were also taken with the multiple scattering corrections turned off, to see the effect of the correction algorithm.

Once multiple data values were recorded the detector was slid out of the view of the camera. The light source was turned on and another movie of a single injection event was recorded with no modifications to the Injection system/specifications. These two movies give a fair idea as to the extent the spray varied between the each injection event. It also is a check that the no abnormal injection event (leakage, pool of liquid etc) was recorded.

4. EXPERIMENTAL RESULTS

4.1 Spray Penetration

Single Hole Nozzle The Spray penetration for a single hole nozzle at a rail pressure of 6.0 MPa is shown in Figure 3 also shown is the penetration of the 1X80 nozzle at all three measured Rail Pressures in Figure 4. The penetration data is measured off the high-speed movie using the inbuilt measurement tool in the software. The Mechanical Clamp was used as the gage. Inherent errors are associated with using the clamp as the gage. The data presented assumes that start of injection is one frame previous to the frame that the spray becomes visible.

The penetration data suggests that as the hole diameter increases penetration increases for a particular rail pressures. Similarly for a fixed nozzle diameter, increase in rail pressure increases the penetration. It is to be noted that even if the Rail Pressure is fixed the actual Injection Pressure might not always be constant between the individual events. The actual injection event is also a function of the solenoid current duration, which we are controlling for particular injection duration. It is not possible in the current setup to measure the actual injection pressure and hence all the data will be presented as a function of the Rail Pressure.

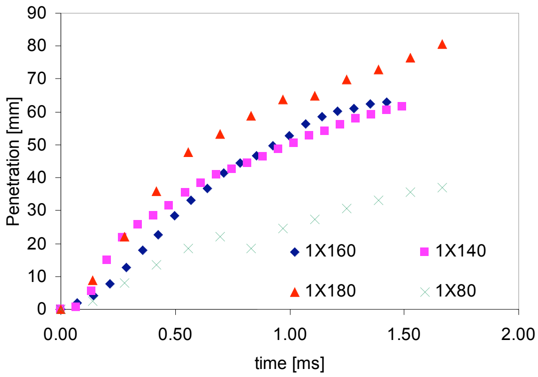

Figure 3 Penetration of nozzles at a RP=6.0 MPa

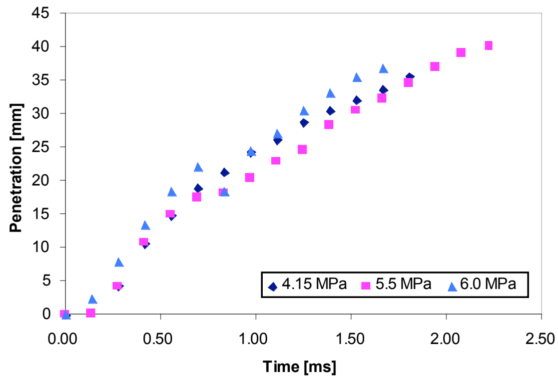

Figure 4 Penetration of a 1X80 nozzle at different Rail Pressures

Multi-Hole Nozzle: The nozzle penetration was also measured for the 2D multi-hole nozzles, the penetration curves are shown in Figure 5 and Figure 6. The nozzles show a similar trend as that of a single hole nozzle, i.e penetration increases with increase in pressure. The difference between the penetration data between the lower two pressure is not really visible possibly because the HEUI is not very stable at such low pressures and it is difficult to get accurate and stable injection duration and injection pressures.

The penetration also increases with increase in number of holes. Figure 5 suggests that the penetration of the 2D5X80C is very close to the 2D4x80L, this is very interesting in that there might be a way to get reduced penetration by changing the way the nozzles are placed.

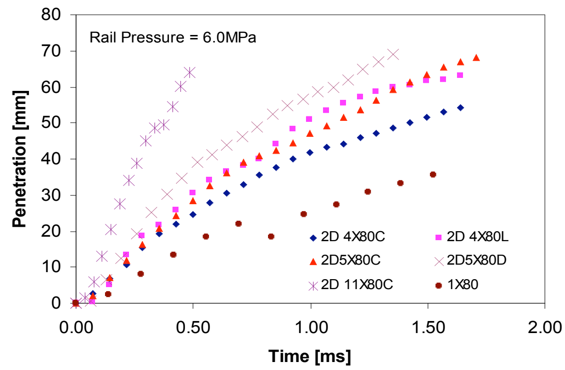

Figure 5 Effect of number of nozzles on penetration

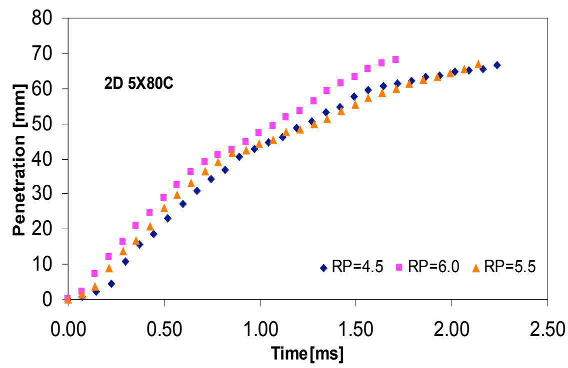

Figure 6 Effect of Rail pressure on a multi-hole nozzle

This change in penetration based on nozzle placement will be analyzed by comparing two nozzles having same number of holes but varies by the way they are placed. Figure7 and Figure 8 shows the penetration data for the 2D5X80C and 2D5X80D nozzles at two different rail pressures. The data suggests that the penetration for the 2D5X80C is significantly less than the 2D5X80D.

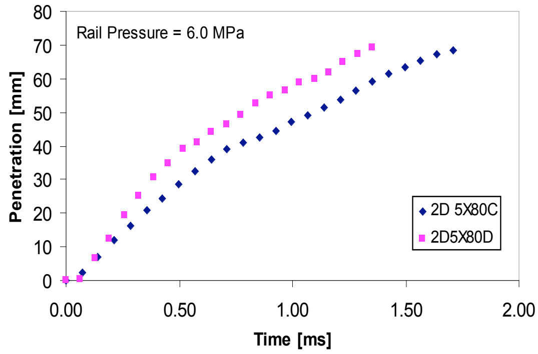

Figure7 Effect of nozzle placement on penetration at a RP of 6.0MPa, 2D5X80

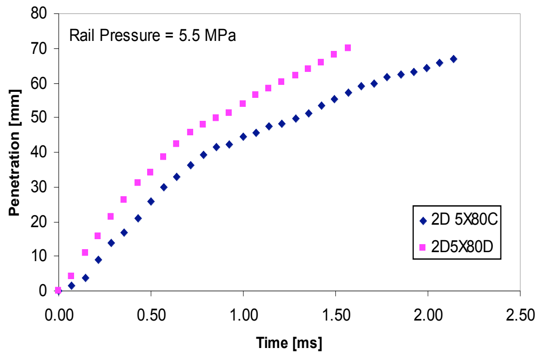

Figure 8 Effect of nozzle placement on penetration at a RP of 5.5 MPa, 2D5X80

Figure 9 and Figure 10 shows the penetration data for the 2D4X80C and the 2D4X80L nozzle. From the penetration data it appears that the 2D4X80C has a lower penetration than the 2D4X80L. These penetration plots are very interesting in that, it suggests that a multi-hole nozzle is different from a single hole nozzle, in the sense that the ***placement*** and number of holes plays an important role. And this difference in the nozzle behavior starts to appear as early as just 4-5 interacting sprays. The nozzles 2D5X80C and 2D4X80C have lower penetration because the nozzles experience more air drag at the spray surface as compared to the 2D4X80L and 2D5X80D. In the case of 2D4X80L the inner two holes see sprays on both their sides and hence the droplets have lesser resistance in addition to being accelerated by the outer two sprays. This is also true for the inner hole for the 2D5X80D case, where the inner hole has limited resistance from air and the inner droplets gets accelerated by the neighboring sprays. But all the multi-hole nozzles experience less drag per spray as compared to a single hole nozzle and hence the penetration of the 1X80 is significantly less than that of the multi-hole nozzles.

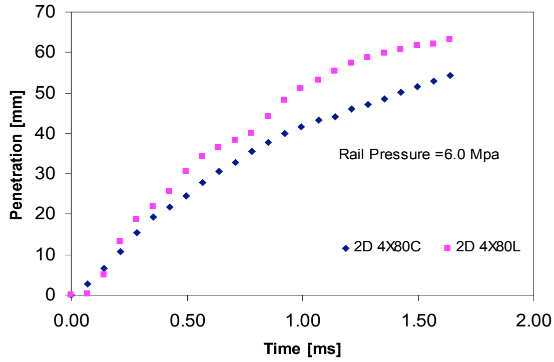

Figure 9 Effect of nozzle placement on penetration at a RP of 6.0MPa, 2D4X80

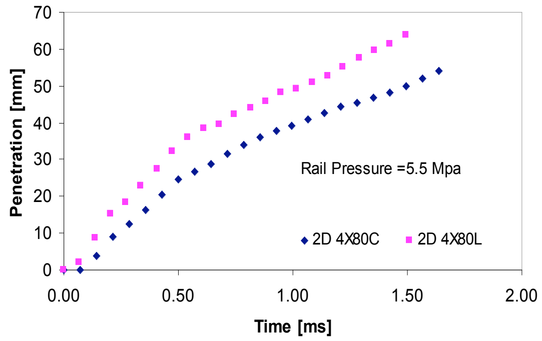

Figure 10 Effect of nozzle placement on penetration at a RP of 5.5MPa, 2D4X80

The most interesting aspect of the multi-hole nozzle spray penetration can be seen in Figure 12. The single hole nozzles were fabricated to have equal flow areas as that of 3X80, 4X80, 5x80 and 11x80 nozzle.

The penetration of a 2D3X80L is similar to its single hole of equivalent area, i.e., 1X140.The penetration of a 2D5X80D is similar to its single hole of equivalent area, i.e., 1X180. The penetration of a 2D5X80C is similar to 2D3X80L and in turn to 1X140. The penetration of a 2D3X80C is *less* than that of its nozzle of equivalent area, i.e., 1X140, but it is still greater than a 1X80, and the penetration of a 2D11X80C is similar to its single hole of equivalent area, i.e., 1X260.

The penetration for a 3D nozzle was not measured as there is no reference axis along which we can measure it. The differences in nozzle behavior can be clearly seen in the images from the High Speed Movies [15]

4.2 SPRAY CONE ANGLE

The spray cone angle for 2D4x80 and 2D5x80 are shown in Figure 11. The cone angle was measured using the embedded software in Phantom.

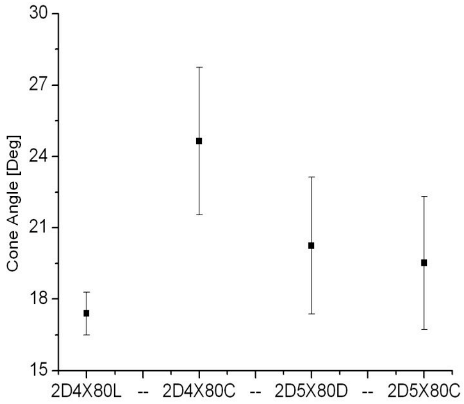

Figure 11 Cone Angle for a 2D Multi-hole nozzle

The exact cone angle measurement is difficult because of the turbulent nature of the spray periphery. The cone angle for the 2D4X80L is very much smaller than the 2D4X80C because the nozzles are placed in a straight line. It is interesting to note that the cone angles for the 2D5X80C and 2D5X80D is similar, though the spray penetration was noticeably different. This suggests that the cone angle is a function of only the outer most array of hole diameter and Rail Pressure other than internal geometry.

The spray cone angle was not measured for the 3D nozzle as they will be very high as compared to the 2D nozzle because of the nozzle curvature and a direct comparison is not possible. In addition, the cone angle varies with time and is not steady because the outer jets get sucked into the center [15].

5. SPRAY STRUCTURE

The spray penetration, cone angle and the SMD results [1] give us a fair indication about the quantitative behavior of the 2D and 3D nozzles. During the course of the experiments about 650 high-speed movies were recorded at frame rates ranging from 7200 to as high as 50000 fps for near nozzle analysis [15]. Figure 13, Figure 14 and Figure 15 show example such movies. The complete description and analysis is beyond the scope of the current paper and will be discussed in a future publication.

6.CONCLUSIONS

The LIGA is an attractive alternative for nozzle-injector development over other fabrication methods like laser drilling because of the high quality nozzle cross-section obtained; i.e., high precision nozzle diameter and length. This high quality is very important for reproducible test results in a research and development setting. These nozzles along with temporary clamps provide an ability to fabricate "Nozzle Standards" to be reused and retested with different injection system for these key baseline data. The results suggest that the LIGA based micro-nozzle will accurately display the spray behavior of both single and multi-hole nozzles. LIGA is immensely more attractive as a research tool when compared to the EDM drilled samples.

For a single hole nozzle, the penetration decreases as the nozzle diameter decreases and injection pressures decreases. The cone angle decreases as the nozzle diameter decreases and the injection pressure decreases

The behavior of a Multi-hole nozzle is more interesting and can be concluded separately for 2D and 3D nozzles.

6.1 2D Multi-hole Nozzle

The nozzles show a similar trend as that of a single hole nozzle, i.e penetration, cone angle increases with increase in pressure. The placement and number of holes plays an important role on penetration. And this difference in the nozzle behavior starts to appear as early as a 4-5 nozzle hole cluster of interacting sprays

An L or a D nozzle would have a penetration equivalent to a single hole nozzle of equivalent area. A C nozzle will never approach a single hole nozzle of equal *diameter*

As the number nozzles increases, even a C nozzle would tend towards behaving like a single hole nozzle of equivalent *area*. (current example being the 2D11x80C)

It is likely that a D nozzle with a large number of holes would have a penetration more than that of a single nozzle of equal area. In other words its proposed that a 2D11x80D would have a penetration greater than 3D11X80C *and* 2D11X80C. Unequivocal conclusions cannot be drawn as we do not have an extensive database to prove this.

We would need additional data to be able to completely accept this to be universally true. The encouraging aspect is that this behavior repeats at all the rail pressures and nozzle configurations in test currently. Previous work by Baik [7,8] used ***only*** D nozzles and it was observed that the penetration scaled with flow areas rather than placement. This should be a highly motivating force for further work on multi-hole nozzles in cold condition in addition to combusting/evaporating environment.

The cone angle varies based on number of nozzles, and injection pressure. The variation seems to be less between a C and a D nozzle, but the geometry of the L nozzle affects the measured cone angle

6.2 3D Multi-hole Nozzle

The current paper does not describe the details of penetration and cone angle for the 3D nozzles as these are *qualitative* measurements and we would need to have extensive pictures from high speed movies to be able to understand the various interactions. The conclusions below are presented to complete the discussion on spray structure more details on the 3D nozzles can be found in reference [15].

The observed penetration for the 3D nozzles shows similar trends as that of a single hole nozzle, i.e., increased rail pressure increases penetration. The placement and number of holes plays an important role on spray tip-penetration. The individual sprays start interacting quite early in their axial penetration, even for the 3D 2X80 nozzle. The spray structures observed through high-speed movies suggest that they are highly dependent on nozzle placement and solid cone angle. There is the distinct opportunity to "tailor" the sprays using multi-hole 3D nozzles

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Table 1 Nomenclature and list of Micronozzles fabricated and tested

Sl No.	Nozzle Nomenclature	Description
1	1X80	Single hole, 80 micron diameter nozzle
2	1X140	Single hole, 140 micron diameter nozzle
3	1X160	Single hole, 160 micron diameter nozzle
4	1X175	Single hole, 175 micron diameter nozzle
5	1X265	Single hole, 265 micron diameter nozzle
6	2D 2X80	Planar nozzle, 2 holes of 80 microns diameter each
7	2D 3X80C	Planar nozzle, 3 holes of 80 microns, in a circle
8	2D 3X80L	Planar nozzle, 3 holes of 80 microns, placed along a line
9	2D 4X80C	Planar nozzle, 4 holes of 80 microns, in a circle
10	2D 4X80L	Planar nozzle, 4 holes of 80 microns, placed along a line
11	2D 5X80C	Planar nozzle, 5 holes of 80 microns along a circle
12	2D 5X80D	Planar nozzle, 4 holes of 80 microns along a circle and an additional central hole of 80 microns
13	2D 7X80D	Planar nozzle, 6 holes of 80 microns along a circle and an additional central hole of 80 microns
14	2D 11X80C	Planar nozzle, 12 holes of 80 micron along a circle
15	3D 2X80L	Curved nozzle, 2 holes of 80 micron along a line (arc)
16	3D 4X80L	Curved nozzle, 4 holes of 80 micron along a line (arc)
17	3D 7X80D	Curved nozzle,6 holes of 80 micron in a circle with an additional central hole of 80 microns
18	3D 11X80C	Curved nozzle, 11 holes of 80 micron along a circle
19	3D 12X80D	Curved nozzle, 6 holes of 80 micron along an outer circle with an additional 5 holes in an inner circle and a central hole of 80 microns
20	3D 41X80D	Curved nozzle, 41 holes of 80 micron diameter distributed

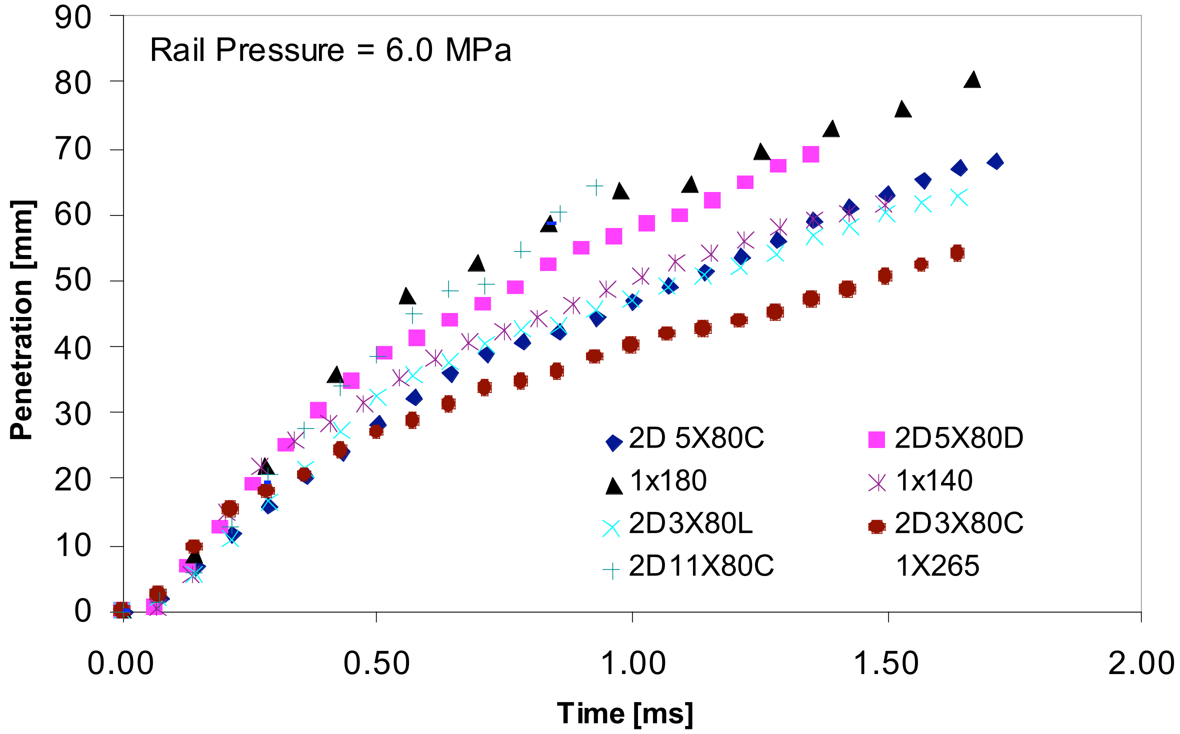

Figure 12 Penetration behavior of a multi-hole nozzle and its relation to a single hole nozzle

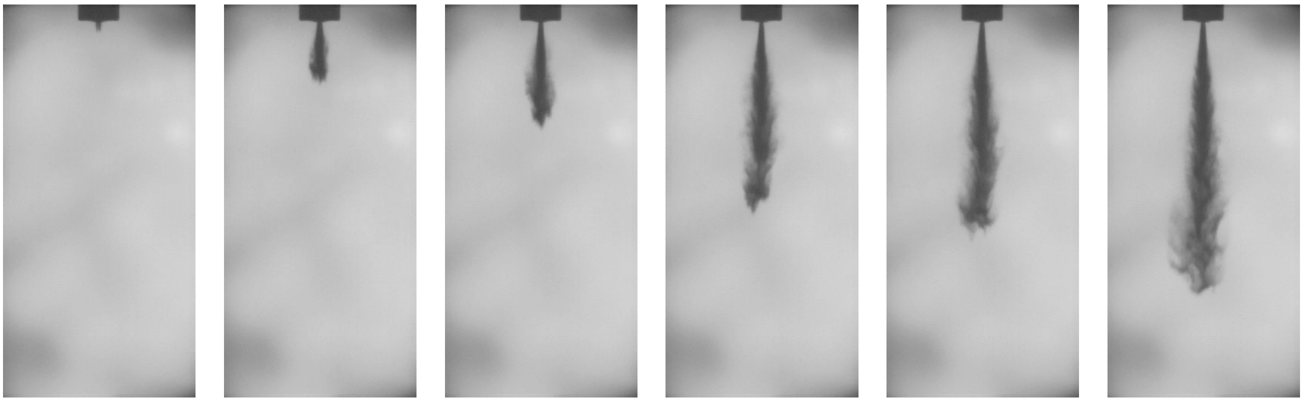

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Figure 13 Still pictures of 2D 5X80C nozzle, RP =6.0 MPa, 14000 fps

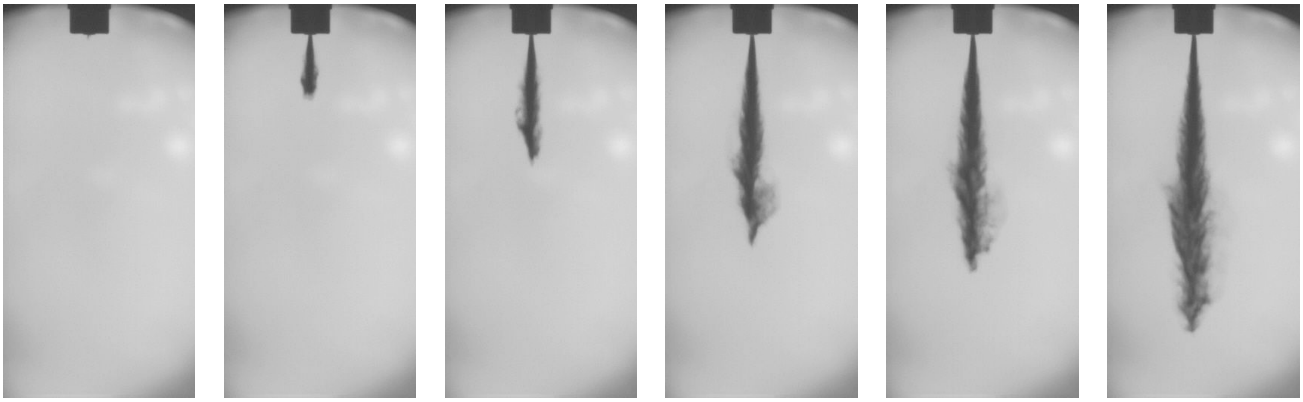

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Figure 14 Still pictures of 2D 5X80D nozzle, RP =6.6 MPa, 14000 fps

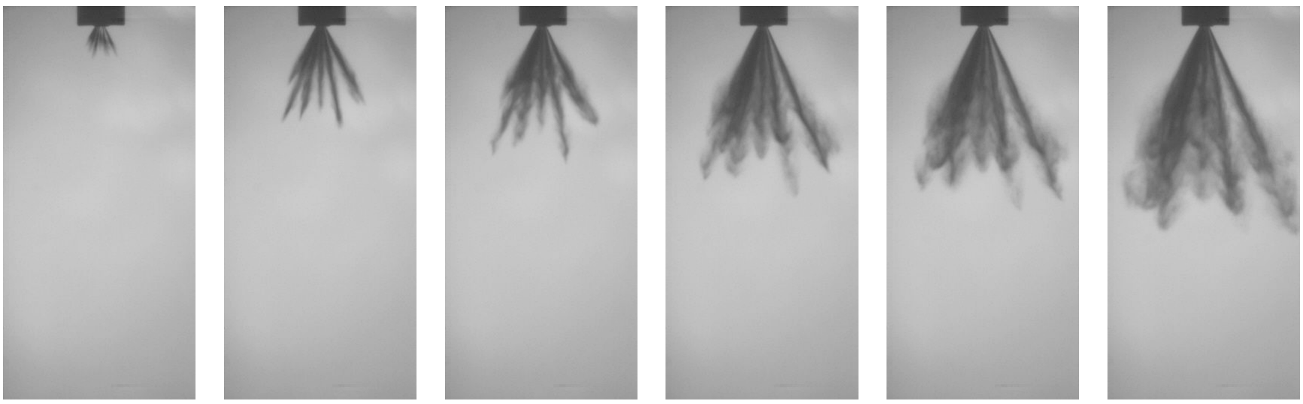

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Figure 15 Still pictures of 3D7x80D nozzle, RP =5.5 MPa, 14000 fps