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Diesel Sprays Through Multi-hole Micro-Nozzles: Droplet Sizing

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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. 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 SMD seemed to increase almost linearly for the 2D nozzle with increase in number of nozzles, but almost remained a constant for the 3D nozzle for a few number of nozzles and then it appears the SMD values starts to increase steeply. For small number of nozzles, it was found within the present experimental condition and nozzle diameter-to-diameter distance that the nozzle placement had almost no effect on SMD values.

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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 [1, 2] as well as other engine research centers [3].

Unlike a traditional Spark-Ignition or Compression-Ignition engine, HCCI combustion would ideally take place spontaneously and homogeneously. This could eliminate heterogeneous air/fuel mixture regions, minimizing soot formation. In addition, HCCI is a *lean* combustion process. These conditions translate into a lower local flame temperature, which lower the amount of Nitrous Oxide (NO_x) produced in the process.

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 [4]. 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 [5]. 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.

Baik et al [6,7] developed and used micro-machined injector nozzles with commercially produced diesel injection systems. Fourteen different circular plates were fabricated with LIGA. These included *planar* single and multiple-hole nozzles with diameters varying from 40 to 260 microns. They found that the SMD decreased as the diameter of orifices decreased. However, the SMD increased as the number of orifices increased. Additionally, the different geometry of single orifice nozzles did not affect the SMD as much as might be expected. The authors hypothesized that droplet coalescence was the cause of the observed results. 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 [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 [9,13]. 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 [6,7,9,13,14], 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.

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 [5]. The X-Ray mask fabrication involves many steps and these are discussed in our previous paper [6]. 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 [9].

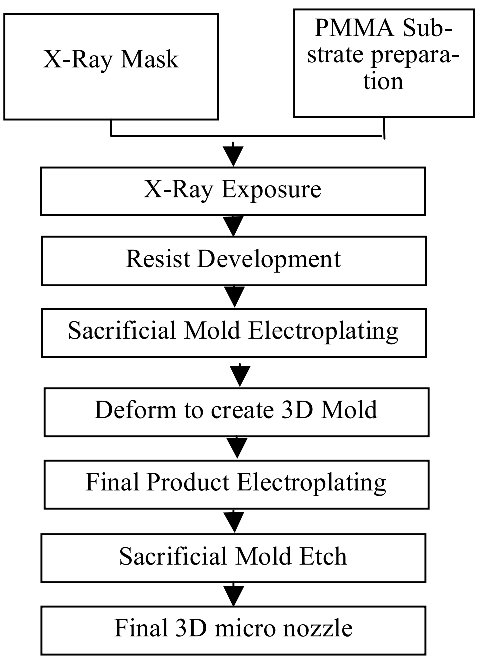

Figure 1 Modified LIGA Process

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.

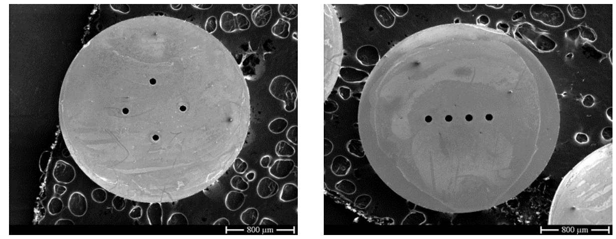

Figure 2 2D 4X80C and 2D 4X80L micro-nozzle

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 [13]. 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 optical system used for high speed movies was a very simple setup 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 [15]. 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 shown in Figure 16 at the end of the paper.

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.

Experimental Results

Single Hole Nozzle

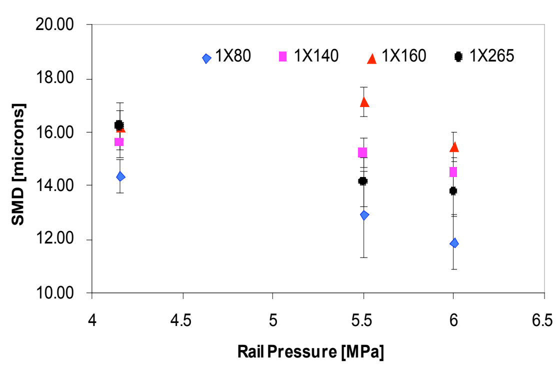

Figure 3 Effect of Rail Pressure on SMD for a single hole nozzle

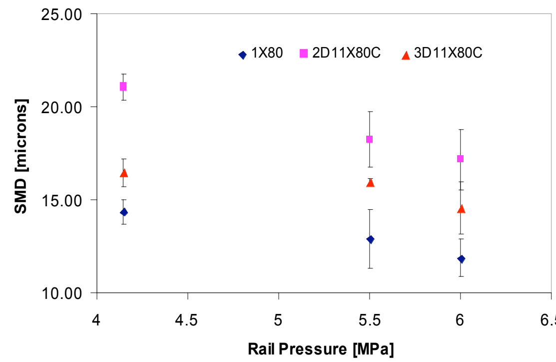

Figure 4 Effect of Rail Pressure on SMD for multi-hole nozzle

Multiple trials were done for each rail pressure and nozzle combination. The measured SMD values were averaged; the error bars shown in all the Figures are one standard deviation values.

The effect of Rail pressure on SMD for a single hole nozzle is shown in Figure 3. It can be seen that as the nozzle diameter decreases the SMD decreases for a particular injection pressure. The average SMD for the 1X265 nozzle was measured to be lower than the 1X160 nozzle, but the error bars for SMD values for each of 1X140, 1x160, 1x265 intersect suggesting that the SMD values for these nozzles are in the same range of data.

Figure 4 shows the SMD as a function of rail pressure for the 1X80, 2D11X80C, 3D11x80C. The SMD tends to decrease with increasing rail pressure even for the multi-hole nozzles, but it is seen that the 1X80 has a lower SMD as compared to both the 3D11X80C and the 2D11X80C, but the 3D11X80C has a lower SMD value than the 2D11X80C. These results are in agreement with the previous results [13]. Now that we understand the behavior of multi-hole nozzle SMD with rail pressure we can try to analyze data to understand how the SMD varies as the number of nozzles changes.

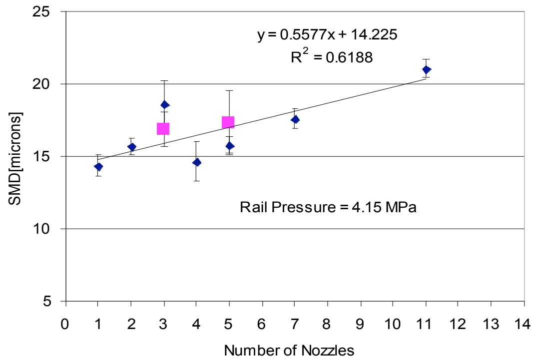

Figure 5 Effect of number of holes on SMD for a 2D nozzle at a Rail Pressure=4.15 MPa

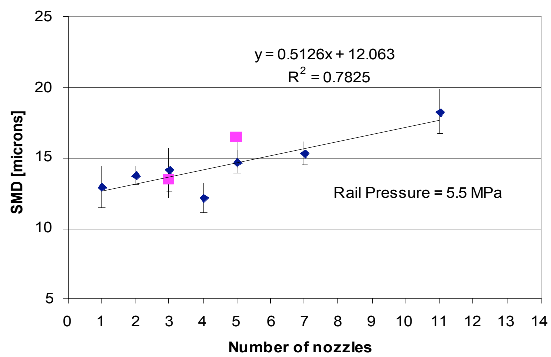

Figure 6 Effect of number of holes on SMD for a 2D nozzle at a Rail Pressure = 5.5 MPa

Figure 5, Figure 6 and shows the variation of SMD as a function of number of nozzles of 80 micron each for a rail pressure of 4.15, 5.5 and 6 MPa respectively. Two additional data points with different color seen in the plot is the 2D 3 and 5 hole nozzle which have two different nozzle placement.

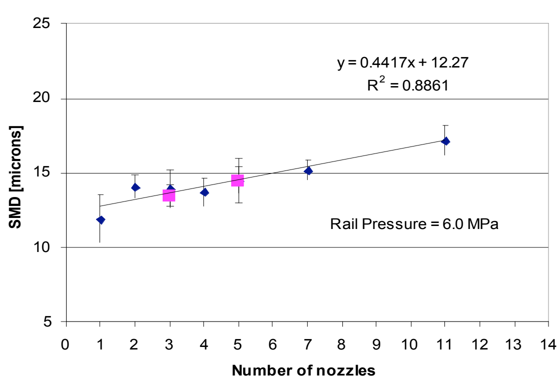

Figure 7 Effect of number of holes on SMD (2D, RP=6.0MPa

The data suggests that it might be possible to fit a curve for these 9 data points. A linear curve seems to be most suited and easiest to attribute a physical parameter (total flow area of the nozzle) even if we can get better curve fits using a higher order polynomial (3rd). The actual curve will probably be a fraction power greater than 1 to take care of secondary effects like air entrainment (or lack of it) and droplet collisions, but it would take additional nozzles being fabricated with greater than 12 holes.

From these SMD plots, it appears for a 2D nozzle the SMD would continue to increase linearly with number of holes at a particular pressure. The rates of increase seem to be almost independent of the injection pressures in the range of pressures tested currently. This is very interesting because even if the curve fit slopes are not correct as an absolute value (based on R^2 value), the trend seems to suggest that an increase in rail pressure will give an lower SMD (and higher penetration), but rate at which the SMD increases seems to be a more direct function of the number of holes or interacting sprays. It is to be noted that though the Rail Pressure is held constant, the injection rate as a parameter is not considered and may be a very important contributor. Based on the SMD and penetration results it might be safe to assume that the injection rate on SMD values will be similar to that of a single hole nozzle but again with an offset toward higher SMD values. Additional experiments might be necessary with the injection rate as a parameter to address this issue. The advantage of the current setup is that HEUI has an inbuilt ECM injection rate control parameter and also the LIGA nozzle as a standard for tests is readily available for any future testing and is suited not only for the HEUI but for *any* kind of injection system as long as the Injection Pressure are within acceptable limits (ANSYS results suggest this limit to be around 80 MPa Injection Pressure for the 300 micron thick nozzle).

Now that we seem to have some understanding of how the SMD varies for a 2D nozzle, we can try to analyze the results for the multi-hole 3D nozzle.

The effect of number of nozzles on the SMD for a 3D nozzle is shown in Figure 8, Figure 9, and Figure 10 for a rail pressure of 4.15, 5.5 and 6.0 MPa respectively.

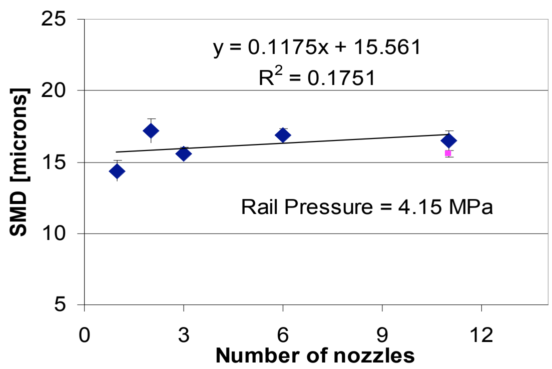

Figure 8 Effect of number of holes on SMD for 3D nozzles at a Rail Pressure = 4.15 MPa

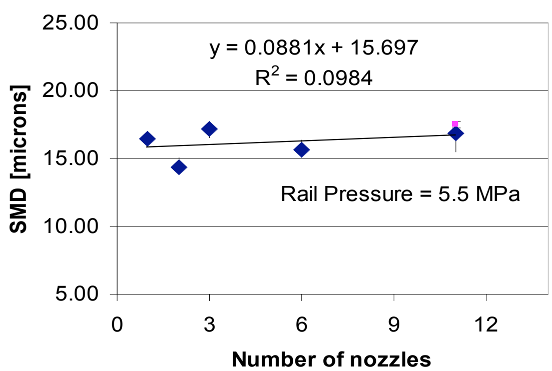

Figure 9 Effect of number of holes on SMD for 3D nozzles at a Rail Pressure = 5.5 MPa

It appears the SMD is NOT a function of number of holes. This is logical considering that the 2 hole, 3 hole 3D nozzle almost do not interact at a large enough length scale to effect a global average like the SMD. It seems interesting that the trend continues even for higher number of holes, as high as 3D11X80. To better understand this behavior it was decided to test the previously fabricated 3D41X80D nozzle. The SMD for this nozzle was markedly higher than the 3D11X80C nozzle. A second order polynomial fit seems to be a very good candidate (R^2 = 0.97) when the 3D41X80D[1] is included in the data set. The SMD values at large number of holes are no longer independent of the number of holes because the sprays start to interact at a much larger scale and secondary effects like air entrainment, droplet collision has a much larger effect.

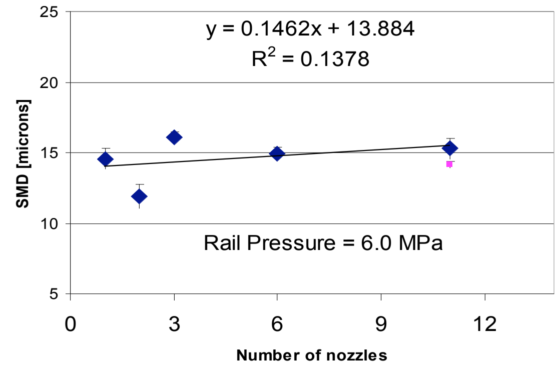

Figure 10 Effect of fewer number of holes on SMD for 3D nozzles at a Rail Pressure = 6.0 MPa

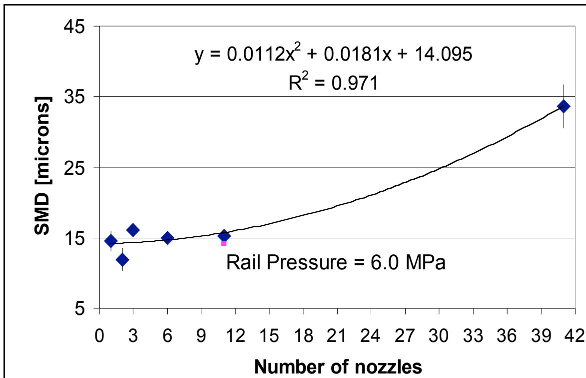

Figure 11 Effect of higher number of holes on SMD for 3D nozzles at Rail Pressure = 6.0 MPa

It would be very interesting to see what the critical number of holes is before the SMD for a 3D nozzle would start increasing at a greater rate with the number of holes. From Figure 11, it appears to be somewhere in between 11 and 41 holes for the current 3D nozzles and the current range of injection pressure. This critical number of holes is directly a function of the solid cone angle (separation between individual holes) and the injection pressure. From the current result it appears that this critical point decrease with increase in Rail Pressure, it would also decrease with decrease in the solid cone angle (separation between individual holes). The next logical step would be to test a 3D nozzle with the same cone angle with holes in between 11 and 41, say 20 to be able to fit a second order polynomial (total of at least 3 points) between these two nozzles.

[1] It is to be noted that the 3D41X80D has a different curvature and hence different solid cone angle. But can be used in the present set to see the effect with the knowledge that the cone angle is different and hence the actual curve would probably be a bit more flat.

Figure 12 and Figure 13 compares the SMD values for a single hole and a multi-hole nozzle of equal areas. The trend is similar to what was observed in our previous work [9,13]

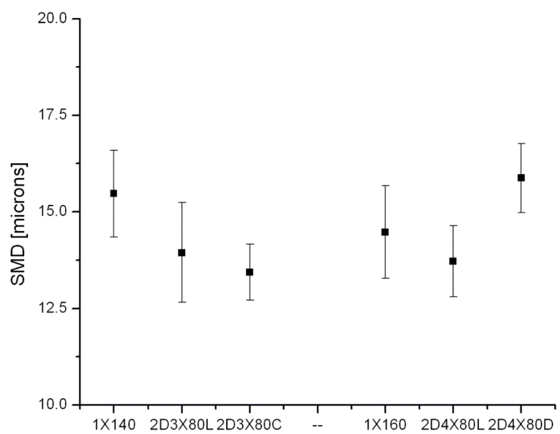

Figure 12 SMD comparison for area-equivalent nozzles of 1X140 and 1X160 (RP = 6.0 MPa)

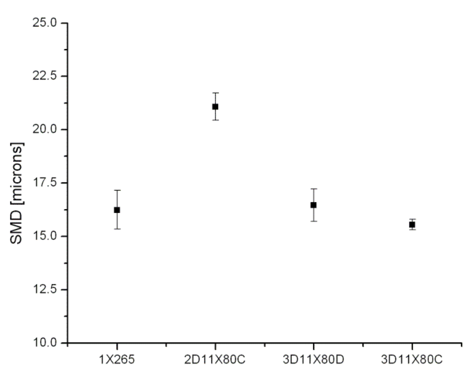

Figure 13 SMD comparison for area-equivalent nozzles of 1X140 (RP = 4.15 MPa)

Figure 14, Figure 15 shows the SMD variation as a function of nozzle placement. It is interesting to see that the SMD does not seem to vary significantly with the placement other than the previously observed aspect of a 3D nozzle having a lower SMD than a 2D nozzle for higher number of holes.

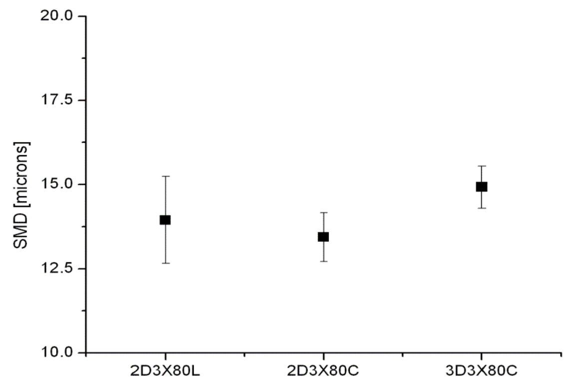

Figure 14 Effect of nozzle placement on SMD for 3X80 nozzles (RP = 6.0 MPa)

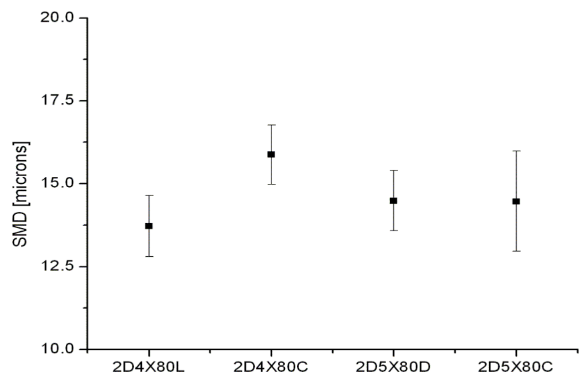

Figure 15 Effect of nozzle placement on SMD for 4X80 and 5X80 nozzles (RP = 6.0 MPa)

It might be safe to conclude that within the rail pressures and nozzle placement (diameter-to-diameter) distance currently used, it appears the SMD is almost independent of placement. It appears that the 2D4X80L has got a lower SMD as compared to the 2D4X80C.

These data are in agreement with previously observed trends with 2D5X40 nozzles[5,7]. Based on the current set of nozzles and the previous work, it might be safe to conclude that SMD is a function of nozzle diameter, number of nozzles, solid cone angle, Rail Pressure, but does *not* significantly depend of placement of the individual holes in the cluster. This conclusion needs to be taken with caution and with the knowledge that laser diffraction method was used to quantify the sprays and multiple scattering, data rejection are a part of the process. One of the issues of for particle sizing is there may not be any other dependable or better way to measure such closely spaced high injection pressure sprays. Even a PDPA system would have a large amount of data rejection as we try to probe near-nozzle.

Conclusions

The ability to fabricate micro-nozzles of high quality and reliability is because of the use of MEMS-LIGA fabrication technique. Modifications to the standard LIGA micro-fabrication technique can be successfully used to fabricate both 2-D and 3-D micro-nozzles. The LIGA can be attractive to other fabrication methods like laser drilling because of the high quality nozzle cross-section obtained. This high quality is very important for research settings. These nozzles along with temporary clamps provide an ability to fabricate "Nozzle Standards" to be reused and retested with different injection system for baseline data.

The following conclusion can be drawn based on the experimental results obtained

The SMD decreases as the nozzle diameter decreases and Injection pressure increases for a single hole nozzle. The behavior of a Multihole nozzle is more complex.

Multihole Planar (2D) Nozzle

The SMD values do not seem to be directly related to nozzle placement but on number of nozzles (flow area) suggesting that droplet collision is the controlling mechanism rather than interfacial forces.

The SMD value seems to increase linearly with increase in number of nozzles

Multihole Curved (3D) Nozzle

The SMD value for the 3D nozzles for less number of nozzles does not seem to depend on the number of nozzles in the present experimental conditions of rail pressure, center-to-center distance and solid cone angle. The SMD ramps up steeply as the number of nozzles are increased

Highly atomized sprays with SMD in the 10μm range are possible with a single hole micro-nozzle using pressure in the range of 100 MPa. The current work on micro-nozzles seems to suggest we may need a non-traditional approach for injection rate, injection pressure and hole-to-hole orientation/spacing for satisfactory use for a diesel application with larger flow areas needed in engines than single hole micro-nozzles.

References

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15. Phantom 6.06 Operating Manual from Vision Research Inc.

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

Table 1 Nomenclature and list of Micronozzles fabricated and tested

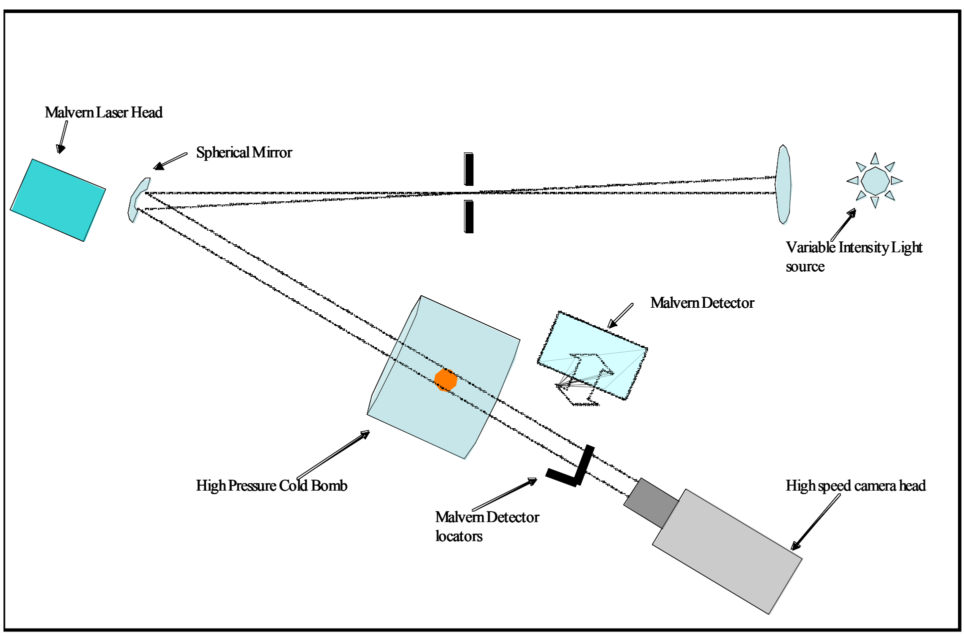

Figure 16 Schematic of the Experimental Set-up