3-Dimensional & 2-Dimensional Micro-Orifice Spray Nozzles: Method of Attachment and its effect on Diesel Spray Behavior

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Abstract

The current work discusses our efforts to fabricate 3-D micro-nozzles using a novel, modified MEMS-LIGA process. These nozzles may provide a spray pattern to continue to reduce spray droplet sizes while minimizing inter-spray drop collisions and optimize the entrainment of air among the array of liquid spray streams. The paper also discusses the efforts made to form a bond between the micro-nozzle tips and the production nozzle, providing an improved attachment scheme by using non-intrusive mechanical clamps and quantifies the effect of the use of such clamps on spray performance. Air-entrainment in the near-nozzle region is critical for obtaining low soot emissions in combusting sprays. The clamps have a finite thickness and hence, may impede air-entrainment in the critical near-nozzle region. The current work examines this hypothesis for non-combusting sprays and if such a difference can be seen in "global" average measurements such as Sauter Mean Diameter (SMD). This work provides baseline test data to be compared with future experiments planned in a hot spray bomb. Three different cross-section clamps are used and the SMD is measured at two axial locations for various nozzle configurations with these three clamp designs. Finally, experimental spray results are presented for various micro-orifice nozzles. These data indicate an improvement in the SMD using these 3D micro-nozzles, but a design methodology to optimize nozzle design is under development. The paper also discusses the efforts to form a permanent bond between the micro-nozzle and production nozzle through use of a laser welding system developed specifically for this purpose.

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]. 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.

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 Fig. 1. The process is discussed in detail in our previous paper [9].

The X-Ray photoresist is used as a mold for electroplating. We place the X-Ray photoresist on top of the conductive substrate. The conductive substrate is required for further electroplating processes. One popular photoresist material used in LIGA is polymethyl methacrylate (PMMA). A synchrotron radiation source can emit a high flux of usable collimated X-rays. The Synchrotron Radiation Center at the University of Wisconsin-Madison has a 1 GeV synchrotron radiation ource and it provides 300 micrometers of practical maximum height of the final product. We then fabricate a sacrificial mold by exposing PMMA. This sacrificial mold will later be used as a negative mold for the final Permalloy metal alloy (Ni-Fe) electroplating step that gives us our micron-size holes. This sacrificial mold is then deformed to form diverging array of metal posts on a compatible substrate.

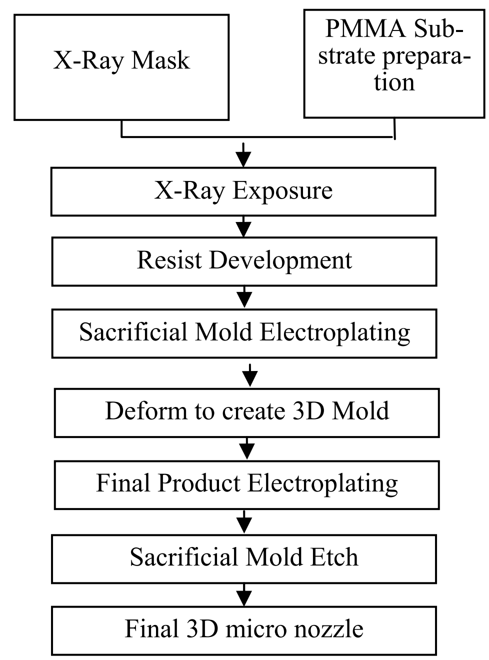

Figure 1. Modified LIGA Process

This successfully fabricated 3D mold is then placed in a Ni-Fe electroplating bath to give the final electroplated micro-nozzle product. We use Electric Discharge Machining (EDM) to cut the outer diameter into perfect circles and then etch away these exposed sacrificial posts to give the necessary 3D micro-nozzles.

Four different configurations of 3D micro nozzles were successfully fabricated using this method. The outer diameter is about 2.5 mm and the thickness varied from 150-300 microns. Three different diameters of 40, 80, 260 microns were fabricated. We found the necessity for a higher degree of process control for the fabrication of the 40 micron nozzle. We were successful in fabricating a few 40 micron nozzles, but with a lower wall thickness and these nozzles would not be able to handle the required injection pressures in the present set of experiments. In addition, the lower strength of the 40 micron posts have yielded nozzles with fewer holes than designed making it difficult for a direct comparison with previously published data for planar micro-nozzles. The SEM of 41X80 (41 orifices of 80 micron diameter) and 4X260 (4 orifices of 260 micron diameter) nozzles are shown in Fig. 2, these were taken before the final EDM step.

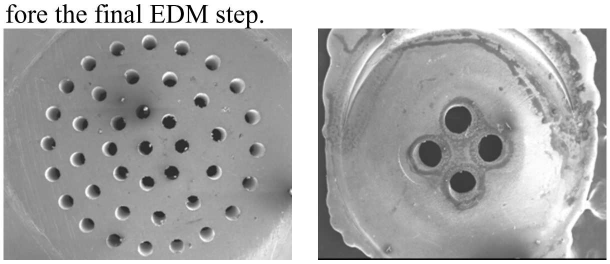

Figure 2. 3D 41X80 and 4X260 micro-nozzle

Metal Joining

The micro-nozzles once fabricated can be attached to any production nozzle. Permalloy is a metal alloy (80/20-NiFe) that is easily electroplated, but brittle and not easily welded to production nozzles with regular welding methods. Different methods are used to attach these micro-nozzles to production nozzle for both cases the sac was milled down to expose the needle.

Metal Clamps

The production nozzle is threaded; mechanical clamps with matching threads are used to clamp the micro-nozzles onto the injector. Fig. 3 shows one such assembly.

Figure 3. Metal Joining – Mechanical Clamp

The current work uses such clamps to facilitate spray testing. The current work attempts to quantify the effect of the use of such clamps on spray performance. Recent work [10,11] has suggested that air-entrainment in the near-nozzle region is critical for obtaining low soot emissions in combusting sprays. The clamps have a finite thickness and hence it is possible they will impede air-entrainment in the critical near-nozzle region. The current work attempts to see if this is true even for non-combusting sprays and if such a difference can be seen even in "global" average measurements such as Sauter Mean Diameter (SMD). This work will help us have a baseline test value to be compared with future experiments planned in a hot spray bomb. The current work uses three different cross-sectioned clamps and the SMD is measured for various nozzle configurations with these three clamp designs. The schematic of the three clamps tested is shown in Fig. 4 .

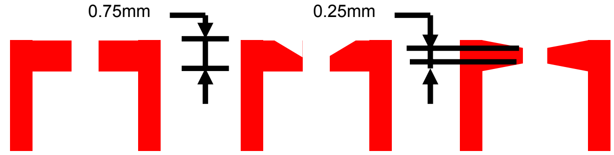

Figure 4. Schematic of clamps being tested

LASER Welding

The mechanical clamps may not be able to handle future test plans of high injection pressure and may cause air-entrainment issues in a hot bomb. To alleviate these problems a permanent weld is highly desirable. This weld would be strong enough to hold high pressure and does not cause undesirable restrictions. Traditional Welding methods are ill-suited for the current metal combination-high carbon steel and Ni-Fe. We have developed a CO_2 pulsed LASER welding system which has shown some very encouraging results [12].

Exhaustive trials were done to obtain the best possible combination of pulse duration, power, weld bead diameter etc. ANSYS calculations were also attempted to better understand the process and to aid in obtaining the best possible configuration. Fig. 5 Shows the effect of pulse duration on weld penetration. Fig 6 compares the experimental weld penetration with the ANSYS calculations. Fig 7 shows a successfully welded steel-permalloy sample.

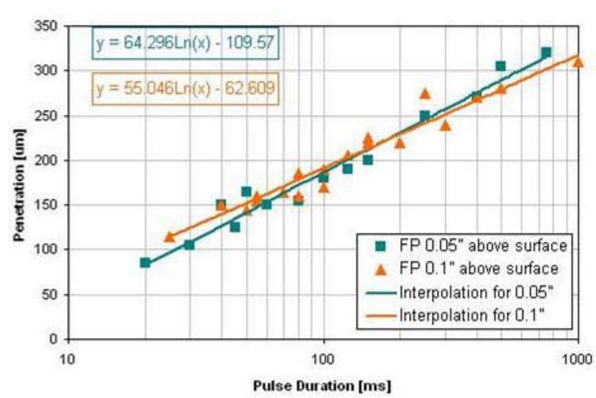

Figure 5 Effect of pulse duration on weld penetration

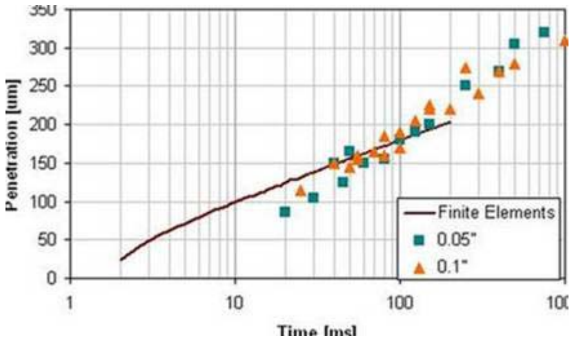

Figure 6. Experimental and simulated weld penetration

Figure 7. Welded Sample, with close up of the weld

These samples were pressure tested using a hydraulic pump and could withstand pressures in excess of 50 MPa. Further work is being done to optimize the parameters to be able to obtain a higher strength weld; i.e., in excess of 150 MPa.

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 intermittent diesel sprays produced by Bosch in-line fuel-injection pump. The pump was driven by a variable speed shunt DC motor through a semi-flexible coupling. The motor speed was about 650 rpm. The maximum injection pressures could be adjusted by changing the rack position. The maximum injection pressure was on the order of 25 MPa for each case. California diesel fuel (ρ_f=841 kg/m^3, ν=3.995cst) was used as a working fluid.

A Bosch injector with needle opening pressures of about 22 MPa was used for this study. The end of the nozzle was cut and the micro-nozzle was attached using a test mechanical clamp. Fuel filters of 7 micron and a 2 micron were used to prevent clogging of the micro-nozzle. The line pressure at the injector end of the high pressure pipe was measured using an absolute pressure transducer. 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 10 mm. The SMD was measured at two axial locations and these were analyzed.

Experimental Results

The injection pressure traces for various nozzle configurations are seen in Fig. 8. The Pressure traces are very similar since the pump rpm is fixed and the injection pressures are quite low for engine applications.

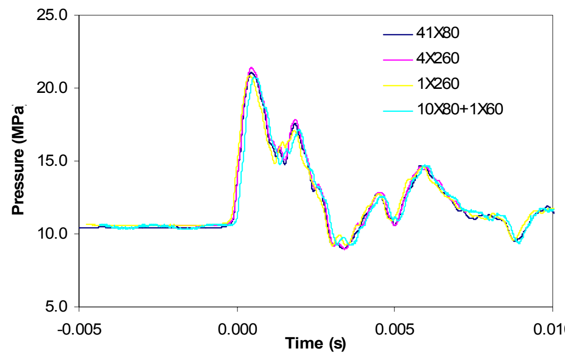

Figure 8. Injection Pressure Trace

The SMD for various nozzle configurations and clamp design is shown in Figs. 9 through 14. Two different flow area nozzles were fabricated and tested. The

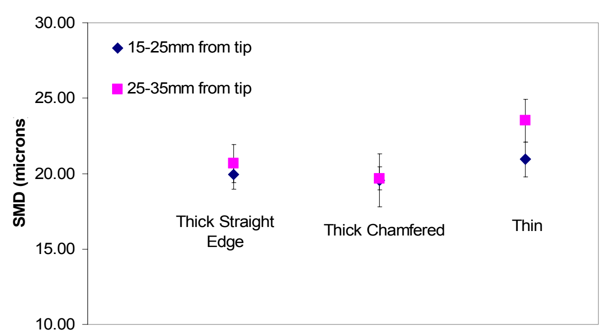

Figure 9. SMD for 1X260 nozzle

3D 10X80+1X60 (3 Dimensional nozzle with 10 orifice of 80 microns and with a central 60 micron orifice) and the planar 40X40+1X60 (planar nozzle with 40 orifices of 40 micron diameter and central 60 micron orifice) have the same theoretical flow area as the 1X260 (1 orifice of 260 micron diameter). The SMD results suggest that the clamps do not seem to have a direct affect on measured particle sizes.

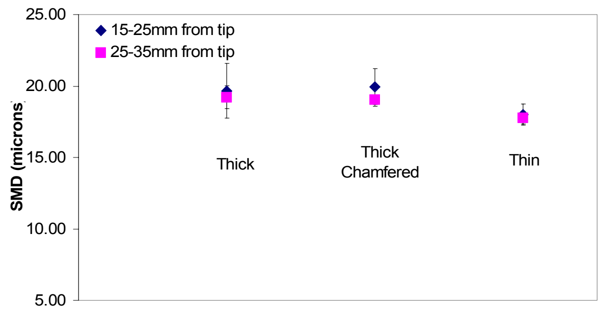

Figure 10. SMD for planar 40X40 +1X60 nozzle

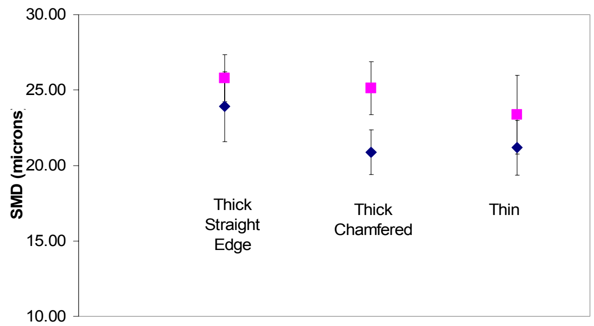

Figure 11. SMD for 3D 10X80+1X60 nozzle

The planar 4X260, 3D 41X80 and 3D 4X260 nozzles have approximately the same theoretical flow area. The clamps do not seem to affect the SMD values even for the higher flow area nozzles. The 3D 4X260 nozzle with the thin clamp could not be tested as the micro-nozzle failed in previous testing. Further comparisons and conclusions can be drawn based on the thick clamp.

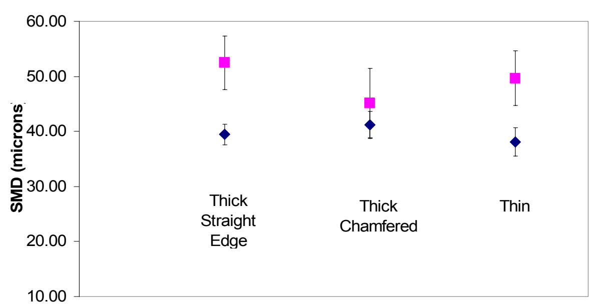

Figure 12. SMD for planar 4X260 nozzle

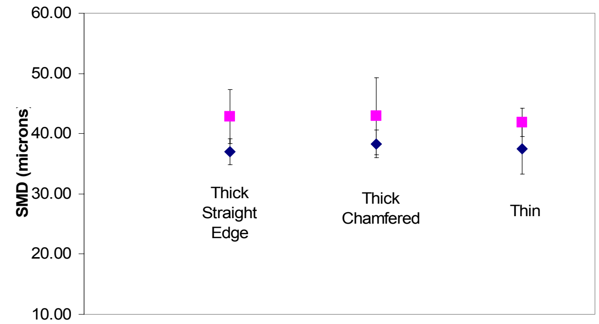

Figure 13. SMD for 3D 41X80 nozzle

Figure 14. SMD for 3D 4X260 nozzle, nozzle failed.

The Fig. 15 shows the SMD for the nozzles with the thick clamp. The 3D 4X260 nozzle has a lower SMD than the 4X260 planar nozzles, but it is higher than the 1X260 nozzle. These results are expected as the 3D nozzle would have lower spray-to-spray interactions as compared to the planar multiple hole nozzle. This leads to lower droplet interactions and hence the probability of droplet coalescence is reduced with a concurrent increase in air entrainment between sprays. The SMD of a 3D nozzle would still be higher than that of a single-hole nozzle. The 3D multiple hole nozzles still have spray-to-spray interaction as compared to the single spray.

Our previous experience with multiple hole nozzles have shown that the SMD of planar multiple hole nozzles seem to have a slightly larger SMD than that of a larger single hole nozzle of the same flow area. The 3D 41X80 nozzles have lower SMD as compared to the planar 4X260 but somewhat higher than 3D 4X260 nozzle. 3D 10X80+1X60 and planar 41X40 nozzles have SMD similar to the 1X260 nozzle. This suggests that for the same flow area, an array of 3D micro-nozzles (80 micron diameter) have lower or at worst similar SMD as compared to the larger diameter planar nozzles (260 micron diameter). Further we see that the SMD of the 3D 10X80+1X60 nozzle is smaller than the 3D 41X80 nozzle. This suggests that although the multiple-hole 3-D micro-nozzles show some improvement, there will be a limit to the extent improvement is possible with a multi-hole 3D nozzle at a given pressure. This limit is related to the extent of spray-to-spray interaction. In addition, air entrainment is always an issue for the multi-hole nozzles. The sprays from the outer circle of holes (for 41X80) restrict the flow of air in reaching the inner row of spray streams. This can be confirmed by observing differences seen in the spray breakup between the inner and outer circle sprays. A multi-hole nozzle would behave as a single-hole nozzle only if there is no interaction with each other and there is sufficient air-entrainment for all the circle of sprays. We are now moving to higher injection pressures (~100 MPa) and optimizing the multi-hole array designs.

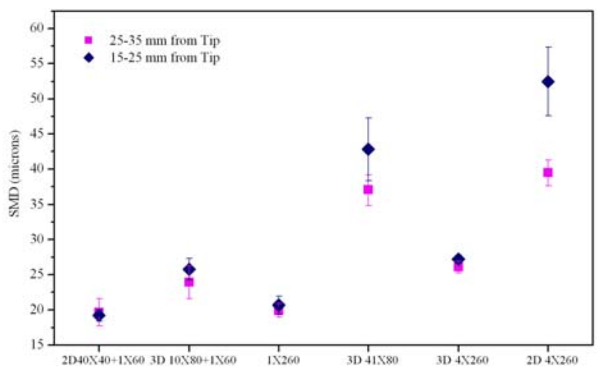

Figure 15. Effect of nozzle configuration with thick clamp on SMD

Conclusions

The modified 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 possible. Fig. 16 shows the cross section of a 260 micron nozzle.

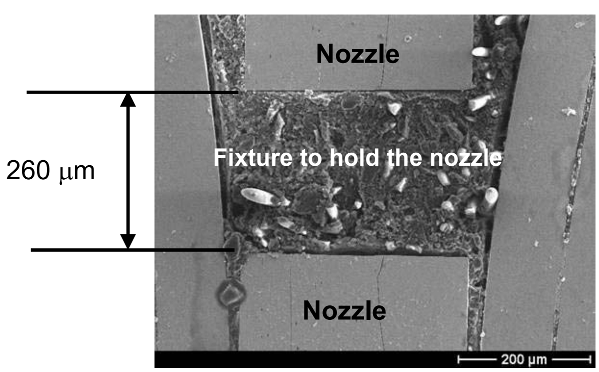

Figure 16. Cross section of a LIGA fabricated nozzle

We have developed a laser-welding technique, which can be used to obtain a permanent bond between the micro-nozzle and the nozzle body. Simulations with ANSYS were used to help in deciding the final welding parameters and decrease experiment time. Further fine-tuning of the laser welding system is in progress.

Finally, using these micro-nozzles with a diesel injection system under prototypic conditions, the SMD data suggested smaller drop size can be obtained by the use of 3D micro nozzles instead of a planar nozzle, although improvement are modest. Significant improvements might be possible with higher injection pressures.

Further reduction in SMD would be possible by ensuring proper air-entrainment for the multi-hole nozzle. This means that not only is the nozzle diameter important, their placement relative to each other is also important. We are now developing a basic methodology to determine the necessary spacing and associated experiments to confirm our analyses. Injection rate could be another effective means of achieving SMD values comparable with the single-hole micro-nozzles.

The SMD data at the current injection pressures, with the three mechanical clamps suggest that the clamps are not directly contributing to a "global" measurement like SMD. Spray imaging may help in understanding if near-nozzle air-entrainment is critical even in non-combusting sprays.

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 work on micro-nozzles done at UW 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.

Our path forward will employ higher injection pressures and study the spray-to-spray interactions, which will be critical for optimal multi-hole sprays.

Acknowledgements

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