

Diesel Spray Behavior with 3-Dimensional Micro-Nozzles

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The current paper discusses the efforts to fabricate 3-D micro-nozzles using a novel, modified MEMS-LIGA process. These nozzles may provide a spray pattern to minimize 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. Finally, experimental spray data test results are presented for various micro-nozzles using this technique. These data indicate an improvement in the SMD using these 3D micro-nozzles, but a design methodology for nozzle use is still under development for diesel sprays.

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 – NO_x, soot emission and noise have precluded its use to a large extent 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 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 to a lower local flame temperature, which would 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 high injection pressures combined with reductions in nozzle diameter. Traditional fuel injection equipment is poorly 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 1-100 microns. 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 [4]. 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.

Snyder et al [5] developed a Gas Efficient Liquid Atomization Device using the LIGA technology. Precise control of both uniformity of hole diameter and inter-hole spacing was found critical to producing a well-dispersed bubbly flow. Results were published for steady-flow atomization with low pressure injection into ambient air. One design of greater than 4000 holes of 7 micron diameter produced average droplet sizes of less than 30 micron via gas assisted liquid film breakup. 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.

The current work is a logical extension of the previous work done at UW. We address the issue of increased SMD for multi-hole nozzles. One of the reasons for increases in the spray SMD might be coalescence of droplets due to the densely placed micron sized nozzles [8]. 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. Simple calculations as suggested by Naber et al [9] show the predicted air-entrainment, spray penetration of a 1X40 micron (1 hole of 40 micron diameter) and 1X260 (1 hole of 260 micron diameter) micron nozzles. 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 further hampered, thus reducing the effectiveness of multiple holes with small diameters to provide the minimize the droplet diameter and yet deliver the required flow.

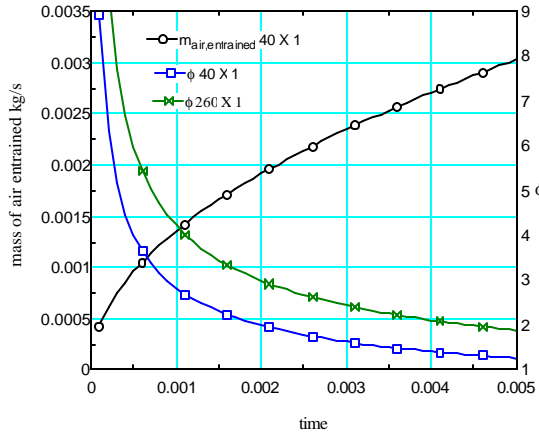


Fig. 1 Air-entrainment and excess Air-Fuel Ratio (ϕ)

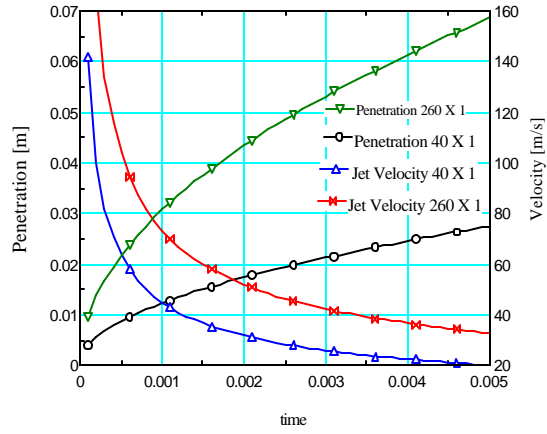


Fig. 2 Penetration and Average Jet Velocity

2. Fabrication of 3D Micro Nozzle using the Modified LIGA Technique

The various steps involved in the fabrication of a 3D micro-nozzle are depicted in Figure. 3.

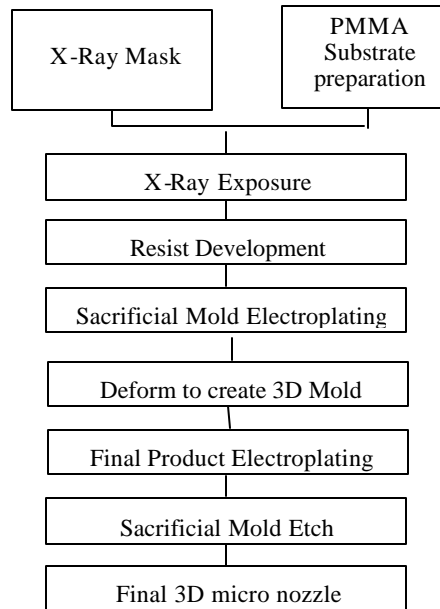


Fig. 3 The Modified LIGA Process

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 [4]. 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 micro-hemispherical nozzles. 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. The X-Ray photoresist material should have a high sensitivity to X-rays, a high resolution, a low internal stress and a high compatibility with electroplating process. One popular photoresist material used in LIGA is poly-methyl methacrylate (PMMA). PMMA has a cross-linked molecular structure. Its molecular weight

decreases dramatically when it is exposed to X-rays. The next step is deep X-ray exposure. A synchrotron radiation source can emit a high flux of usable collimated X-rays. X-ray lithography is superior to optical lithography because of its shorter wavelength and a very large depth of penetration. The Synchrotron Radiation Center at the University of Wisconsin-Madison has a 1 GeV synchrotron radiation source and it provides 300 micrometers of practical maximum height of the final product. The process reproducibility is extremely high. The X-Ray photoresist is exposed to X-rays under the X-Ray mask in this step. We then fabricate a sacrificial mold by exposing PMMA using the traditional method. 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.

This successfully fabricated 3D mold is then placed in a Ni-Fe electroplating bath to give the final electroplated micro-nozzle product. The Permalloy (Ni-Fe alloy) tends to plate over all of the conductive substrate, and also *over* the conductive posts. The next step would then have to be to find a way of cleaning the excess Ni-Fe from the top of the post. 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, these nozzles thickness 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 80 and 260 micron nozzles are shown below, these were taken before the final EDM step. The diameter configurations were chosen such that a case to case comparison could be made between a 3D nozzle, a single orifice nozzle and planar multiple orifice nozzles of Baik et al [6,7].

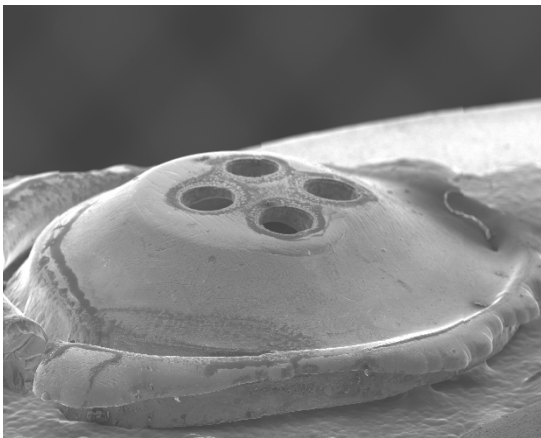


Fig. 4 The 4X260 nozzle before the final EDM



Fig. 5 Diverging exits of a 4X260 nozzle

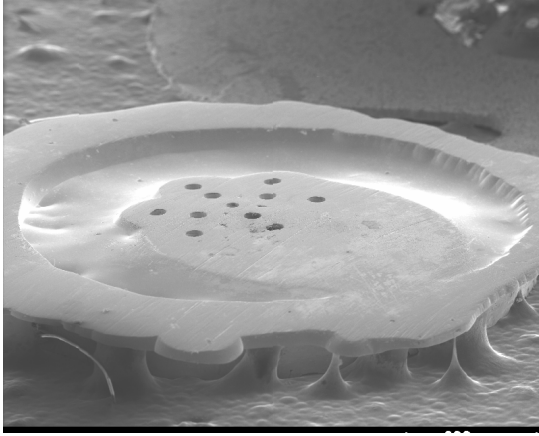


Fig.6 The 10X80;1X60 nozzle

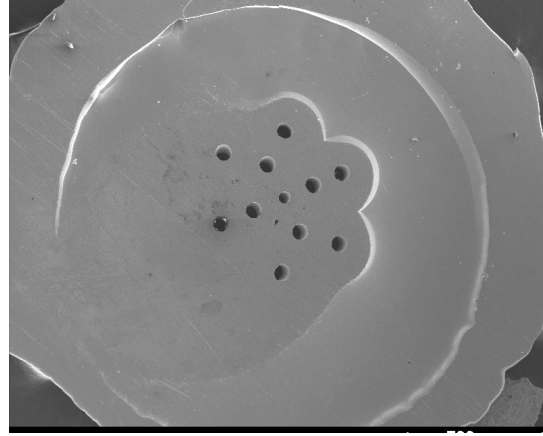


Fig.7 Diverging exits of a 10X80;1X60, nozzle

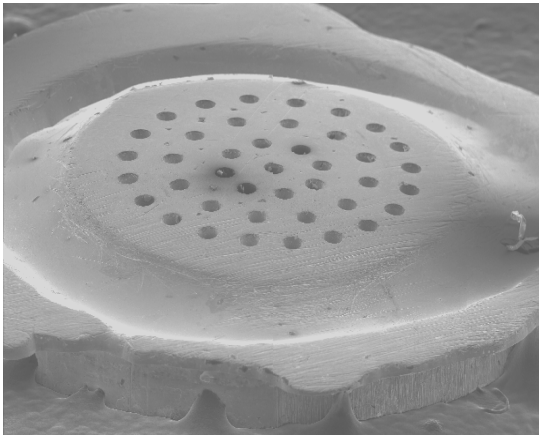


Fig. 7 The 41X80 nozzle

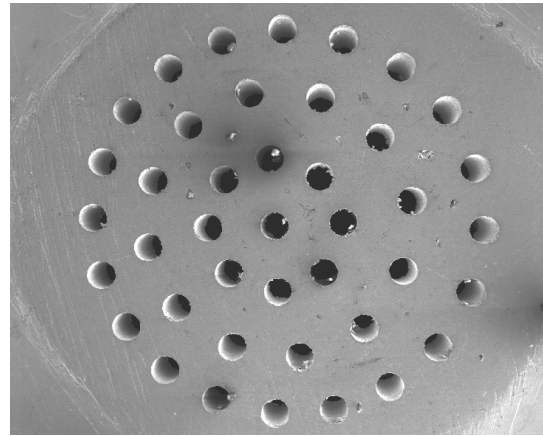


Fig.8 Diverging exits of a 41X80 nozzle

3. Metal Joining Process

The micro-nozzles once fabricated can be attached to any production nozzle. The sac was milled down to expose the needle. Permalloy is a relatively brittle metallic material and cannot easily be welded to the production nozzle using regular welding methods. We have successfully used mechanical clamps with outer diameters on the order of the production nozzle diameters. We believe with a few modifications, these clamps can take combustion pressures and temperatures and can be made to fit easily into combustion chambers of production engines. We have seen encouraging results with other novel and advanced ways of attaching these two dissimilar metal materials, and these are being currently pursued.

4. 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 and the motor speed and the injection pressure was on the order of 250 bar for each case. California diesel fuel ($\rho_f=841\text{kg/m}^3$, $v=3.995\text{cst}$) was used as a working fluid.

A Bosch injector with needle opening pressures of about 220 bar was used for this study. The end of the nozzle was cut and the micro-nozzle was attached using a modified 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. A Bosch type rate of injection meter was used for injection rate tracing [12]. Laser diffraction-based commercial system from Malvern/Insitac, 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 compared with previously published data for planar micro-nozzles.

5. Experimental Results

5.1 Injection rate/pressure

The injection rate and pressure profiles can be seen in Fig. 9 and Fig. 10. The fuel injection pump and high-pressure pipes have been not optimized for this set of nozzle diameters in this set of experiments. This leads to an atypical behavior of more than one injection pulse downstream of the main injection pulse. The present set of experiment considers only the first pulse for all further calculations and discussion. Future trials with the micro-nozzles will be done with a HEUI injector, and we expect to eliminate these “after-injections” given a better pump-nozzle match with the HEUI injectors.

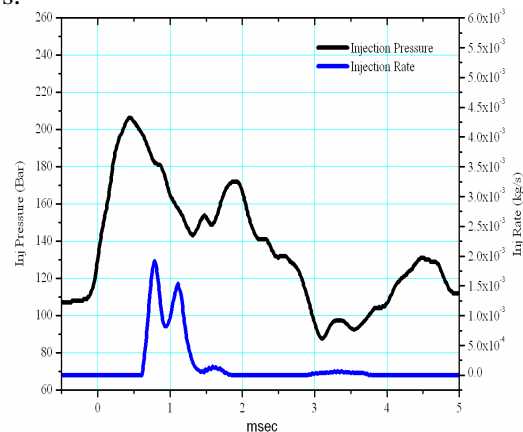
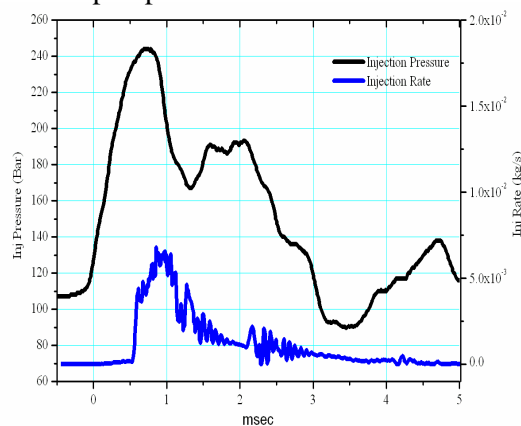


Fig. 9 Injection Rate and Pressure for 3D 4X260 nozzle

Fig. 10 Injection Rate and Pressure for 3D 10X80 +1X60 nozzle

5.2 SMD comparison

A comparison of SMD can be seen in Fig. 11 and Fig. 12. The present study was to compare the increase in SMD between a single-hole nozzle and the multiple-hole nozzle and to consider the cause for this increase. Fig. 11 shows the SMD for the 1X260, 4X260 planar and the 3D 4X260 nozzles (3 dimensional 4 holes of 260 micron diameter). 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 nozzle s still have spray-to-spray interaction as compared to the single spray.

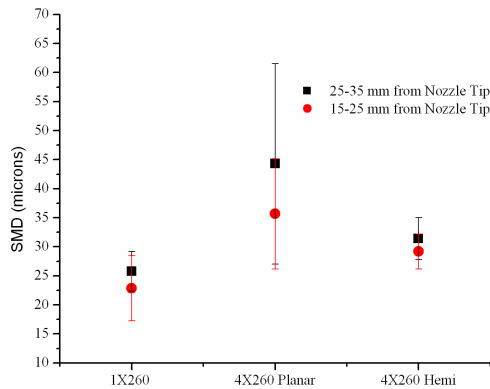


Fig. 11 SMD comparison of 260 micron nozzle

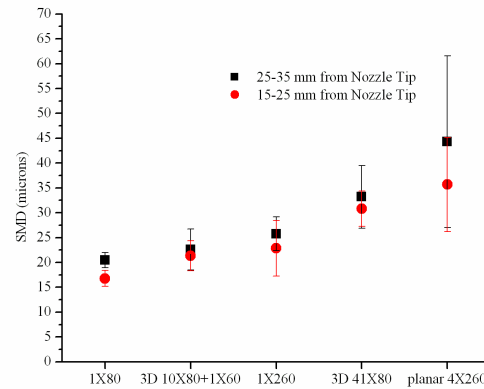


Fig. 12 SMD comparison of 80 micron nozzle

The theoretical flow area of the 3D 10X80+1X60 (3 Dimensional nozzle with 10 holes of 80 micron and a central hole of 60 micron diameter) is the same as that of a 1X260 nozzle and the 3D 41X80 nozzle has approximately the same flow area as that of a 4X260 nozzle. 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 SMD for the 1X80, 3D 10X80+1X60 and the 3D 41X80 nozzles can be seen in Fig. 12. The 3D 41X80 and 3D 10X80+1X60 nozzle s have lower SMD as compared to the planar 4X260 and 1X260 nozzles respectively even with uncertainties considered This suggests that for the same flow area, an array of 3D micro-nozzles (80 micron diameter) have lower SMD as compared to the larger diameter 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 an improvement, there will be a limit to the extent SMD spray improvements are possible with a multi-hole 3D nozzle. 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 developing a basic methodology to determine the necessary spacing and associated experiments to confirm our analyses.

6. Conclusions

We have successfully developed a modified LIGA process capable of producing 3D micro nozzles. This novel fabrication process was used to successfully fabricate 80 micron and 260

micron nozzles. We have also developed a metal-clamping technique to affix these micro-nozzles and working on more advanced metal-joining processes. 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. 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. The next step in our work is to have better process control over the fabrication process. This will help us fabricate nozzles with larger thicknesses and larger curvature spray angles. This would also facilitate fabrication of nozzles with diameters smaller than the ones in the present work. We are now developing a basic methodology to determine the necessary spacing and associated experiments to confirm our analyses.

7. Acknowledgements

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8. References

- [1] Noda, T., Foster, D., *A Numerical Study to Control combustion Duration of Hydrogen-fueled HCCI by using Multi-zone Chemical Kinetics Simulation*, SAE 2001-01-0327, 2001
- [2] Aroonsrisopon, T, *An Experimental investigation of homogeneous charge Compression ignition operating Range and engine Performance with Different Fuels*, M.S. Thesis, Mech Engg Dept., Univ. of Wisc-Madison, 2002
- [3] Christensen, M., Johansson, B., *Influence of Mixture Quality on Homogeneous charge Compression Ignition* SAE 982454, 1998
- [4] Guckel, H., Christenson, T, T., Skrobis, K., *Metal Micromechanisms via Deep X-Ray Lithography, Electroplating and Assembly*, J.Micromech. Microengg. 2,1992, pp225-228
- [5] Snyder H.E., Reitz, R.D., *Gas Efficient Liquid Atomization using Micro-Machined Spray Nozzles*, SAE 960859, 1996
- [6] Baik, S., Goney, K.H., Kang, S., Murphy J., Blanchard, J., Corradini, M., *Development of Micro-Diesel Injector Nozzles via MEMS Technology and Initial Results for Diesel Sprays* SAE 1999-01-3645
- [7] Baik, S., Kang, J., Blanchard, J., Corradini, M., *Development of Micro-Diesel Injector Nozzles via MEMS Technology and Effects on Spray Characteristics*, Eight Intl. Conf. Liquid Atomization and Spray Sys., Pasadena, CA, USA, July 2000
- [8] Jiang, Y.J, Umemura, A., Law, C.K., *An Experimental Investigation on the collision behavior of Hydrocarbon Droplets*, J. Fluid Mech. (1992), vol. 234, pp. 171-190
- [9] Naber, J.D., Siebers, D. L., *Effects of Gas Density and Vaporization on Penetration and Dispersion of Diesel Sprays*. SAE Paper 960034, 1996
- [10] Bower, G., Foster, D.E., *A Comparison of the Bosch and Zuech Rate of Injection Meters* SAE Paper 910724, 1991