Fuel injector Holes
(Fabrication of Micro-Orifices for Fuel Injectors)

George Fenske, Nicholaos Demas, and Robert Erck
Argonne National Laboratory
June 10th, 2010

This presentation does not contain any proprietary, confidential, or otherwise restricted information
Overview

Timeline
- Project start date: FY04
- Project end date: FY12
- Percent complete: 70%

Barriers
- Emissions – reduction of in-cylinder formation of particulates
- Efficiency – improved combustion & mitigation of aftertreatment fuel consumption

Budget
- Total Project Funding: ~$1.6M
- DOE Share: ~$1.5M
- Collaborator Share: ~$0.1M
- FY09: $350 K
- FY10: $400 K

Partners
- Imagineering Finishing Technologies
- Fuel system OEMs
- Engine OEM
- Small business - integration of electroless nickel (EN) process into nozzle production line
- U.S. EPA
Main objective/goal of the project is the development of fuel injector manufacturing technology to reduce diesel emissions by reducing in-cylinder production of particulates.

- Potential secondary benefits to improve fuel efficiency through improved fuel atomization & combustion, and, reduction in the use of fuel for regeneration of particulate matter (PM) traps

Multiple paths being pursued by DOE & industry to reduce emissions

- Aftertreatment devices (NO\textsubscript{x} & PM traps)
- Alternative combustion cycles (homogeneous charge compression ignition, low temperature combustion)
- Improved fuel injector designs – fuel atomization (in-cylinder reduction of particulates)

DOE Workshop “RESEARCH NEEDS RELATED TO FUEL INJECTION SYSTEMS IN CIDI AND SIDI ENGINES” identified specific needs:

- Manufacturing technologies that would be used for cost effectively producing ultra-small holes and controlling dimensions with ultra precision
- Materials and coatings to resist fatigue, wear, and corrosion; sensors and controls; non-traditional fuel injection; modeling & simulation, etc.
Objective of Work

- Combustion studies have demonstrated that reducing the orifice diameter on an injector decreases the amount of particulates formed during combustion
- Objective of research is to develop technologies to fabricate 50-µm diameter (or less) micro-orifices for high-pressure diesel injectors
  - Reduce in-cylinder production of particulates (lower emissions) with no fuel economy penalty
  - Improve combustion of fuel (improved fuel efficiency)

![Image of injector with orifice sizes 125 to 200 µm]
Project Milestones

- **FY 2009**
  - Preparation of multi-sized (40/145 μm) micro-orifices on commercial nozzles for spray visualization studies at the U.S. EPA (completed)
  - Establishment of collaborative agreements with engine and nozzle OEMs to accelerate technology validation
    - Negotiating level and type of effort between Argonne and nozzle OEM – level and effort negotiations completed, publication rights under negotiation

- **FY 2010**
  - Demonstration of x-ray absorption imaging technique for nondestructive evaluation (NDA) of internal coated orifice surfaces (completed)
  - Evaluation of ASTM Method G32-09 to determine cavitation erosion performance of plated nozzles (in progress)
  - Preparation of 2nd generation multi-orifice nozzles (50/110 μm) for nozzle OEM evaluation (in progress)
Approach

- Identify potential micro-orifice fabrication techniques
  - No technology exists to economically produce robust 50 µm orifices
- Down select – 50 µm, maturity, cost, scale-up
- Demonstrate feasibility (lab)
- Identify and resolve technical barriers
  - Uniformity, adhesion, deposit formation, hardness, fatigue, reduced flow, etc.
- Treat prototypic components (Tech Transfer)
- Spray visualization studies (EPA)
  - Single-size orifices (50 µm)
- Multi-sized orifices (e.g. 40 µm & 145 µm) orifices on the same nozzle to maintain fuel flow capability and improve combustion
  - Detailed microstructural analysis

- NDE of multi-size orifices (x-ray imaging)
- Cavitation erosion studies
- Engine emission & efficiency studies
Accomplishment – Demonstrated feasibility to coat interior surfaces of small injector orifices using EN.

- Autocatalytic EN process generates hydrogen bubbles that adhere to surface and prevent uniform coverage.
- Multiple mechanical techniques pursued to mitigate adhesion of H₂ bubbles successfully.
Accomplishment: Addressed and resolved early issues related to coating adhesion.

- Initial adhesion issues were addressed and resolved with proper control of precleaning/etching, control of solution chemistry, and post-deposition annealing.

Accomplishment: Transferred concept/technology to industrial plater/coater.

- Lab-scale process transferred to commercial size operation.
  - Reduced small-batch chemistry variations.
  - Standardized cleaning and post-deposition treatments.
  - Access to knowledge base.
Progress/Accomplishment: Flow Visualization - Demonstrated enhanced flow characteristics in single size orifices (100, 75, and 50 μm) at 3000 bar.

Argonne Nozzle: 7x0.05x157
Argonne Nozzle: 7x0.075x157
Ann Arbor Nozzle: 7X0.10mmx160

Courtesy – Ron Schaefer, USEPA/NVFEL
Accomplishment – Demonstrated feasibility of 3-D x-ray imaging to examine the uniformity of EN coatings applied to commercial fuel injectors (multi-size orifice).

- Potential of a high-resolution (< 2 μm) x-ray absorption technique was investigated to image the internal volume of the orifices after plating.
  - Original expectation was to image the void regions only.

- Imaging capabilities exceed original expectations.
  - In addition to imaging the void region, the technique was also able to delineate the coating (Ni-P alloy) from the ferrous injector alloy.
3-D x-ray movie of coated injector (showing outer surface)
3-D x-ray movie of coated injector (showing outer surface)
3-D x-ray movie of coated injector (illustrating interior of injector - bottom/up scan)
3-D x-ray movie of coated injector (illustrating EN coating on interior orifices)
Accomplishment - Currently fabricating 2nd generation multi-sized orifice nozzles for OEM evaluation.

- Current multi-size orifice nozzles fabricated for EPA testing used commercial nozzles with pre-existing orifices
  - 120-μm orifices (6)
  - EN plating (to 40 μm) orifices
  - Electrodischarge machining (EDM) larger orifices (145 μm)
  - Abrasive slurry honing
  - EPA testing

- Second generation design starting with blank nozzles (no orifices)
  - EDM 120-μm and 180-μm orifices (completed)
  - Abrasive slurry honing (in progress)
  - EN plating (to 50 and 110 μm) orifices (July 2010)
  - OEM evaluation
Accomplishment – Evaluated application of high-frequency vibratory technique to simulate cavitation erosion.

- Cavitation phenomena can lead to accelerated erosion of injector orifices and alter the spray characteristics of fuel entering the combustion chamber.
- EN coatings must be adherent and resistant to cavitation erosion over the lifetime of the injector.
- Recent efforts (FY09) demonstrated excellent adhesion of EN coatings to fuel injector orifices (using a micro-indentation technique at coating/substrate interface – see photo at right).
- During FY10, a cavitation erosion test rig was developed based on ASTM Test Method G 32-09.
Accomplishment – Cavitation erosion (cont’d)

- ASTM G32-09: Method to simulate cavitation damage in a benchtop rig
- Quantify change in mass (mass loss) and erosion rate of test coupon as a function of time
  - Impact of different alloy composition and treatment on erosion
  - ASTM G32-09 will be used to evaluate adhesion and erosion properties under conditions that simulate cavitation
- Current activities:
  - Evaluating peak amplitude characteristics of test rig as a function of transducer power and coupon mass
  - Preliminary results demonstrate technique is capable of producing measurable erosion in reasonable time.
  - Designing coupon fixture to accommodate coated fuel injector coupons

![Image of polished steel sample illustrating cavitation erosion induced by ultrasonic agitation]
Collaborations/Coordination with Other Institutions

- Development of processes to fabricate micro-orifices on commercial nozzles involves coordination of different manufacturing steps:
  - Electrodischarge machining (EDM) of orifices on existing commercial nozzles (either nozzle blanks or nozzles with pre-existing orifices) [LEER (industry)]
  - High-pressure abrasive honing of EDM orifices to increase flow characteristics [Extrude Hone (industry)]
  - Electroless nickel plating of nozzles [Imagineering (industry)]

- Evaluation of micro-orifice nozzles
  - Spray visualization studies [U.S. EPA (government)]
  - Fuel injector OEM [industry – NDA]
  - Engine OEM [industry – confidentiality]
Proposed Future Work

- **Near Future (FY10/11)**
  - Flow visualization studies by U.S. EPA
  - Preparation of 2\textsuperscript{nd} generation multi-size orifice nozzles for nozzle OEM
  - Cavitation erosion studies
  - Development of 3-D x-ray imaging for in-situ characterization of orifice surfaces and cavitation erosion

- **Longer Term (parallel) Activity (FY 10/12)**
  - Combustion studies on instrumented single-cylinder rigs (national labs)
  - Engine emission studies
    - National labs
    - Engine OEM
  - Integration of overall fabrication processes
    - Nozzle and/or engine OEM
Summary

- Based on studies that demonstrated significant reductions in soot production with decreasing orifice diameter, initiated efforts to identify and develop processes to fabricate micro-orifices on commercial nozzles.
  - Improved fuel atomization reduces soot/particulate formation and improves air entrainment, thereby improving combustion efficiency.
- Examined multiple approaches early in the project with a down selection to EN.
- Demonstrated the EN process for fabricating micro-orifices on commercial fuel injectors.
- Worked with industry: technical barriers were identified and resolved (uniformity, adhesion, hardness).
- Completed spray visualization studies in collaboration with the U.S. EPA:
  - Smaller orifices resulted in shorter liquid penetration length and an appreciably shorter spray core length.
  - Smaller orifices enhanced atomization.
- Successfully demonstrated ability to fabricate multi-size orifices 6 @ 40 μm + 6 @ 145 μm.
- Demonstrated 3-D x-ray NDE technique to image orifice and coating on treated nozzles.
- Efforts in FY10/11 will focus on spray visualization studies of multi-sized orifices (EPA) and performance evaluation with nozzle OEM.
- Future efforts will focus on engine emission studies.