IV.B.1 An Innovative Injection and Mixing System for Diesel Fuel Reforming

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Objectives

- Develop reliable, cost-effective diesel fuel injection and mixing systems for use with an auto-thermal reformer (ATR) or catalytic partial oxidation (CPOX) reformer in solid oxide fuel cell (SOFC) auxiliary power units (APUs), including a fuel preheating concept and a piezoelectric concept
- Determine operation and performance limitations of both injection and mixing concepts for diesel fuel reforming applications
- Optimize both injector/mixers for diesel fuel reformers to operate with no steam/water usage and minimize air and fuel supply pressure
- Test and analyze various anti-carbon formation coatings to improve the preheating injector life by reducing carbon formation in the fuel injector passages

Accomplishments

- Completed the design and fabrication of two different preheating fuel injection concepts and a piezoelectric injection concept, optimized through statistical design of experiment studies utilizing an optical patternater.
- Completed heated air temperature uniformity testing for the preheating fuel injection concepts.
- Conducted a detailed computer analysis and characterization of air flow field of the preheating fuel injector.
- Created a carbon formation test rig and down-selected to three most promising anti-carbon coatings using the statistical design of experiments technique.

Introduction

Fuel reformers are a very important component of SOFC systems, enabling them to compete with conventional auxiliary power units in remote stationary and mobile power generation markets. Currently, liquid fuel processing technology is not yet viable for commercial applications in SOFC systems. One of the major technical barriers for liquid fuel processing is reactor durability. The performance of the reforming catalysts in the reactor quickly deteriorates as a result of carbon deposition, sulfur poisoning and loss of precious metals due to sintering or evaporation at high temperatures. To mitigate these problems, research efforts are being conducted to optimize catalyst materials and to improve fuel reactor design/operation.

Problems associated with liquid fuel reactors could possibly be alleviated by improvement of feed stream preparation. Proper feed stream preparation can significantly improve reactor durability and minimize problems of inadequate fuel atomization, wall impingement, mixture recirculation and non-uniform mixing. These problems can easily lead to local conditions that favor carbon deposition, auto-ignition and formation of hot spots in the reactor. Because liquid fuels are extremely difficult to reform, a proper understanding of injection and mixing systems for feed stream preparation plays an essential role in the development of reliable and durable liquid fuel reformers.

Approach

To achieve a Solid State Energy Conversion Alliance (SECA) goal of improved feed stream preparation, two promising fuel injection and mixing chamber concepts were proposed for a thorough evaluation using both computational and laser diagnostic techniques. The key performance parameters included in the evaluation involved fuel atomization, droplet evaporation, mixing, uniformity of mixture temperature, velocity, concentration, wall impingement, flow recirculation, carbon deposits, feed stream supply pressure, power consumption, complexity, and reliability of injector design/operation.

One obstacle with preheating the fuel before injection into the feed stream is carbon formation in the fuel injector. Carbon can restrict the fuel flow in the injector and reduce atomizer performance. Several anti-carbon coating applications were proposed for evaluation, to determine their ability to reduce carbon formation within the fuel circuit of the preheating atomizer.

Results

A carbon formation test rig was designed and fabricated to test carbon formation rates on surfaces of various test specimens. This carbon formation test rig has the ability to preheat the fuel to 200°C and heat a test specimen to 600°C inside an N_2 purged oven (fuel is back pressured to reduce fuel boiling). This rig gives the flexibility to test specimens at wetted wall temperatures up to 500°C. Six anti-carbon formation coatings were tested. All six coated specimens and an uncoated baseline were tested at four different test conditions using ultra-low sulfur diesel. The specimens were tested inside the oven at two fuel preheating temperature levels of 150°C and 175°C, while the oven temperature was varied between two temperature levels of 425°C and 480°C. Figure 1 shows a picture of the carbon formed on a specimen tested at a fuel preheat temperature of 175°C, and an oven temperature of 480°C. As seen from Figure 1, the carbon that has formed on the surface is beginning to cover-up the tooling marks on the test specimen. This image was taken using a scanning electron microscope at 1.18K magnification. The coating tested in Figure 1 is AMCX Inertium diffusion bonded to 347 stainless steel base metal. Three coatings from the original six have been selected for further testing (AMCX Inertium, AMCX AMC26, & Restek Silcosteel AC). A final back-to-back test with injector components is planned to select a single preferred coating for use in the preheating injector.

Two preheating fuel injector concepts have been designed, fabricated, and tested. Build 1 utilized large flow recirculation zones to maximize fuel air mixing. This caused some concern since recirculation zones potentially lead to spontaneous ignition of the fuel rich mixture. Also, this work focuses on creating a nozzle that doesn't require H_2O/steam injection, which would be deterrents to auto-ignition. Therefore, Build 2 improved over Build 1 by eliminating these recirculation zones. Computational fluid dynamics (CFD) was utilized to help predict flow rates, pressure drops and flow non-uniformities associated with Build 1 and 2 design modifications. CFD was also utilized to simulate the overall flow-field structure and potential mixing capabilities, providing a qualitative assessment of the injector/mixer performance under the actual reformer operating conditions. The computation domain contains a flow path from the feed stream inlets, through the injector circuits and the diffuser section of the mixing chamber, terminating at the 72 mm diameter diffuser exit. The grid system for the flow path consists of over 1.3 million computational cells, with clustering tailored to regions of expected high gradients. The solutions were obtained using FLUENT 6.2 software to solve the unsteady, Reynolds-averaged Navier-Stokes equations, with the RNG k-ε turbulence model, wall-functions and differential viscosity models. Figure 2 shows a comparison of time-averaged velocity contours of the Build 2 preheating injector. Counter rotating air streams were utilized to produce mixing of the fuel and air. CFD predictions indicated that the preheating injector Build 2 design produces no recirculation zones.

For fuel atomization evaluation of the Build 2 preheating injector, detailed measurements were made at various operating conditions using phase/Doppler interferometry and using a SETscan OP-600 patternator produced by En'Urga Inc. The SETscan OP-600 is a high frequency statistical extinction tomography based optical patternator. The SETscan allows detailed visual and numerical characterization of spray quality in terms of cone angle, asymmetry, streaks, voids, and patternation number. Figure 3 presents SETscan

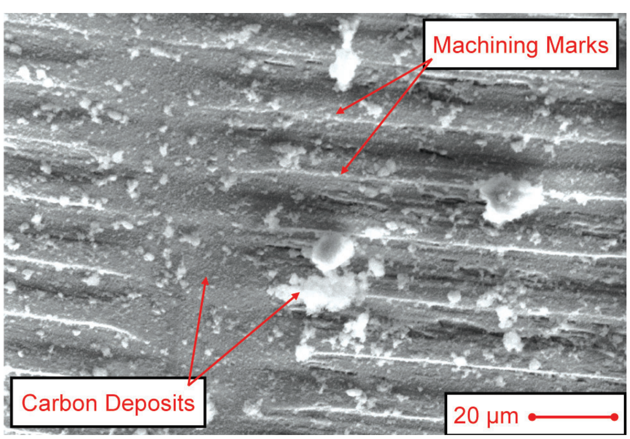

FIGURE 1. Typical carbon formation image via SEM. Anti-carbon formation coating is Inertium at 1.18K magnification.

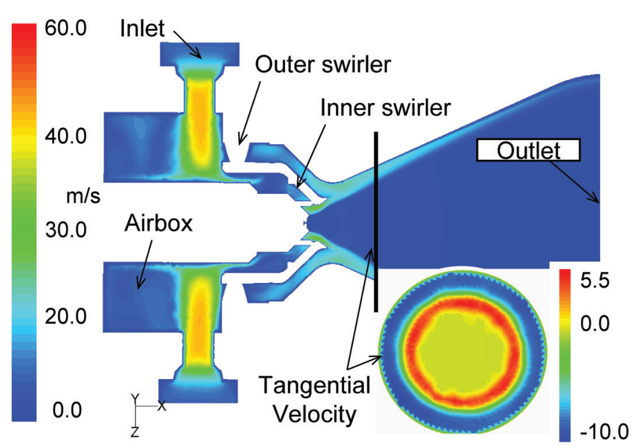

FIGURE 2. CFD Contours of Velocity Magnitude (m/s) of Build 2 Preheating Injector which Avoids Separation (Strong Jets in Air Box Will Be Reduced)

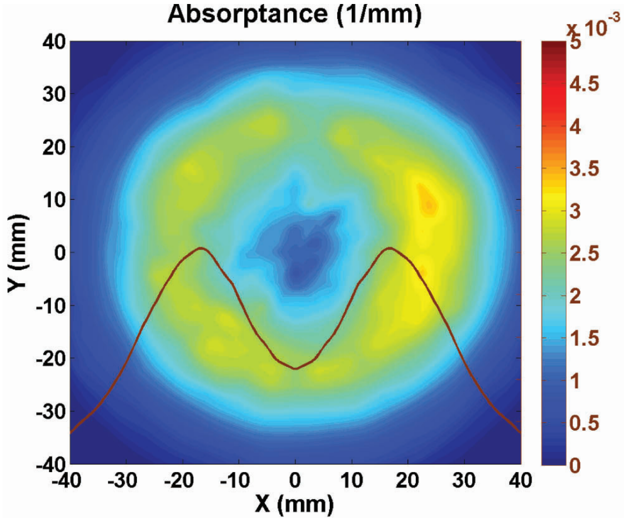

FIGURE 3. Fuel Absorptance Contours and Radial Distribution of Build 2 Preheating Injector 2 Inches Down Stream from Fuel Injection Point

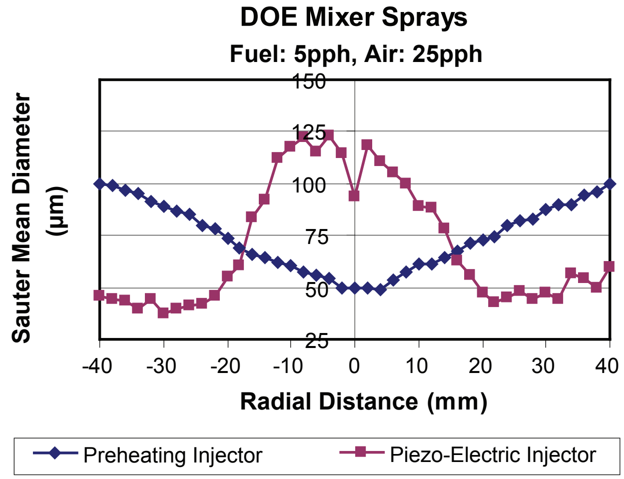

FIGURE 4. A Comparison of the Radial Distribution of Sauter Mean Diameter for the Build 2 Preheating Injector and Piezoelectric Injector at a Simulated 5 Kilowatt Load Condition

contours and radial distribution of absorption (1/mm) for the preheating Build 2 injector at a simulated 5 kilowatt load condition. This contour is taken at the diffuser exit plane (diffuser was not attached during this test). As shown, the fuel air mixture fills the 72 mm exit uniformly and evenly. It is expected that a mixing chamber will be able to capitalize on this optimized injector and further mix the fuel and air to allow complete vaporization of the fuel. Figure 3 test points were performed at ambient conditions with no preheating of the fuel.

A Phase Doppler Particle Analyzer (PDPA) system was used to measure droplet size and velocity. The PDPA was used to collect droplet information via two different methods: a continuous traverse method for global spray measurement and a point-to-point method. The continuous traverse method provides mean droplet diameters that represent the entire spray and the point-to-point method offers detailed local distributions of droplet size, velocity and fuel volume flux. This information is extremely useful in determining the spray dynamic structure and to identify differences between injector concepts. Figure 4 shows point-to-point measurements taken at a location three inches below the preheating injector exit, at a simulated 5 kilowatt load condition. For this test, the fuel pressure was 22 psi and the air pressure was 0.7 in. H_2O, with fuel and air temperatures at ambient conditions. Also shown in Figure 4 are PDPA measurements of the piezo-electric injector described below at the same flow rates.

A single piezo-electric fuel injector concept has been designed, fabricated, and tested. Though only one concept for this injector was created, several variations of sub-components were made. As with the preheating injector design, evaluation of the piezo-electric injector has been performed using both the SETscan OP-600 and the PDPA system. This concept utilizes piezo-electric crystals to induce mechanical vibration for atomizing the fuel, rather than large pressure differentials. Employing piezo-electrics to aid in atomization allows for minimization of air and fuel supply pressures. To date, tests have included a range of operation such that air pressures range between 0.10 in. H_2O – 3.0 in. H_2O, and fuel pressures less than 1 psi for flow rates up to 4.08 kg/hr. This design allows for low pressures, and consequently low velocities, while generating small droplets in the atomization process. When coupled with the high operating temperatures required by SOFCs, the small droplets and low velocities will allow for vaporization of the fuel within a very short distance. Therefore, this design promises to yield a smaller mixing chamber and overall a more compact injector/mixing unit.

Conclusions and Future Directions

- Feed stream preparation and injector selection are extremely important in improving the performance and durability of liquid fuel reformers.
- A preheating simplex injector has been developed into a promising concept for diesel fuel processing which could be used in SOFC APUs in commercial diesel truck applications with diesel fuel flow rate applications between 5 to 20 lb/hr (PPH).
- A piezoelectric injector has been developed into a promising concept for diesel fuel processing which could be used in SOFC APUs in commercial diesel truck applications with diesel fuel flow rate applications up to 5 PPH.

- Three anti-carbon coatings applied to 347 SS have shown reduced carbon formation rates over uncoated 347 SS. A final back-to-back test is pending to determine which coating will be recommended for use in the preheating injector.

Special Recognitions & Awards/Patents Issued

1. "Fuel Injection and Mixing Systems and Methods of Using the Same," Patent Pending, Filed April 12, 2007.

FY 2007 Publications/Presentations

1. "Innovative Fuel Injection and Mixing Systems for Diesel Fuel Reforming," Poster, SECA 7th Annual Workshop & Peer Review, September 12, 2006, Philadelphia, PA.