**Design and Validation of a Fuel-Air Mixer for a Portable Reformer**

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**Abstract**  
The challenge of atomizing and fully vaporizing a low flow rate of jet fuel in a logistic fuel reformer intended for portable fuel cell applications was met through a combined experimental and modeling effort. The design constraints led to the selection of a commercial, off-the-shelf twin-fluid atomizer for the mixer. Unheated, unconfined spray tests with the atomizer were conducted to acquire droplet size measurements at a 0.39 kg/h flow rate and at air-fuel ratios of 4 and 6. CFD modeling used these data to help define inlet boundary conditions and predict the mixing and vaporization performance of the fuel injector under heated conditions in a confined cylindrical geometry. Heated tests verified that the spray was fully vaporized before the exit plane of the cylindrical mixer. All of the constraints for the mixer were met with the atomizer except for the gas pressure drop, which was 20 to 40 times higher than the design target.

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Introduction

Fuel cells have been used to generate power for buildings, large vehicles, and vessels for which storing a sufficient supply of hydrogen to fuel the stack is not an issue. The limitations associated with hydrogen storage will need to be resolved, however, for portable or mobile applications. This problem can be overcome if (1) a supply of energy-dense liquid fuel such as diesel, jet fuel, ethanol, or methanol is readily available; (2) reformers can process these fuels to produce H₂; and (3) the fuel cell can accept the other constituents from logistic fuel reformate—namely CO and sulfur compounds. Of the various fuel cell types, solid oxide fuel cells (SOFCs) can tolerate CO at high levels and are more resistant to sulfur because they operate at high temperatures (650-1000 °C) [1]. In fact, due to the water-gas shift process, CO will react with the water formed by the reaction of hydrogen and oxygen, producing carbon dioxide and additional hydrogen. SOFCs are attractive for use in military applications because power can be generated in the field with low thermal and acoustic signatures using logistic fuels that are readily available for reformation [2].

To process the jet fuel, various reforming technologies can be employed. Technologies such as autothermal reforming (ATR) and catalytic steam reforming (CSR) require a steam supply, which consequently increases the size and weight of the system. Catalytic partial oxidation (CPO) offers the most compact means of reforming the fuel with air. By utilizing a compact CPO reformer, the system maintains a low thermal mass that enables rapid startups. The tradeoff in foregoing the steam supply, however, is the loss of a high pressure drop of steam that could have potentially assisted with fuel atomization. With a CPO reformer, the fuel must be atomized through hydraulic means or with a low pressure drop of air.

The objective of this study was to design a mixer for a portable SOFC system with a CPO-based reformer to process jet fuel. The mixer, which comprises the atomizer, mixing tube, and catalyst, is supposed to meet size and weight requirements while attaining complete fuel vaporization and mixing with air within the confined volume. This paper describes the methodology behind the fuel-air mixing design which included identifying and characterizing an atomizer for the system, modeling the spray vaporization and mixing to predict the mixer performance, and testing the mixer design at practical operating conditions to validate the model predictions.

Mixing Design Constraints

Figure 1 presents a general layout of the mixer. Fuel at temperatures below 100 °C and air at temperatures above 350 °C are injected into the mixing volume through the injector. The fuel that was used in the tests was Jet-A. The air to the mixer was supplied at flow rates that achieved air-to-fuel mass flow ratios (A/F) between 4 and 6. Atomized fuel is vaporized and mixed with air in the mixing zone. The fuel-air mixture passes through the CPO catalyst where the gas reacts to form CO and H₂ reformate. All of the liquid fuel must be vaporized and fully mixed with air before reaching the CPO catalyst. The presence of any liquid fuel can damage the catalyst, while non-uniform mixing can lower the catalyst’s efficiency.

![Figure 1. Schematic of the CPO mixer.](image)

One of the main constraints on the mixer design was provided by a system-level model of a CPO-based SOFC power plant that included other components such as a fuel pump and air blower. The system model restricted the air pressure drop across the mixer to 5.5 kPa. Higher air pressure drops would otherwise have required a larger air blower that would increase the volume and mass of the system.

Cold Flow Characterization of Selected Injector

Injector Selection

To select an appropriate fuel atomizer for the mixer, various physical and operational factors were considered (see Table 1). Physical characteristics included ensuring that the fuel injector was compact and lightweight and that the fuel passages in the injector were not prone to clogging.

A minimum fuel passage size was specified in order to avoid blockages in the injector due to foreign particles or fuel coking. A fuel filter could be installed to remove this specification, but a filter would add additional volume and weight and would not prevent the injector from clogging because of coking. Various references have suggested minimum fuel orifice sizes to prevent clogging. Lefebvre [3] recommends using a minimum orifice size of 0.3 mm, while Bayvel [4] suggests using a minimum diameter of 0.5 mm. For this study, the atomizer design targets a 0.5-mm minimum
orifice diameter, which agrees with our previous experience.

Operational constraints that the fuel atomizer had to satisfy included the fuel flow rate, the air-flow capacity and supply pressure, a maximum drop size, and a maximum spray angle. The fuel flow rate was set at 0.39 kg/h and air flow rates were set at 1.56 kg/h and 2.34 kg/h, corresponding to air-fuel ratios of 4 and 6, respectively. The available air pressure supply to the mixer is 106.8 kPa (absolute), which allows for a maximum air pressure drop of 5.5 kPa. A one-dimensional droplet vaporization analysis predicted that a maximum droplet diameter of 50 μm was required to achieve a fully vaporized fuel-air mixture within a conservatively-sized mixing volume. Although not specified, the spray angle should also be considered, since coke can form if liquid fuel impinges on the wall.

Table 1. Design criteria for the fuel atomizer.

<table>
<thead>
<tr>
<th>Atomizer Design Criteria</th>
<th>Target</th>
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<tbody>
<tr>
<td>Physical</td>
<td></td>
</tr>
<tr>
<td>Volume and Mass</td>
<td>Compact</td>
</tr>
<tr>
<td>Minimum fuel orifice diameter</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Operational</td>
<td></td>
</tr>
<tr>
<td>Fuel flow (Jet-A)</td>
<td>0.39 kg/h</td>
</tr>
<tr>
<td>Air flow</td>
<td>1.56 – 2.34 kg/h</td>
</tr>
<tr>
<td>Air supply pressure</td>
<td>106.8 kPa</td>
</tr>
<tr>
<td>Maximum air pressure drop</td>
<td>5.5 kPa</td>
</tr>
<tr>
<td>Fuel temperature</td>
<td>&lt; 100 °C</td>
</tr>
<tr>
<td>Air temperature</td>
<td>&gt; 350 °C</td>
</tr>
<tr>
<td>Maximum drop size</td>
<td>50 μm</td>
</tr>
</tbody>
</table>

Various fuel atomizer types were considered for the mixer. Atomizers that required external power sources such as ultrasonic and intermittent injectors were excluded because of space and weight limitations. Injectors that utilize power also would decrease the overall efficiency of the system because they would consume some of the generated power. Intermittent injectors were also excluded because of the complexities associated with injection timing and achieving uniform mixing with air.

Pressure atomizers can meet both space and weight requirements. However, no commercially available pressure atomizer that can meet the fuel flow rate and minimum orifice diameter specifications and that can produce droplets less than 50 μm was identified. For plain orifices, Lefebvre [3] notes that the minimum fuel pressure drop that is required to achieve appreciable atomization is 150 kPa. For this pressure drop, a 0.096 mm orifice diameter is required to atomize the 0.39 kg/h fuel flow rate. For pressure atomizers, this low flow rate is a challenge to atomize without constraining the orifice diameter to increase the pressure drop of the liquid and hence the energy to atomize the liquid.

Twin-fluid atomizers that flow both liquid fuel and air offered the most promise in meeting the design requirements. These atomizers can be made compact, but with flow passages that are typically larger than those in pressure atomizers. Twin-fluid atomizers can also achieve good atomization for any liquid flow rate as long as the energy of the atomizing air can overcome the surface tension energy of the liquid jet. An additional benefit of twin-fluid atomizers is that the air can mix with the fuel as soon as both are injected from the atomizer.

After considering various twin-fluid atomizers on the market, a commercial off-the-shelf (COTS) injector was chosen as a possible candidate for the mixer. The selected COTS injector (Spraying Systems 1/8 JJ-SS, SU J11) is compact, with the body taking up a space measuring approximately 26 mm x 31 mm x 13 mm. Figure 2 shows a schematic diagram of the internal fuel and air flow passages of the injector tip. The fuel orifice diameter, D\textsubscript{FUEL}, is 0.5 mm, while the spray exits an orifice diameter, D\textsubscript{SPRAY}, of 1.2 mm. Details of the rest of the internal geometry such as the inlet dimensions and the L/D of these orifices were not specified. The sketch suggests that the liquid and air combine in a mixing chamber that subsequently transitions into the spray orifice.

Figure 2. Cross-sectional schematic of the COTS twin-fluid atomizer.

Spray Characterization

The COTS injector was tested at room temperature and atmospheric pressure conditions to evaluate its performance. The air pressure drop and spray quality were the primary metrics used to assess the injector performance. The data from these tests were also used as initial conditions to the CFD model.

Pictures of the sprays at air-fuel ratios of 4 and 6 are presented in Figure 3. The measured pressure drop
of air across the injector was 128 kPa for an air-fuel ratio of 4, and 236 kPa for an air-fuel ratio of 6. These values are, respectively for each condition, at least 20 and 40 times the desired maximum pressure drop of 5.5 kPa. These high pressure drops indicate that there is choked flow at the orifice, which is confirmed by calculating the air velocity for the given flow rates and orifice diameter.

The injector also produces a compact spray for both air-fuel ratio conditions. As seen in the images, the cone angles of the sprays were less than 10 degrees. The design of the mixer needs to consider this spray angle to ensure that wall wetting does not occur.

![Figure 3. Pictures of the spray at the targeted fuel and air flow rates.](image)

Phase Doppler Interferometry (PDI) was used to measure the droplet size and velocity distributions in the sprays. The PDI instrument (Aerometrics DSA) utilized 500 mm focal length lenses on the transmitter and receiver. The transmitter beam spacing was set at 66 mm, and a 100-μm aperture in the receiver was used. The PMT gain on channel 1 was set at 350V throughout the spray.

Measurements were acquired at 0.5-mm intervals at a plane located 25.4 mm downstream of the injection point. Because the spray was assumed to be axisymmetric, only one axis of data was acquired at each air-fuel ratio. These points were positioned along the line perpendicular to the transmitter axis. Data were acquired at points where the instrument measured a minimum rate of 10 counts/sec.

Figure 4 presents the \( D_{0.1} \), \( D_{0.5} \), and \( D_{0.9} \) representative diameters that were measured for the injector. These diameters correspond to the droplet diameter below which 10%, 50%, and 90% of the spray volume falls, respectively. The profiles across the axis are relatively uniform except for that of \( D_{0.9} \), where the profile is higher near the edge of one side of the spray for both air-fuel ratios. While the \( D_{0.1} \) diameter was similar for both air-fuel ratios, the air-fuel ratio of 6 produced a spray with lower \( D_{0.5} \) and \( D_{0.9} \). This observation is consistent with the ability of twin-fluid atomizers to produce smaller droplet size distributions as the air-fuel ratio is increased [3]. The other observation from Figure 4 is that most of the droplets measured in the spray at the 25.4-mm plane fall below 50 μm, which was the maximum droplet size in the spray that was predicted to achieve complete vaporization in the mixer.

![Figure 4. Representative droplet diameter distributions measured at the 25.4-mm plane for (a) A/F=4 and (b) A/F=6.](image)
Figure 5. Droplet size, velocity, and spray volume flux profiles measured at the 25.4 mm plane.

CFD Modeling of Vaporization and Mixing

The COTS injector was modeled with computational fluid dynamics (CFD) using the commercially available code, FLUENT (ANSYS-Fluent, Lebanon, NH). Droplet size information obtained in the cold-flow tests described above was used to define the initial droplet size distribution. The distribution was assumed to exist in a small region near the orifice, consistent with the narrow spray angle observed in the data. Because the droplets were measured (1) in cold flow and (2) near the injector orifice, a secondary droplet breakup model was used during the calculations to provide a more realistic spray distribution under hot-flow conditions. Two groups of calculations were performed. In the first group, the flow was confined in a mixer tube that was open at its far end, in anticipation of the validation tests that were subsequently performed and described in the next section. In the second group, the effects of back-pressuring the system due to the catalyst bed (represented as a porous plug in the CFD simulations) were examined. As can be expected, the streamline patterns for these two situations differ, as shown below.

Consider first the case in which the mixer tube is open to the atmosphere at its downstream end. Streamlines for this case for an air-fuel ratio of 4 are shown in Figure 6. Note the presence of a corner recirculation zone at the upstream end of the mixer. This recirculation zone is due to the fact that the orifice diameter is small relative to that of the mixer, so that the flow undergoes a sudden expansion from the nozzle to the mixer tube. Due to the large amount of flow that exits the orifice, together with the volumetric expansion of the total flow due to vaporization of the fuel, the pressure drop within the mixer is nearly 186 kPa (clearly, both an unrealistic and unacceptably high pressure drop). The results show that nearly 99 percent of the fuel is vaporized. However, the mass flux of fuel in the location where the catalyst bed will be located is highly non-uniform, as shown in Figure 6, whereas the flows are well mixed, as can be seen by the essentially uniform air-fuel ratio profile. Similar results were obtained for the case of an air-fuel ratio of 6. As noted in the next section, experiments based on the open-tube mixer configuration confirmed that the fuel was completely vaporized.

In the intended application, the downstream end of the mixer tube contains a porous plug coated with a catalyst. CFD results were also obtained for this configuration. Streamlines for an air-fuel ratio of 4 are presented in Figure 7 and show the presence of both the upstream recirculation region and a long recirculation region that occupies most of the mixer upstream of the catalyst bed. Again, essentially complete vaporization was predicted to occur and the pressure drop is about 186 kPa. However, due to the backpressure effect on
the flow structure, the mass flux is nearly uniform and the fuel and air are thoroughly mixed, as can also be seen in Figure 7. The results for an air-fuel ratio of 6 are similar.

![Figure 7. Streamlines and fuel vapor distribution in the COTS mixer at 350 °C for the A/F=4 condition; catalyst bed effects simulated.](image)

**Injector Performance Under Heated Conditions**

Tests were conducted at elevated temperatures to confirm that the flow was fully vaporized for the case of the mixer without the catalyst. The mixer in these tests did not have the adiabatic boundary conditions that were used in the CFD model. The heated tests thus provided a conservative estimate of whether the fuel-air mixture would fully vaporize in the actual reformer.

Figure 8 shows the general layout of the elevated temperature experiment. The test section consisted of an NPT cross fitting that housed the mixer. The COTS injector was installed at the inlet to a quartz mixing tube that confined the spray. This assembly was installed through the top port of the cross. The side ports of the cross were fitted with quartz windows through which the spray could be viewed. The mixer was long enough such that the tube could be inserted past the ports on the tee.

Jet-A was heated to 80 °C and nitrogen was heated to a temperature of 350 °C. The tests were conducted with nitrogen instead of air to prevent autoignition. The atomized spray and gas mixture exit the quartz tube and is discharged through the exit port of the cross into an exhaust tee. A low cross-flow of nitrogen is used to carry away the exhaust.

To determine whether the spray was vaporized, a He-Ne laser and video camera system was set up to record the presence of droplets. A partially vaporized spray that contains droplets will scatter the light from the laser beam while a fully vaporized spray will not. A port for the laser beam was drilled at an angle of 37° from the line of sight of the camera. This arrangement enabled the camera to capture the forward Mie scattering of light. To illustrate the type of information that the images revealed, Figure 9 shows the mixing tube at a 50.8-mm distance from the injector for a condition in which the spray is not fully vaporized. At the same location, Figure 10 shows the mixing tube for a fully vaporized spray.

![Figure 8. Setup for the heated spray experiments.](image)

![Figure 9. Images of a partially-vaporized spray at a 50.8 mm downstream location show laser beam illumination by droplets present in the flow (left) and wall wetting when the background light is turned on (right).](image)

The series of tests fixed the fuel at a flow rate of 0.39 kg/h and a temperature of 80 °C. The nitrogen flow rate was varied to test air-fuel ratios between 4 and 6 and temperatures between 350 °C and 500 °C. For each test condition, the spray was classified as being either partially vaporized (as in Figure 9) or fully vaporized (as in Figure 10). The pressure drops of the gas and fuel across the injector were also noted.
Figure 10. Images of a fully-vaporized spray at a 50.8 mm downstream location show laser beam scattering only at the walls of the quartz tube (left) and no visible wall wetting.

All of the conditions within the targeted design range confirmed the model results in producing a fully vaporized spray. To determine a condition at which the spray did not fully vaporize, the air-fuel ratio was decreased below the design range. Liquid was observed to film the quartz tube at an air-fuel ratio of 2.4. CFD calculations with little or no heat loss, however, predicted that complete vaporization still occurred at this air-fuel ratio. At the other extreme, a cold mixer wall at 27 °C produced a mixture with less than half of the fuel vaporized. While the extent of heat loss is unknown in the experiment, the experimental results qualitatively agreed with the CFD results. Further refinement of the CFD model would require a full characterization of the heat loss in the experiment.

The catalyst was not available to confirm the model prediction with the simulated blockage. However, it was assumed that a similar fully vaporized mixture would be produced in the experiment because the blockage serves to increase the residence time of the fuel-air mixture within the volume, which further increases its vaporization.

The pressure drop of gas across the injector for the targeted design range varied from 120 kPa to 250 kPa at the respective air-fuel ratios of 4 and 6. This pressure drop range is 20 to 45 times higher than the desired design point of 5.5 kPa. The pressure drop of the gas can be reduced by taking a portion of the gas flow rate through the injector and redistributing the flow through bypass ports in the mixer. However, reducing the gas flow through the injector will reduce the relative velocity of the gas and liquid and result in coarsely atomized droplets. In this case, the larger droplets may not be able to vaporize completely within the length of the mixer.

Summary
The design and validation of a small-scale, compact fuel-air mixer intended for a logistic fuel reformer was accomplished through a combined experimental and modeling effort. A COTS twin-fluid atomizer that met the geometric design criteria was identified for the mixer. Spray measurements of the COTS injector under ambient temperature and pressure conditions in an unconfined environment showed that the injector can deliver droplet sizes that vaporize fully within the mixer volume. FLUENT modeling was used to evaluate the injector performance under heated conditions and in a confined geometry, but without the catalyst. The model predicted that the injector produces a fully vaporized spray at the exit of the mixer across the range of targeted fuel and air flow rates and temperatures. Experimental tests in a separate rig confirmed these results. Though the effect of the catalyst bed was not tested in the rig, the model predicts that the blockage provided by the catalyst bed will still produce a fully vaporized spray in addition to a uniform fuel-air profile.

The COTS mixer was largely successful in meeting the geometric constraints while producing a spray that achieved excellent vaporization and mixing characteristics. However, the high pressure drop of air that is required to atomize the spray is a barrier to applying this injector in the final design. While another injector that will meet all of the constraints needs to be identified, the design methodology that was developed with the COTS injector provides a valid procedure to evaluate the performance of other potential candidates.

References