Replacing batteries with fuel cells is a promising approach for powering portable devices; however, fuel cell systems face the critical issue of hydrogen generation and storage. A potential solution to this problem is on-site fuel reforming, in which a rich fuel/air mixture is converted to a hydrogen-rich syngas. Our research goal is to convert jet fuel to syngas (a mixture of hydrogen, carbon monoxide and minor species) for use in small-scale, portable devices. In this paper, we present experimental results of the conversion of jet fuel (Jet-A) and air to syngas by noncatalytic filtration combustion in a porous media reactor. We studied this process experimentally over a range of equivalence ratios and inlet velocities. Experimental results include species concentrations in the exhaust, gas temperatures, and reaction front propagation speeds. Because the focus of this study is on the production of syngas, our primary results are the hydrogen yield, the carbon monoxide yield, and the energy conversion efficiency as functions of equivalence ratio and inlet velocity. This study is intended to increase the understanding of liquid fuel filtration combustion for syngas production.

1. Introduction

A compact and robust means of converting jet fuel to syngas has significant applications for both military and commercial portable fuel cell systems. The traditional method of converting fuels to syngas is by catalysts, which are often susceptible to performance degradation especially when fuels, like jet fuel, with high sulfur content are used [1, 2].

In our research we convert fuels to syngas by noncatalytic partial oxidation using high temperatures to achieve the reaction rates necessary to convert rich and ultra-rich fuel/air mixtures to syngas. These elevated temperatures are achieved by recirculating heat from the combustion products to the reactants. Special reactors, such as filtration reactors, swiss roll reactors and counterflow reactors are different designs to accomplish heat recirculation [3-7]. In a filtration reactor, which was used for this study, gaseous reactants flow through and react...
within an inert porous matrix. As the reaction proceeds heat is transferred upstream from the hot products to the reactants through the porous matrix by conduction and radiation. Depending on the operating conditions the reaction front may slowly (~ 1 cm/min) propagate upstream or downstream. In downstream propagation the front is moving into a preheated solid resulting in additional heat gain to the reactants resulting in superadiabatic temperatures. Under upstream propagation, the opposite occurs and subadiabatic temperatures result. An additional benefit of combustion in heat recirculating reactors is that the burning rates can far exceed the laminar flame speed, thus allowing high turn-down ratios [7].

As a demonstration of the principle of noncatalytic conversion of jet fuel to syngas, we performed experiments over a range of rich equivalence ratios and inlet velocities and measured temperature and species in the exhaust. Experiments were performed with three different reactors: a packed bed of aluminum oxide pellets, YZA (yttria stabilized zirconia/alumina) porous ceramic and ZTM (zirconia toughened mullite) reticulated porous ceramic.

2. Experimental apparatus

The experimental apparatus (Fig. 1) consisted of the reactor, the fuel vaporization system, the reactant delivery system and the data acquisition system.

![Figure 1. Experimental Apparatus](image)
The reactor was an insulated cylinder of porous media, 20 cm long and 5.59 cm in diameter. In our previous work in filtration combustion, various materials were used as the porous medium. Alumina pellets of 3 mm in diameter have been successfully used by our group [8, 9] and others [10, 11] for various fuels. Two other materials YZA (yttria stabilized zirconia/alumina) ceramic foam and ZTM (zirconia toughened mullite) ceramic foam were also tested as porous media. Both YZA and ZTM have been used in previous experimental work in our group [12, 13] for radiant burners operating at lean conditions. YZA has also successfully been used in our group for the conversion of methane to syngas [14].

Zirconia (ZrO₂), alumina (Al₂O₃) and mullite (Al₆Si₂O₁₃) have melting points of 2717°C [15], 2072°C [16], 1840°C [17], respectively, and temperatures in the type of reactor that is employed here typically reach no more than 1800°C. However, Mathis [18] noted with regard to the ceramics (YZA and ZTM) that are used in this study that “the manufacturer’s specifications indicate that the maximum exposure temperature for YZA and ZTM it is 1870 K and 1920 K, respectively.” Since the manufacturer specifies a lower temperature than typical peak temperatures in a reactor like this, material changes or degradation seemed possible, if not likely.

The vaporization system consisted of an air-atomizing nozzle and a quartz chamber for mixing. The atomized fuel droplets, approximately 20 microns in size, were vaporized in a separate heated air stream in the quartz chamber. The base of the chamber, which held the nozzle and air heater, was machined from stainless steel. The outer surface of the quartz chamber was wrapped with resistance heaters and insulation to prevent condensation of the fuel. Portions of the band heaters and insulation were removable so that any potential condensation of the jet fuel could be observed.

The reactant delivery system included a tank, a pump and rotameters for jet fuel and flow regulators for compressed, dry laboratory air. The air entering the nozzle and the air entering the inline air heater were controlled with separate flow regulators.

For these experiments, jet fuel from Berry Aviation at the San Marcos Municipal Airport was used. The fuel is supplied by AVFuel Corporation. Since jet fuel can have a varying composition, an average chemical formula must be assumed. In this work a chemical formula of C₁₁H₂₁ was used [19]. The density, as measured by a laboratory scale, was 797 kg/m³, and the lower heating value was assumed to be 6555.438 MJ/kmol as given by [20].

Measurements included temperatures and exhaust species. The temperatures were measured with 11 B-type thermocouples. The thermocouples were spaced at 1.5 cm intervals with the junctions at the centerline of the reactor for the alumina experiments and at the inside diameter of the alumina insulation for the YZA and ZTM experiments. Additionally, the temperature of the reactant mixture was measured with a K-type thermocouple just before entry to the reactor. The exhaust species were measured by a Varian, Inc. gas chromatograph (GC), which was calibrated to measure the following species: hydrogen, oxygen, nitrogen, methane, carbon dioxide, carbon monoxide, ethylene, ethane, acetylene, propane, iso-butane, n-butane, iso-pentane, n-pentane and n-hexane.
3. Experimental Method

In the experiments, jet fuel and air were controlled to flow into the reactor in mixtures with specific equivalence ratios and inlet velocities. During the experiments, the vaporization chamber was frequently monitored for condensation. If condensation was observed, the measurements were discarded and the temperature of the heated air stream was increased. The temperature of the inlet mixture was between 170°C and 200°C as measured by the thermocouple placed before entry to the reactor. The inlet velocity is defined as:

$$inlet \ velocity \ (V) = \frac{R \times T \times \sum \dot{N}}{P \times A}$$

Where $A$ is the cross-sectional area of the reactor, $R$ is the universal ideal gas constant, $T$ is the temperature, $P$ is the pressure, and $\sum \dot{N}$ is the total molar flow rate of air and jet fuel.

At each operating condition, the GC sampled the exhaust gas for measurement multiple times. The first measurement was discarded and the rest of the measurements were averaged. Measurement uncertainty was calculated using a Student-t distribution. Uncertainties for all calculations were based on sequential perturbation.

Assuming that diatomic nitrogen ($N_2$) did not react, the total molar outflow of gas was calculated:

$$mole \ outflow \ (dry \ & \ carbonless) = \frac{0.78 \times \dot{N}_{air}}{[N_2]}$$

where $\dot{N}_{air}$ is moles per second and $[N_2]$ is the dry, carbonless mole fraction.

Important metrics for syngas production are the hydrogen yield and the carbon monoxide yield. These metrics, defined below, describe how effectively the reactor converts hydrogen and carbon bound in jet fuel to diatomic hydrogen and carbon monoxide, respectively.

$$hydrogen \ yield = 100 \times \frac{2 \times \dot{N}_{H_2}}{21 \times \dot{N}_{C_{11}H_{21}}}$$

$$carbon \ monoxide \ yield = 100 \times \frac{\dot{N}_{CO}}{11 \times \dot{N}_{C_{11}H_{21}}}$$

where the units of $\dot{N}_{C_{11}H_{21}}$, $\dot{N}_{H_2}$ and $\dot{N}_{CO}$ are moles per second.

We also calculated values for the chemical energy conversion efficiency. These metrics describe how much chemical energy in jet fuel was converted to chemical energy in the various exhaust species. The energy conversion efficiencies were calculated using the LHV of the individual species as described by the following representative equation for hydrogen:
where $\dot{N}_{H_2}$ and $\dot{N}_{C_{11}H_{21}}$ units are moles per second and the LHV values are in units of kJ per mole.

We also calculated the total energy conversion efficiency, a measure of how much energy in jet fuel was lost to thermal energy in the process. The total energy conversion efficiency was calculated as follows:

$$
\text{total energy conversion efficiency} = 100 \times \frac{\sum \dot{N}_i \times LHV_i}{6555438 \times \dot{N}_{C_{11}H_{21}}}
$$

The summation is performed over all species in the exhaust with positive LHV and with non-negligible concentration (concentration $> 0.1\%$). LHV data were taken from [21].

4. Results and discussion

**Experiments with alumina pellets – discussion of materials**

Experiments were conducted with porous media consisting of a bed of 3 mm diameter alumina pellets. After continuously burning jet fuel and air mixtures at various equivalence ratios and inlet velocities for approximately 6 hours, the reactor was purged and cooled with nitrogen in order to examine soot buildup. Upon inspection, it was found that the alumina pellets had degraded enough to form a large cavity in the packed bed (Figure 2).

After removing the top layer of the pellets, a somewhat hardened bank of soot-covered alumina pellets was observed (Figure 3). To remove the pellets shown in the figure, a metal tool with significant applied pressure was required.
A sample of the pellets from the reactor was taken and compared with unused pellets: 373 used pellets and 275 unused pellets were independently weighed and placed in graduated cylinders for a volume estimate. It was found that the used pellets had decreased in weight by 12% and decreased in volume by 53%. These data are shown in Table 1.

<table>
<thead>
<tr>
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<th># of pellets</th>
<th>weight (g)</th>
<th>volume (ml)</th>
<th>weight/pellet (g)</th>
<th>volume/pellet (ml)</th>
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<td>9.12</td>
<td>7.50</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>New</td>
<td>275</td>
<td>7.70</td>
<td>12.00</td>
<td>0.03</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 1. Weight and Volume of Alumina Pellets

In addition to finding a mass and volume decrease of the individual pellets, seemingly melted AL₂O₃ was taken from the apparatus (Figure 4). A sample of this material with no visible alumina pellets was analyzed by X-ray diffraction. The material had a major phase of AL₂O₃ (corundum/alumina) and a trace phase of Al₆Si₂O₁₃ (mullite). The melting point of alumina is 2072°C [16] and the melting point of mullite is 1840°C [17]. The peak temperature measured in the bed during all experimentation was 1689°C, so melting was not expected. Further experiments are required to determine the reason for the alumina degradation.
Experiments with alumina pellets – discussion of fuel conversion

Although the pellets had clearly degraded throughout the course of these experiments, data for jet fuel reforming was still obtained. These data must be qualified, however, by the fact that the experimental apparatus was changing in time. It is not possible to know when the degradation occurred, and further experimentation is necessary to understand the observed phenomena.

At a constant inlet velocity of 40 cm/s, the equivalence ratio was varied and measurements of exhaust species were taken. Figure 5 shows the hydrogen yield and the carbon monoxide yield as a function of equivalence ratio. Near zero hydrogen and carbon monoxide is observed at an equivalence ratio of 1, and a large increase in both yields is seen from equivalence ratios of 1 to 2. The carbon monoxide yield peaks at $\phi = 2$ with a value of about 75%, and the peak hydrogen yield of about 50% occurs at $\phi = 2.5$. The carbon monoxide yield decreases rapidly with increasing equivalence ratio after the peak, and the hydrogen yield decreases more smoothly. These results are similar in trend and magnitude to our previous results for methane [14], n-heptane [9] ethanol [8] and n-butanol [22].

Figure 6 shows the energy conversion efficiency as a function of equivalence ratio for hydrogen, carbon monoxide and the total energy conversion efficiency. The total energy conversion efficiency is relatively constant with equivalence ratio at values of $\phi = 2$ and above except for an anomalous drop at $\phi = 4$. These data show that about 40% of energy in jet fuel was lost to heat in the conversion process. The conversion of energy in jet fuel to energy in carbon monoxide and hydrogen both decrease after their peaks near $\phi = 2$. The difference between the total chemical energy and the sum of the hydrogen and carbon monoxide energy is contained in other species, such as methane, ethylene and acetylene, which increase rapidly with increasing equivalence.
At $\phi = 5$, 15% of the energy in jet fuel is converted to energy in methane and 6-7% was converted to both to ethylene and to acetylene.

The adiabatic flame temperature of a mixture is not a function of the flow rate (inlet velocity), but the rate of energy input to the system is directly proportional to the inlet velocity. Since the rate of heat loss, by convection and radiation, is proportional to the temperature of the system this heat loss is greatest, as a fraction of the energy input, at the lowest inlet velocities. Therefore the lowest reactor temperatures are expected at the lowest inlet velocities. A consequence of these low temperatures is low yields [9].

Figure 8 shows the carbon monoxide and hydrogen yield as a function of inlet velocity with the equivalence ratio held constant at 3. As expected, the lowest yields and lowest temperature (Figure 9) occur at the lowest inlet velocity, 25 cm/s, a trend that has been seen in our previous work [8, 9, 14]. However, the decrease in yield at velocities higher than 40 cm/s is not consistent with our previous work [8, 9, 14]. In our filtration combustion experiments with other fuels, the yields are almost always increasing with inlet velocity. The decrease in yield is, however, consistent with the peak temperatures measured in the bed (Figure 9) Degradation of the porous media is suspected as the cause of this anomalous behavior, though more testing is required.
Experiments with YZA – discussion of materials

After discovering that the alumina pellets were degraded over the range of experimental conditions, another rig was built of stacked cylinders of YZA (yttria stabilized zirconia/alumina) reticulated ceramic in place of the alumina pellets. Pre-experiment X-ray diffraction showed that the YZA was mostly cubic (tazheranite) zirconia with some alumina and some regular phase (monoclinic baddeleyite) zirconia.

After running experiments for approximately 7 hours, the reactor was purged with air instead of nitrogen gas, burning off any soot that had accumulated in the reactor during experimentation. Since the behavior of the reactor seemed to change over the course of the experiments (based on real-time observation of temperature and species data), the YZA cylinders were removed and examined for evidence of degradation. It was found that the YZA had degraded from the unused state (left hand side of Figure 10). The image on the right of Figure 10 shows some seemingly melted YZA and/or alumina insulation. The image in Figure 11 shows internal struts that have also seemingly melted. The maximum temperature achieved during the experiments with YZA was 1740°C as measured by thermocouples placed at the outer edge of the cylinders (as opposed to at the centerline of the reactor as was done with the packed bed of alumina pellets). Samples of the used YZA were tested for composition by X-ray diffraction and the same constituent materials were found as were found in the pre-experiment testing.
Experiments with YZA – discussion of fuel conversion

Though the porous media had degraded over the course of the experiments, and it is impossible to know when the degradation occurred, data were still obtained over a range of equivalence ratios and inlet velocities. Again, these results must be qualified by the fact that the experimental apparatus experienced significant structural changes during experimentation.

Figure 12 shows the hydrogen and carbon monoxide yield as a function of equivalence ratio for a constant inlet velocity of 40 cm/s. The peak hydrogen and carbon monoxide yield occurs at the same equivalence ratios that the peaks had occurred at for the experiments with the alumina pellets, though the magnitudes are smaller. Some of the reasons for a lower yield at the same velocity and equivalence ratio include having different material properties (conductivity, tortuosity, albedo, etc.) and having a different residence time (the inlet velocity is defined by the cross-sectional area of the insulating cylinder, not including the porosity of the medium, so equal inlet velocities for different porous media have equivalent mass flows of air and fuel, but different residence times in the reactor).

The energy conversion efficiency is shown in Figure 13. Similar to the experiments with the alumina pellets, about 45% of the energy in the jet fuel is lost to heat. As the equivalence ratio is increased, more energy is contained in species other than hydrogen and carbon monoxide as shown in Figure 14.
Holding the equivalence ratio constant at 2.5, the inlet velocity was varied from 30 to 60 cm/s, and the hydrogen and carbon monoxide yields for these conditions are shown in Figure 15. There is little variation in the hydrogen and carbon monoxide yield as inlet velocity is changed, though the hydrogen yield has a fairly noticeable decrease with increasing inlet velocity, again contrary to our previous results with other fuels [8, 9, 14].

With the YZA reactor, we were able to produce another set of data; the inlet velocity was held constant at 60 cm/s and the equivalence ratio was varied through the same range as was done while holding the inlet velocity constant at 40 cm/s. These data are shown in Figure 16. Though Figure 15 shows a slight decrease in yield as the inlet velocity is increased and the equivalence ratio is held constant, a comparison between Figure 12, showing yield vs. equivalence ratio at 40
cm/s and Figure 16, shows an overall trend of higher yields at the higher inlet velocity, 60 cm/s. At $\varphi = 2.5$ and greater, the yields are lower than the yields at the same equivalence ratio with the velocity at 40 cm/s, but the yields at $\varphi = 2$ and 2.25 are significantly higher at 60 cm/s. The unexplainable trends in the data suggest that porous media degradation over the course of experiments may have significantly affected yields.

One other notable result from the YZA data is shown in Figure 17. At an equivalence ratio of 3 and 60 cm/s, a very significant amount of energy in jet fuel is converted to species other than hydrogen and carbon monoxide. About 17% of the energy in jet fuel is converted to methane and about 10% is converted to ethylene.

### Experiments with ZTM – discussion of materials

Lastly, ZTM reticulated ceramic foams of the same size and shape as the YZA were used as a porous medium. The ZTM (zirconia toughened mullite) ceramic was examined by X-ray diffraction before the experiments, and the constituents were found to be mostly monoclinic ZrO$_2$ and Al$_2$O$_3$ with minor phases of AL$_6$Si$_2$O$_{13}$ and cubic ZrO$_2$. These experiments were performed primarily to determine if this material would also degrade, though species and temperature data were also taken. Experiments were run for approximately 3 hours until the rig became inoperable (the top piece of ZTM popped out of the top of the reactor, creating a large cavity within the reactor). The rig was purged and cooled with air and disassembled. Significant degradation of the ZTM was observed as shown in Figure 18. Samples of the seemingly melted pieces of material were shown to be, again by X-ray diffraction, equal monoclinic and cubic ZrO$_2$ with some Al$_2$O$_3$. The pre and post usage X-ray diffraction patterns seemed to indicate that the mullite phase had been carried away in the gas flow. Further testing will help us to understand the material changes.
Experiments with ZTM – discussion of fuel conversion

A limited data set was obtained before the rig had become inoperable. Figure 19 shows the hydrogen and carbon monoxide yield as a function of equivalence ratio at an inlet velocity of 40 cm/s. Consistent with the previously discussed results, the peak yields appeared to occur near an equivalence ratio of 2. The peak hydrogen and carbon monoxide yields, about 47% and 70%, respectively, are also similar in magnitude to the alumina and YZA results.

Conclusions

This work has shown that jet fuel can be converted by filtration combustion to syngas. However, the porous media degraded during the experiments indicating a need for further work to
understand the conditions which lead to the degradation. Additionally, the authors plan to perform the experiments with different porous media, such as silicon carbide.

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