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Development of a Non-Catalytic JP-8 Reformer

Chien-Hua Chen, PhD
Joel Crawmer
Brad Richard
Howard Pearlman, PhD
Advanced Cooling Technologies, Inc.
Lancaster, PA

Paul Ronney, PhD
Department of Mechanical Engineering
University of Southern California
Los Angeles, CA

ABSTRACT

Advanced Cooling Technologies, Inc. (ACT) has been developing a Swiss-roll type, non-catalytic, thermal partial oxidation JP-8 reformer. The principle is using effective heat recirculation to increase the partial oxidation reaction temperature, which maximizes the H_2 *and CO yield without using catalyst. The gas phase reaction eliminates catalyst-associated issues, such as poisoning, coking, degradation, etc. Since the process uses only air and JP-8 fuel as the reactants, and is self-sustained (no external energy input), minimum balance-of-plant is required. One challenge of this reforming technology is the "out-of-center" reaction. Due to being highly preheated, the fuel and air mixture from the inlet is auto-ignited before entering the designed center reaction zone. The out-of-center reaction causes low reforming efficiency and potentially damages the inlet channel walls. In the previous study, direct injection of JP-8 fuel into the center reaction zone is able to avoid the out-of-center reaction. However, without proper mixing of fuel and air, the reaction happens in a non-premixed fashion that results in a large amount of soot formation in the reformate. To overcome this issue, a center mixing chamber is designed. JP-8 fuel is directly injected in this mixing chamber and mixed with preheated air before entering the center reaction zone. Experimental results show a significant improvement in the reformate quality after the implementation of the mixing chamber. Test data of syngas (*H_2 *and CO) yield and reforming efficiency (chemical enthalpy in the reformate compared to the parent fuel) are also reported.*

INTRODUCTION

Partial oxidation is a simple method to convert high energy density hydrocarbon fuels (propane, natural gas, gasoline, JP-8, etc.) to syngas, which can be readily used by a solid oxide fuel cell (SOFC) for electrical power generation, or further purified for high purity hydrogen generation. Since the partial oxidation reformate retains the majority of the input chemical energy, the resulting reaction temperature, raised by the mild reaction exothermicity, is not high enough, to produce equilibrium products at a high conversion efficiency. Catalysts are typically used to advance the reaction to its chemical equilibrium state. However, military fuels such as JP-8 have high sulfur content and longer hydrocarbon chains that create significant challenges for reforming catalysts.

A Swiss-roll type of non-catalytic reformer has been developed to avoid catalyst associated issues.

The principle is to recuperate the heat from products to the reactants (Figure 1), resulting in a high reaction temperature (Figure 2) and therefore high syngas yield, without using catalysts. In addition, the Swiss-roll geometry effectively minimizes major heat losses (e.g. surface loss and flue gas loss). The reduced energy losses during the reformation process enables high energy content in the reformate and therefore high reforming efficiency.

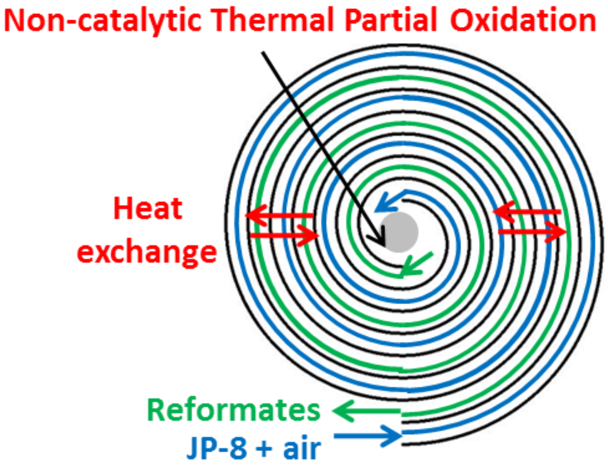

Figure 1: Schematic of the Swiss-roll reformer. The heat in the reformate is transferred to the reactants via a counter-current spiral heat exchanger.

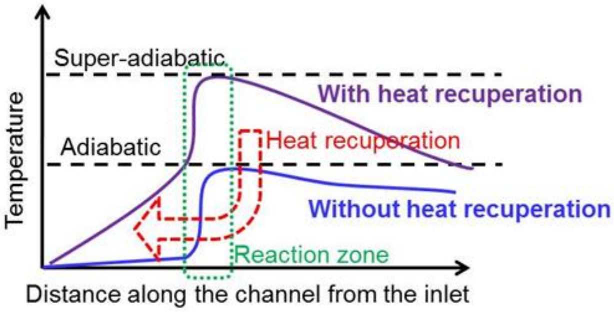

Figure 2: Schematic shows the reaction temperature profiles for the cases with heat recuperation and without heat recuperation.

One challenge for gas-phase fuel reforming in a reactor of this geometry is an out-of-center reaction. The highly preheated fuel and air mixture causes spontaneous ignition (auto-ignition) before it enters into the desired reaction zone, where the reaction has the longest residence time and therefore the highest conversion efficiency can be achieved. In a previous development, a center fuel injection method was applied to address this challenge. With only air in the inlet channel, this method ensured the reaction only happened in the center reaction zone. Since air makes up > 80% of the reactants total thermal mass, thermal energy from the products can still be recuperated. However, the separation of air and fuel resulted in insufficient mixing before entering into the partial oxidation reaction zone. This non-premixed reaction caused high soot yields in the reformate, especially when reforming JP-8.

To solve this issue, a mixing chamber, located in the center reaction zone, was applied. The mixing chamber was designed to provide the residence time between the mixing time (determined based on experiments described in the later section) and auto-ignition time (determined based on the CHEMKIN calculation), so that a homogeneous mixture can be achieved before the partial oxidation reaction to avoid soot formation from the non-premixed reaction. The experimental setup and the results are described in the following sections.

EXPERIMENTAL SETUP

A Swiss-roll reformer was made via Direct Metal Laser Sintering (DMLS) using stainless steel material (Figure 3 and 4). The Swiss-roll's geometrical design was the same as previous work, [8], except a mixing chamber was added to the inlet of the center reaction zone as shown in Figure 5.

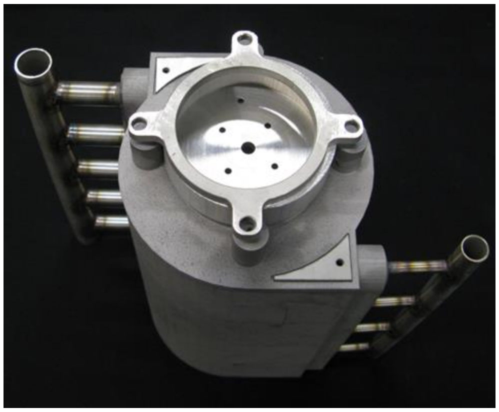

Figure 3: Picture of the 3D metallic printed (DMLS) Swiss-roll reformer.

Figure 4: Cross-section of the 3D printed Swiss-roll reformer.

The preheated air enters the mixing chamber (spiral duct) where the vaporized JP-8 is injected. The homogeneous mixture leaves the outlet of the mixing chamber and then enters the center reaction zone. To determine the appropriate mixing channel length, first, a CHEMKIN calculation was performed to obtain the auto ignition time scale. Then, the mixing time was determined experimentally using four injection ports (A, B, C and D) installed along the mixing channel (Figure 6). To determine which port was able to provide sufficient mixing, air was introduced through the channel inlet, while an equal part CO_2 was injected in one of the ports. If the measured CO_2 concentrations at each of the ten sample locations were at similar level (~50% CO_2), then sufficient mixing was achieved for a given injection port. Data from the injection port selection experiments is shown in next section.

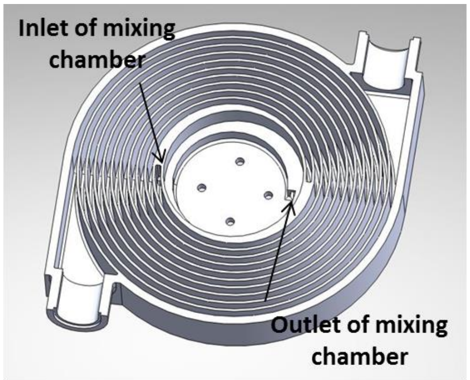

Figure 5: Schematic of the mixing chamber design.

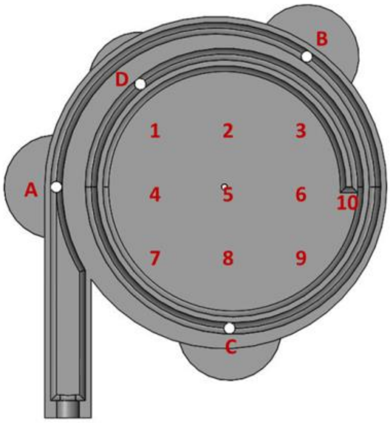

Figure 6: Four different injection ports were installed along the mixing channel. The proper one was determined experimentally.

The fuel reforming experimental setup is shown in Figure 7. The air flow rate was controlled via mass flow controller from a compressed air supply. A peristaltic JP-8 pump forced a prescribed amount of liquid fuel through a fuel heater to vaporize the fuel before injection into the mixing chamber. Multiple thermocouples were installed to record the thermal profile. A LabVIEW control system allowed the user to prescribe the input flow conditions, total flow rate and fuel percentage, and displayed and recorded the real-time temperature and pressure measurements. The reformate species composition was measured for a range of input reaction conditions, using a SRI Gas Chromatograph (GC), to characterize fuel reforming performance.

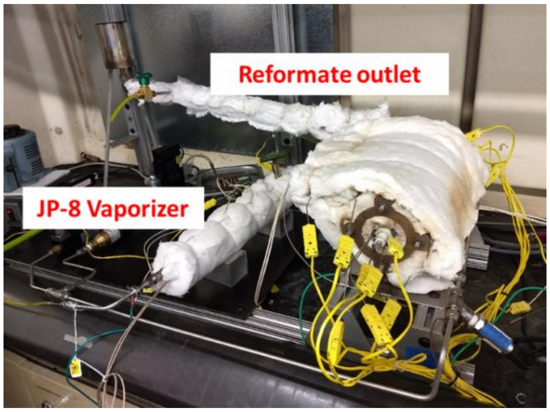

Figure 6: Swiss-roll fuel reformer experimental setup.

RESULT AND DISCUSSION

Mixing Length Requirement

Figure 8 shows the CO_2 concentration at different sample locations when it was injected from port D. Although port D had the shortest mixing length, the data suggested that it provided sufficient mixing time. The residence time in the mixing channel is less than the CHEMKIN calculated auto-ignition time (~10 ms). Based on this result, port D was used for the following tests.

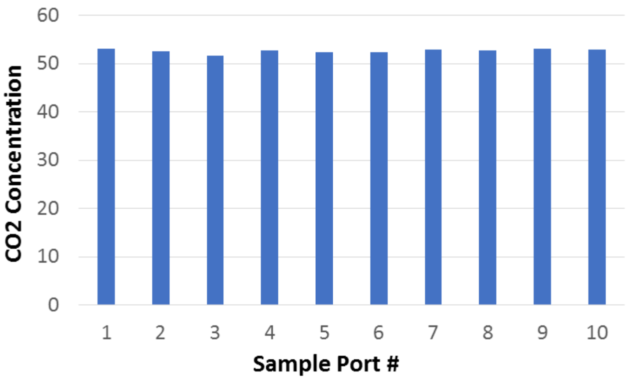

Figure 8: Measured CO_2 concentration was similar (~50%) across the 10 sample locations when CO_2 was injected through port D.

Thermal Profile

Figure 9 shows the thermal profile or a Swiss-roll without a mixing chamber (top) and with mixing chamber (bottom). It can be seen that a more stable reaction zone, without temperature fluctuations, was achieved with a mixing chamber. The one without a mixing chamber shows higher reaction zone temperature, when compared to the one with a mixing chamber (>1200°C vs. < 1050°C), most likely because non-premixed combustion results in local reaction hot spots.

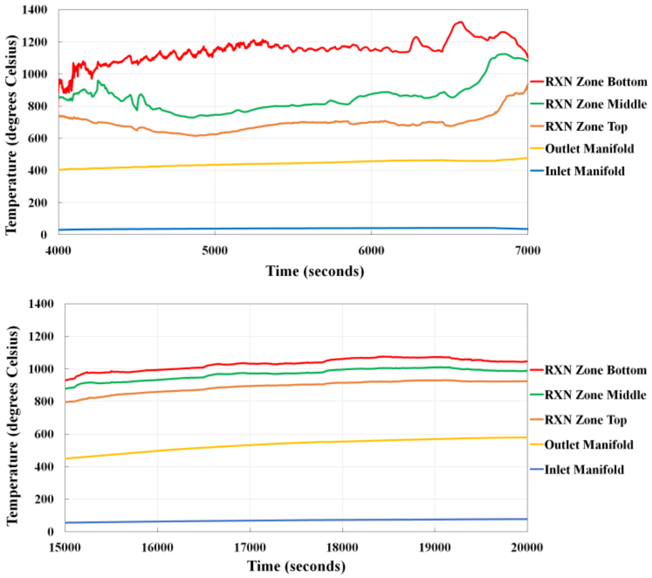

Figure 9: Thermal profile. Top: Without mixing chamber. Bottom: With mixing chamber.

Reformate Compositions

During the experiment, special attention was given to observing the reformate flare color, size, and steadiness at different reaction conditions. These visual observations showed the reaction performance by characterizing soot formation. For reference, a pure hydrogen flare is essentially invisible to the human eye since it is free of CH radicals (blue flare color) or soot particles (yellow flare color). In this case, a blue flare color was ideal since the reformate stream was syngas instead of pure hydrogen. In addition to the flare attributes, the flare can and exhaust pipe was constantly checked for physical soot buildup, which is an obvious sign of a high degree of soot formation. The test showed that a blue JP-8 reformate flare was able to be achieved (Figure 10 Right), which is a significant improvement compared to the one without a mixing chamber (Figure 10 Left).

Figure 10: Reformate flare color. Left: Without mixing chamber. Right: With mixing chamber.

The reformate composition under a variety of input flow conditions was measured. Since hydrogen and carbon monoxide are major equilibrium products from thermal partial oxidation (TPOX), their composition maps are provided in Figure 11 and Figure 12 respectively. Also, included in the figures is the thermodynamic equilibrium concentration. The reaction condition that was closest to thermodynamic equilibrium was 30 SLPM total volume flow rate and 2.66% JP-8 (equivalence ratio of ϕ = 2.4), with H_2 yields at ~74% of equilibrium and CO yields at ~98% of equilibrium. This reaction also yielded the highest temperature during testing since it was the closest to stoichiometry at the largest flow rate tested. As expected, reaction temperature played an important role since conditions with higher temperature were closer to equilibrium.

In previous work, the prototype without a mixing chamber demonstrated ~85% of equilibrium for H_2 yield and ~100% of equilibrium for CO yield at 30 SLPM and 3.33% JP-8 (equivalence ratio of ϕ = 3). At the same reaction conditions in the prototype with mixing chamber, the H_2 and CO yields were 50% and 70% of equilibrium respectively. The reduced yield can most likely be attributed to the nearly 100-200°C lower temperature observed during testing. However, the center reaction zone of the prototype without a mixing chamber was severely oxidized and damaged after testing. Therefore, high temperature operation was avoided for the prototype with a mixing chamber, by limiting the input flow rate.

With the reduced yields of H_2 and CO came increased yields of methane (CH_4) and ethylene (C_2H_4). In each reformate sample, significant quantities of methane, 3-6 vol%, and ethylene, 1-5 vol%, were measured. The increased yield of these hydrocarbons could be due to the continuous reaction after the center reaction zone, or merely from inefficient fuel reforming caused by the slightly reduced reaction temperature.

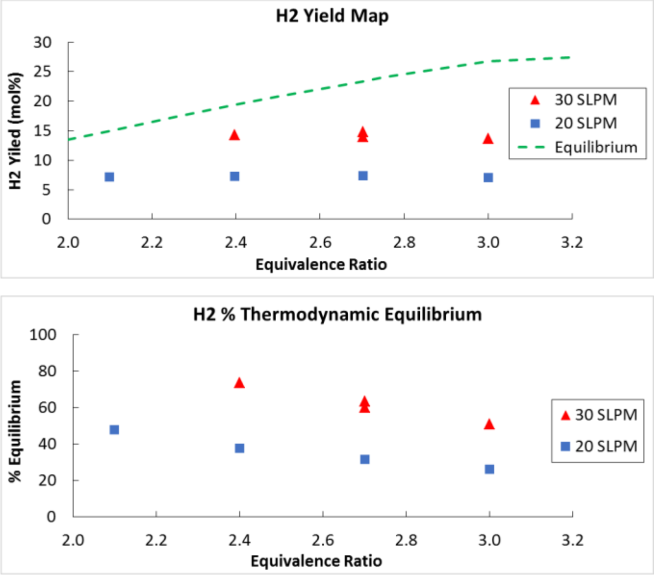

Figure 11: The H_2 species concentration map across different reaction conditions.

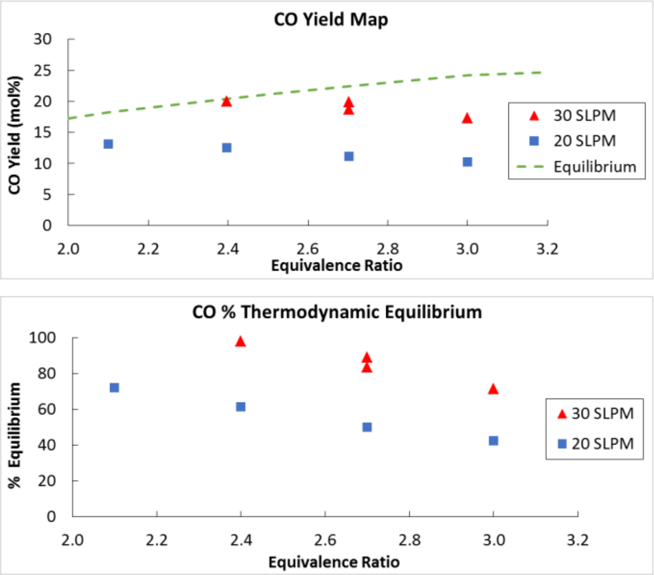

Figure 12: The CO species concentration map across different reaction conditions.

Table 1: Input condition of 8 different samples.

Sample #	Total Flow Rate (SLPM)	Equivalence Ratio	Reynolds Number	Chemical Enthalpy Input (W)
1	20	3	110.3	3814.4
2	20	2.7	110.3	3436.4
3	20	2.4	110.3	3046.9
4	20	2.1	110.3	2668.9
5	30	3	165.45	5721.5
6	30	2.7	165.45	5154.5
7	30	2.7	165.45	5154.5
8	30	2.4	165.45	4570.4

Enthalpy in the Reformate

The overall conversion efficiency (chemical enthalpy in the reformate / input chemical enthalpy) was calculated based on the measured reformate composition. Table 1 shows the input conditions of the 8 different samples in Figure 13. As can be seen in Figure 13, higher Reynolds number (Re) results in a higher conversion efficiency, due to less heat loss impact for higher Re. In addition, stronger mixtures (equivalence ratio closer to 1) also have higher conversion efficiency and less C2s formation. A conversion efficiency greater than 90% can be achieved for the Re = 165.45 with equivalence ratio = 2.4. Both increasing flow rate and reducing equivalence ratio result in a higher reaction temperature.

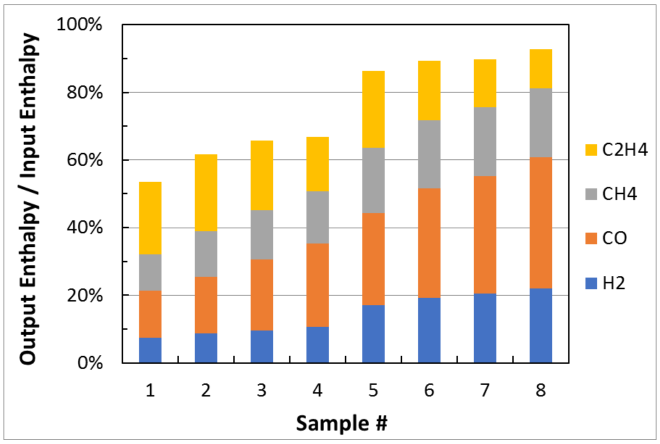

Figure 13: Chemical enthalpy in the reformate / Input chemical enthalpy.

While C_2H_4 in the reformate can be hydrogenated to CH_4 by integrating a downstream "post reforming catalyst", and the CH_4 can be used by SOFC via internal steam methane reforming, the additional post reforming system increases overall system complexity, which is less ideal than a single-stage, non-catalytic reforming system. To further increase the syngas yield and reduce C2s formation, material for 3-D metallic printing that can survive at higher temperature is needed.

CONCLUSION

The Swiss-roll reformer with an integrated mixing chamber has shown a significant improvement in reaction zone stability and reduced soot formation when compared to the prototype without a mixing chamber. Due to high heat recirculation and minimized heat loss, a large amount of chemical enthalpy remains in the reformate. However, since the operating temperature is limited by the current material (15-5ph stainless steel), a high concentration of C2s remains in the reformate. It is anticipated that by using material such as Inconel or Haynes, the reformer is able to be operated at much higher flow rate and reaction temperature, at which higher syngas yield can be achieved.

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