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A Swiss Roll Style Combustion Reactor for Non-Catalytic Reforming

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Abstract: Reforming higher hydrocarbons into synthesis gas is a process that has been heavily researched in the past twenty years. The process typically requires use of a catalyst to achieve a meaningful conversion at lower temperatures. The use of heavy hydrocarbon liquids and gases however poses challenges including sulfur poisoning and coking of the catalyst. The implementation of a non-catalytic system which tackles both of these issues has been studied. The system uses a specialized combustion reactor design called a “Swiss Roll.” Due to its high heat recuperation, the Swiss Roll combustion device allows for super-adiabatic temperatures in the core, where the reaction takes place. The temperature reached is around 1200°C, high enough for thermal partial oxidation (TPOX). The system is able to produce meaningful quantities of synthesis gas from JP-8, a fuel that is very abundant in the US military but also contains high quantities of sulfur, as the feedstock. The reformer’s capability in producing hydrogen from such a fuel without the aid of a catalyst is discussed. Finally, additional post-reformer operations, to refine the product for the current application, are discussed.

Key Words: *Thermal Partial Oxidation, Non-Catalytic Reforming, Swiss Roll Reactor*

1. Introduction

Various technologies for the reforming of higher hydrocarbons into syngas have been studied in recent years. Some of the most studied methods include catalytic partial oxidation reforming (CPOX), but more recently in the past 10 years, researchers have searched for alternative methods such as plasma aided reforming [1-4].

Catalytic methods have various advantages and disadvantages for hydrocarbon fuel reforming, but common catalysts face challenges when the fuel contains high levels of sulfur. Sulfur is often found in higher hydrocarbon liquid fuels such as JP-8, which contains sulfur concentrations up to 3,000 ppm by mass [5]. Sulfur will poison many catalyst technologies, causing the need for a replacement of the catalyst or pretreatment of the fuel before introduction to the reforming system.

Plasma aided methods have shown reasonable conversion efficiencies, however the energy input required to produce the plasma contributes to a lower overall energy efficiency. The additional power input also contributes to size, weight, and system complexity.

Advanced Cooling Technologies, Inc. has worked under contract with The Department of Defense to develop a non-catalytic, and therefore sulfur tolerant, JP-8 reformer. The technology relies on the process of thermal partial oxidation (TPOX) to produce syngas. Using a high heat recuperation combustion device, known as the “Swiss-roll”, partial oxidation at elevated temperatures can be

self-sustained to allow for near equilibrium conversion of the hydrocarbons to syngas. The Swiss-roll design recycles thermal energy from the reformat stream to preheat the inlet reactants. With this heat recovery, the Swiss-roll combustion device extends the flammability limits of the fuel and sustains extremely high temperature partial oxidation even at very rich fuel to air ratios.

Figure 1A shows a schematic of the Swiss-roll concept. The cold reactants (Air and JP-8 in fuel-rich conditions) flow through the inlet channel and into the center reaction zone. After partial oxidation, the hot products (reformat) flow out from the center through the adjacent outlet channel. The heat exchange through spiral heat exchanger significantly increases the reactants' temperatures and thus the reaction zone temperature. Figure 1B further illustrates the temperature increase resulting from heat recirculation. Without heat recirculation, the reaction temperature increase is due to the exothermic reaction only, yet with heat recirculation, the reaction zone temperature is increased by both chemical reaction and heat recirculation. As such, the resulting reaction temperature can be higher than the adiabatic flame temperature; this is called the "super-adiabatic" flame temperature. For example, for a propane and air mixture with equivalence ratio (Φ) equal to 3, the adiabatic flame temperature is around 800°C, while the experimental measurement shows more than 1100°C can be easily achieved in the center of the reaction zone.

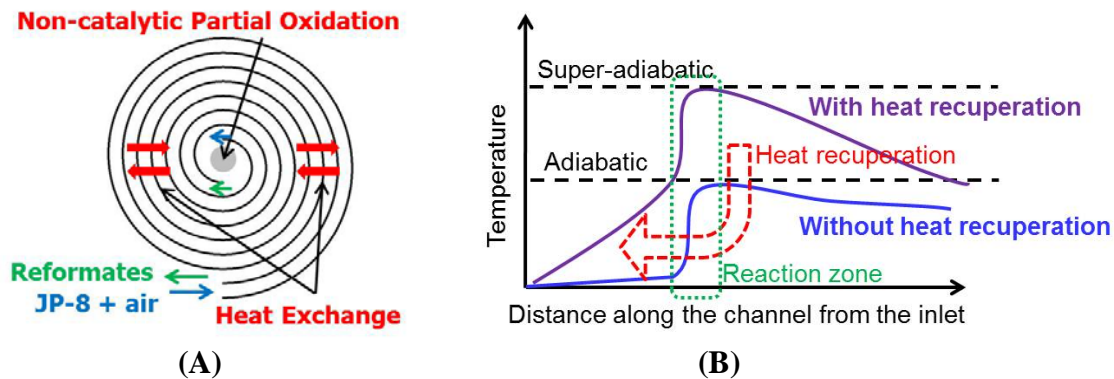


Figure 1: (A) Schematic diagram of the Swiss-roll reformer. (B) Temperature profile for reaction with and without heat-recirculation.

The Swiss-roll combustor was first proposed by Professor Weinberg in 1974 [6, 7]. Many studies have demonstrated its superior performance in heat recirculation and the effect on promoting internal reaction [8-11]. Specifically, it has been shown effective at extending the flammability of a variety of fuels and enabling achievement of equilibrium state concentrations. Several features make the Swiss-roll combustor extremely thermally efficient. First, the large heat transfer to heat loss area ratio enables highly efficient heat exchange in a very confined volume. Second, the curvature of the channel creates a centrifugal instability (Dean vortices) that further enhances heat transfer. Third, the reaction zone, which has the largest propensity for heat loss, is surrounded by the spiral heat exchanger so most of the heat loss is actually recovered. Fourth, long inlet channels with elevated temperature provide a long residence time that may significantly reduce the formation of non-equilibrium state products such as soot.

2. Methods / Experimental

In this work a Swiss-roll fuel reformer was fabricated by additive manufacturing. This method allows for high precision construction of all the inner geometry of the Swiss-roll. The material used was stainless steel PH1, which is the powder form of stainless steel used in 3-D printing to produce a material with the same chemistry as stainless steel 15-5. [12]

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The Swiss-roll test setup was designed to maximize heat recuperation with a high temperature ceramic insulation wool. The Swiss-roll, along with welded-on manifolds, was piped to a tank of propane and compressed air. The reactant flow was controlled using mass flow controllers wired to a DAQ and monitored through the DaisyLAB interface. The inlet air was preheated before it flowed through the vaporizer, where JP-8 was injected via nebulizer. The fuel-air mixture then traveled through a flashback arrestor into the inlet of the Swiss-roll. The temperatures at several key points in the Swiss-roll were closely monitored using an array of thermocouples inserted through pre-drilled holes. Figure 2 depicts the initial setup, detailing the key features of the first-generation Swiss-roll fuel reformer.



Figure 2: Test setup with air preheater, JP-8 vaporization chamber, Swiss-roll, and exhaust flare.

The outlet manifold of the Swiss-roll contained a port for reformat sampling to analyze the composition using a gas chromatograph. The remaining reformat was flared off for safety purposes.

3. Results and Discussion

For simplicity and proof-of-concept, preliminary testing was conducted with propane as the fuel, instead of JP-8. As a precautionary measure, a bake-out was performed on the Swiss-roll before the tests to eliminate surface oxides. Figure 3 shows preliminary test results at varying flow rates and fuel compositions. In each test, the propane was premixed with air and the resulting reformat was collected in a syringe from the exhaust port and analyzed by a gas chromatograph. The tests showed repeatable results with hydrogen yields in close proximity of one another.

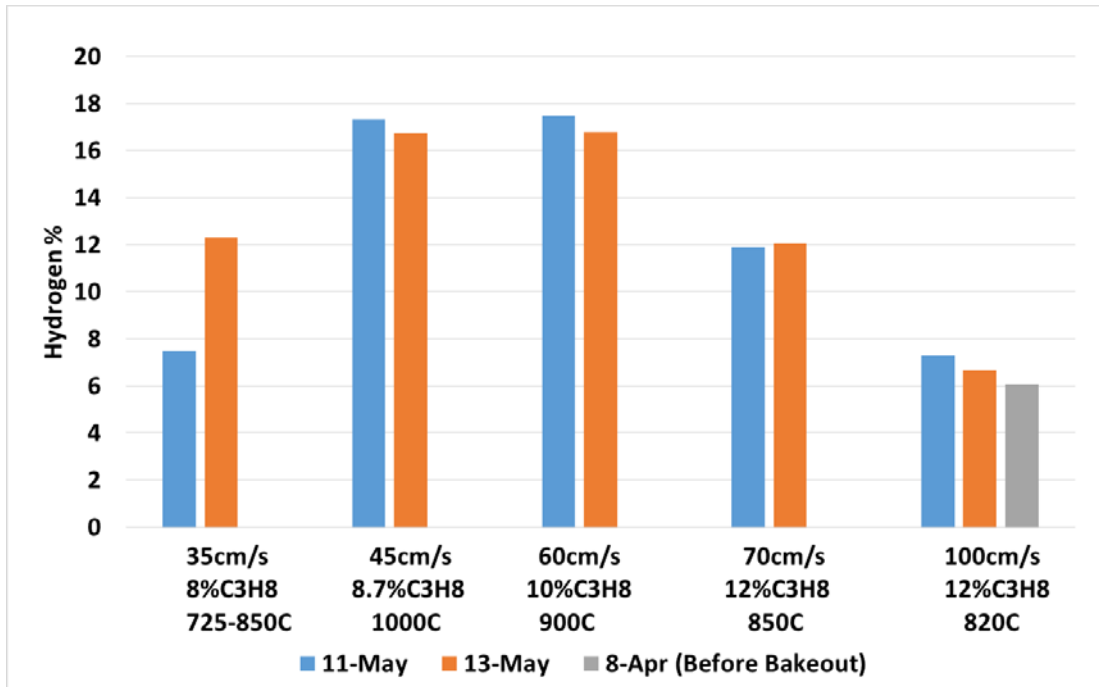


Figure 3: Repeated tests of the 3-D printed Swiss-roll.

The repeatability of the tests shows that a wall catalytic effect may have little effect on the final reformat composition. There is, however a noticeable effect of the location of the reaction zone. The temperature readings from the various thermocouples locate the reaction zone in the Swiss-roll during testing. Figure 4 shows one such thermal profile.

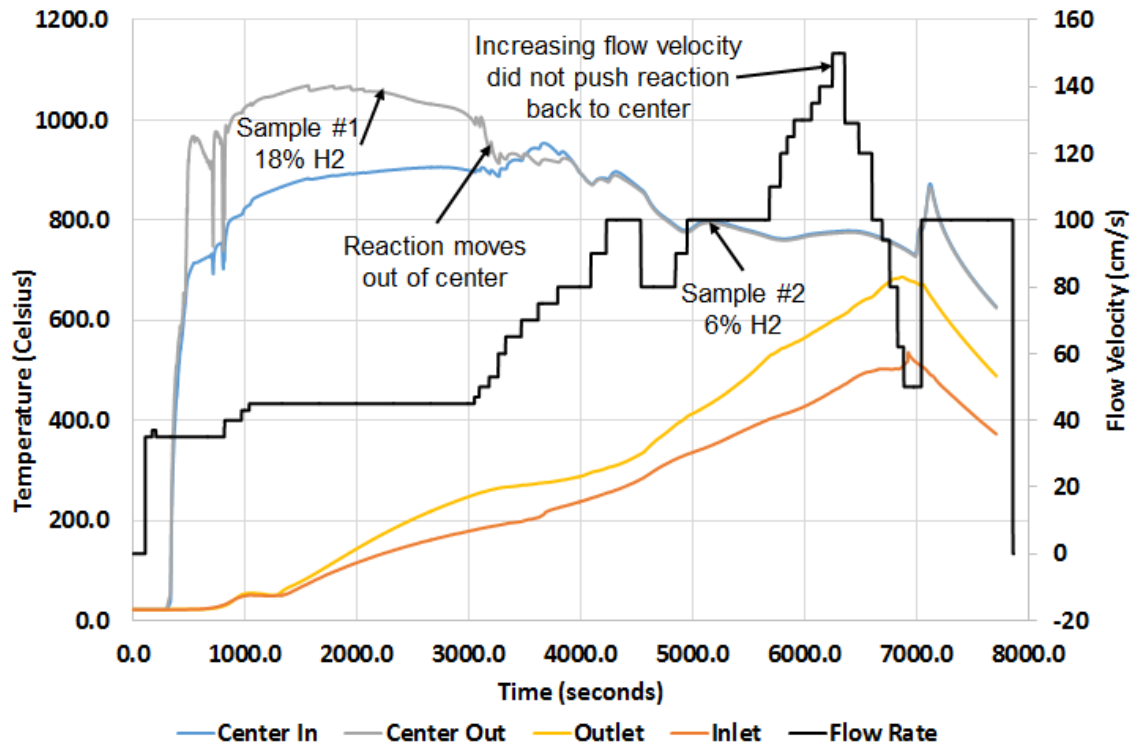


Figure 4: The time history of the temperature and flow rate during the test.

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At the beginning of the test, from 1000 to 3000 seconds, the reaction is stabilized in the center reaction zone and an 18% hydrogen yield was observed. However, as the Swiss-roll heated up, the reaction moved out of center and stabilized in the inlet channel. The GC reading with the reaction out of center only showed 6% hydrogen due to the reduced residence time. An effort to push the reaction back to center by increasing the reactant velocity was unsuccessful. Several measures have been taken since these tests were performed to improve the design of the Swiss-roll in our second-generation design and stabilize the reaction in the combustion zone.

JP-8 tests were conducted after the preliminary propane tests. The reformer was started up as described before with propane, however after a stable reaction was present in the center of the reformer, propane was gradually decreased and JP-8 was gradually introduced. The stoichiometric fuel to air mass ratio for JP-8 is 0.068 [13]. In order to keep the equivalence ratio at 3, the calculated JP-8 in air concentration was 4.59% JP-8. As the propane was reduced and the JP-8 was increased, the reaction quickly moved out of the center reaction zone and into the channels as shown in figure 5.

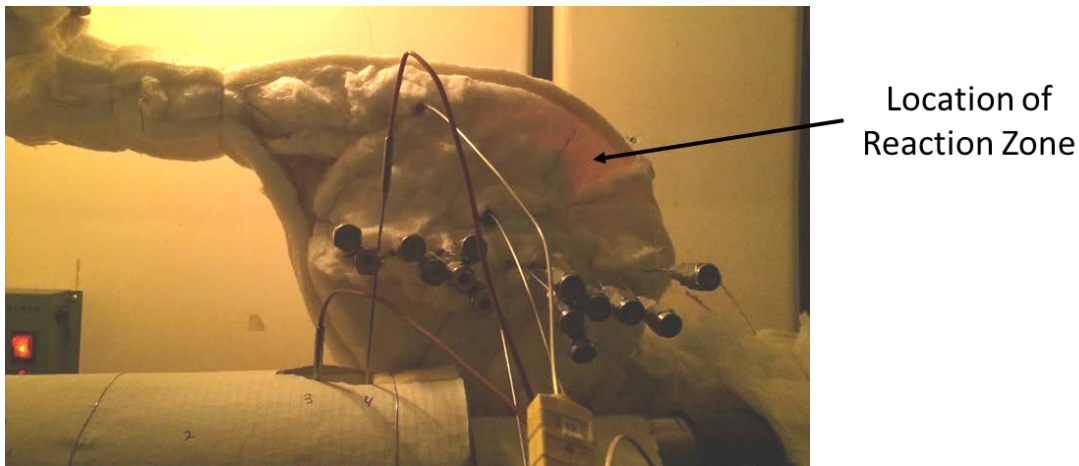


Figure 5: Reaction zone indicated by the red-hot area has propagated to an outer channel during the JP-8 reforming test.

This result continued to occur in each subsequent JP-8 test conducted. This phenomenon is attributed to the autoignition temperature difference between JP-8, which is known to be around 210°C, and propane, which is around 470°C. Design changes need to be made and a second-generation Swiss-roll reformer is in the final steps of fabrication as of the completion of this paper.

4. Conclusions

The Swiss-roll reformer is capable of reaching and sustaining temperatures around 1000°C, which is sufficient TPOX fuel reforming of hydrocarbon fuel. The desired product is produced without the use of a catalyst, eliminating sulfur poisoning challenges. With a gaseous fuel, the reaction zone can be stabilized in the center by adjusting the flow rate and inlet air/fuel mixture.

The Swiss-roll can self-sustain a reaction using only a fuel-rich mixture of JP-8 and air, but the reaction quickly moves from the center reaction zone to the inlet channel. As shown in the propane testing, the highest yield of hydrogen will occur when the reaction takes place in the hot center reaction zone due to the longer residence time at elevated temperatures. In order to ensure the

flame front stabilizes in the center reaction zone, several modifications have been made to the Swiss-roll reformer in what is called the generation II design. This design includes a fuel injection at the center, a ceramic flow straightener, and thinner channels to increase the linear velocity of the inlet gas.

Other considerations include the downstream post-reformer operations. For the DoD contract, the sulfur must be eliminated from the reformat. We also must eliminate any unreformed higher hydrocarbons. ACT is currently working on two post reformer operations including a catalyst to eliminate unreformed hydrocarbons and a sorbent to remove sulfur. The status of these operations remains in early stage R&D.

5. Acknowledgements

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6. References

- [1] Moon, Dong. "Hydrogen Production by Catalytic Reforming of Liquid Hydrocarbons." *Catalysis Surveys from Asia* 15.1 (2011): 25-36.
- [2] Jeon, Yukwon, Chanmin Lee, Junki Rhee, Gicheon Lee, Jae-ha Myung, Myunggeun Park, Joo-Il Park, Hisahiro Einaga, and Yong-Gun Shul. "Autothermal reforming of heavy-hydrocarbon fuels by morphology controlled perovskite catalysts using carbon templates." *Fuel*, 187, 446-456.
- [3] Besser, R.S., and P.J. Lindner. "Microplasma reforming of hydrocarbons for fuel cell power." *Journal of Power Sources* 196.21 (2011): 9008-9012.
- [4] Sugawara, M., and S. Futamura. "Reforming of Aliphatic Hydrocarbons With Silent Discharge Plasma." *IEEE Transactions on Industry Applications* 44.1 (2008): 46-52.
- [5] *AFPET Laboratory Report*. Rep. Wright-Patterson AFB, (2014). Print.
- [6] Lloyd, S. and Weinberg, F., "A Burner for Mixtures of Very Low Heat Content," *Nature*, 251, 47-49 (1974).
- [7] Jones, A., Lloyd, S., and Weinberg, F., "Combustion in Heat Exchangers," *Proceedings of the Royal Society of London Section A*, 360, 97-115 (1978).
- [8] Ronney, P., "Analysis of Non-adiabatic Heat-recirculating Combustors," *Combustion and Flame*, 135, 421-439 (2003).
- [9] Chen, C. and Ronney, P., "Three-dimensional Effects in Counterflow Heat-recirculating Combustors," *Proceedings of the Combustion Institute*, 33, 3285-3291 (2011).
- [10] Chen, C. and Ronney, P., "Scale and Geometry Effects on Heat-recirculating Combustors," *Combustion Theory and Modelling*, 17, 888-905 (2013).
- [11] Chen, C. and Ronney, P., "Geometrical Effects on Swiss-roll Heat-recirculating Combustors," *PhD Thesis* (2011).
- [12] Electro Optical Systems. (2008). *StainlessSteel PH1* [Material Data Sheet]. Retrieved from [<http://gpiprototype.com/images/PDF/EOS-StainlessSteel-PH1.pdf>]
- [13] Summer, Steven M. Limiting Oxygen Concentration Required to Inert Jet Fuel Vapors Existing at Reduced Fuel Tank Pressures. U.S. Department of Transportation, Aug. 2003. Web.