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Swiss-roll JP-8 Fuel Reformer with Direct Center Fuel Injection and Mixing Chamber Design

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Abstract: Reforming higher hydrocarbons, such as the military logistic fuel JP-8, into synthesis gas has been heavily researched to enable the use of fuel cells in military operations while conforming to the single fuel policy. Reforming JP-8 is specifically challenging due to its notoriously high sulfur content, which poses serious poisoning challenges for catalyst-based systems. A non-catalytic fuel reforming system can be advantageous when reforming fuels with non-ideal compositions. The proposed system studied in this work uses a “Swiss-roll” combustion reactor to recuperate heat losses using a spiral heat exchanger, which enables self-sustained thermal partial oxidation at super-adiabatic temperatures near 1200°C (gas temperature). While the effective heat recirculation achieves high reforming efficiency without using catalysts, one challenge is the auto-ignition of the preheated reactants before they enter into the desired reaction zone. In this work, an advanced Swiss-roll fuel reformer was designed, fabricated, and experimentally tested to address this challenge. In particular, a new approach to Swiss-roll reactant injection, by directly injecting the fuel to the center reaction zone, was integrated with a mixing chamber design to ensure the reactants are completely mixed before the partial oxidation reaction without auto-igniting. The experimental results and potential applications are discussed in detail.

Keywords: *Swiss-roll, Thermal Partial Oxidation (TPOX), Non-Catalytic Fuel Reforming*

1. Introduction

Fuel cells are a promising technology for efficient electrical power generation from hydrogen, or hydrocarbon fuels, with no moving parts, harmful emissions, or noise. Promising commercial applications have already been realized in Fuel Cell Electric Vehicles (FCEV) and stationary power generation plants. However, enabling fuel cells for widespread use, especially military applications, presents challenges due to the availability of the fuel source. Most commercial fuel cell systems use a reliable source of high purity hydrogen, or methane, as the input chemical energy, but for military applications these fuel infrastructures are not available. In fact, the U.S. Army has instituted a Single Fuel Policy built around JP-8 fuel, meaning all systems requiring a fuel source must operate on JP-8 to simplify fuel logistics. Therefore, new technologies for military applications must be proven to adhere to this policy.

Since fuel cells operate using hydrogen (or syngas) a fuel reformer must be used in order to enable operation with JP-8 fuel. Reforming JP-8 fuel using a precious metal catalyst has been studied in the past, but there are still challenges to overcome due to catalyst deactivation from coking or

sulfur poisoning. Thermal partial oxidation is an ideal reforming technique for JP-8 fuel due to its high tolerance to undesired species, but its low exothermicity at fuel-rich reforming conditions makes it difficult to achieve the high-temperature reaction conditions required.

A Swiss-roll reactor, first discovered in 1974 by Dr. Felix Weinberg, uses heat recuperation to raise the temperature of a given reaction to super-adiabatic conditions [1-2]. The device surrounds a reaction chamber with a spiral heat exchanger to effectively reduce the propensity for thermal losses. In this way, a Swiss-roll fuel reformer enables the desirable TPOX reforming mechanism for JP-8 fuel. Past research has shown the Swiss-roll's capability in producing a robust, super-adiabatic reaction zone with no external energy input at steady state [3-7]. The reactor is inherently sulfur tolerant, self-sustaining, compact, and has no moving parts.

2. Methods / Experimental

A Swiss-roll JP-8 fuel reformer was designed, fabricated, and tested in this work to address the aforementioned challenges with Swiss-roll TPOX fuel reforming. In particular, the design included direct fuel injection to the Swiss-roll reaction zone with an integrated mixing chamber to eliminate fuel auto-ignition in the spiral heat exchanger while maintaining a premixed gas-phase reaction to reduce soot formation. Based on this design, a stainless-steel Swiss-roll reactor was fabricated via additive manufacturing using a technique called Direct Metal Laser Sintering (DMLS). A model of the design and the Swiss-roll part integrated with the experimental test setup are shown in Figure 1.

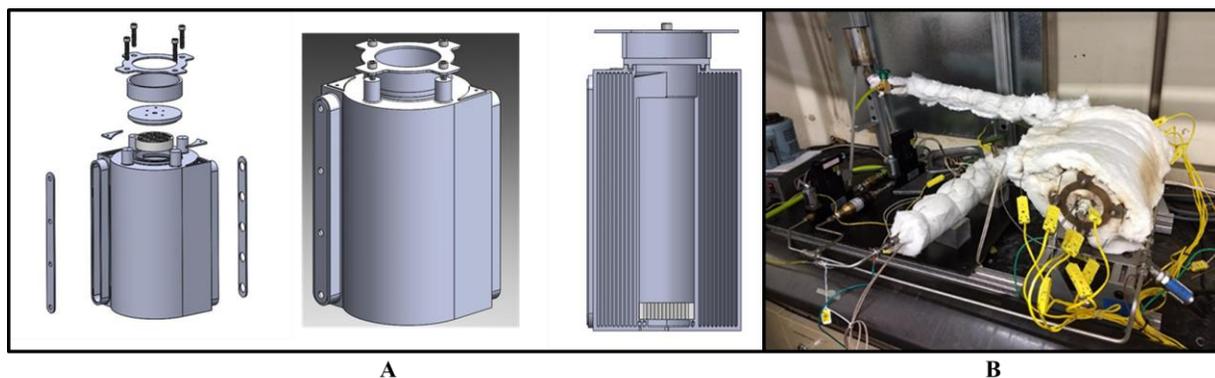


Figure 1: (A) A 3-D model of the Swiss-roll fuel reformer prototype design. The vertical section view shows the mixing chamber integrated at the bottom of the center combustion zone. (B) The Swiss-roll fuel reformer prototype integrated with the experimental test setup.

The Swiss-roll prototype was tested at a variety of fuel-rich reaction conditions, using JP-8 fuel, to characterize the TPOX reforming performance of the device. Compressed air was supplied to a mass flow controller to precisely control the amount of air entering the reactor. Similarly, a second mass flow controller metered propane into the reactor to preheat the device at startup, before injecting JP-8. A peristaltic JP-8 pump forced a prescribed amount of liquid fuel through a fuel heater to vaporize the fuel before injection into the Swiss-roll center. Strategically placed thermocouples measured the temperature throughout the reactor system to create a thermal profile for the device, while a single pressure transducer upstream of the Swiss-roll reactor measured the pressure drop across the system. 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.

3. Results and Discussion

The results from JP-8 fuel reforming tests show successful conversion of the target fuel to syngas using high-temperature, gas-phase TPOX reforming with no significant soot formation. The thermal and flow profiles in Figure 2, show the temperature of the reaction at the prescribed input fuel and air settings for each experimental condition. The Swiss-roll reactor was able to produce a stable, high-temperature reaction zone (often between 900-1000°C), at a variety of flow conditions.

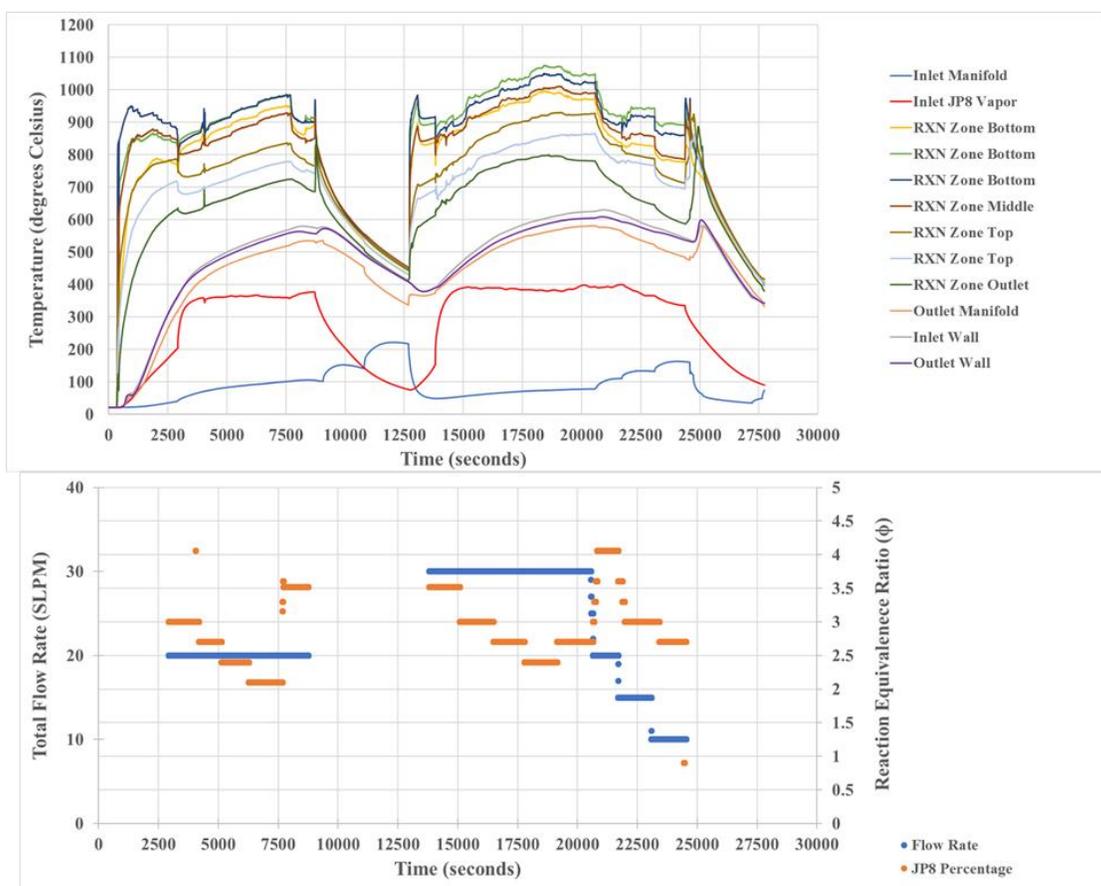


Figure 2: The thermal and flow profiles from JP-8 testing with the Swiss-roll fuel reformer prototype.

For each set of flow parameters, a reformate sample was extracted and analyzed by the GC. The species yield for each of the two main constituents of syngas (hydrogen and carbon monoxide) is shown in Figures 3 and 4 respectively. For a rough comparison, theoretical thermodynamic equilibrium concentrations were calculated using an isoctane/oxygen/nitrogen reaction using GASEQ software.

In general, lower equivalence ratio tests for a given flow rate produced the closest yields to estimated thermodynamic. This was due in part to the higher reaction temperatures achieved and the lower maximum theoretical equilibrium values. However, at a total flow rate of 20 SLPM,

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equivalence ratios 3.5 and 4 produced higher yields and were closer to theoretical equilibrium than values measured at lower equivalence ratios for the same flow rate. The reaction condition which was closest to thermodynamic equilibrium for both hydrogen and carbon monoxide concentrations was 30 SLPM total flow rate and $\phi=2.4$. At this set point, the hydrogen yield was nearly 75% of equilibrium while the carbon monoxide yield reached about 98% of equilibrium. Non-coincidentally, this condition also produced the highest temperature during testing at nearly 1100°C. As predicted, the reformat yield, and therefore the reactor performance, is highly dependent on reaction conditions and the temperature in the reaction zone.

Despite not reaching estimated thermodynamic equilibrium, the chemical enthalpy in the fuel reforming system was mostly conserved when considering all major flammable species measured. Figure 5 shows the reaction chemical efficiency defined as the chemical enthalpy in the reformat over the chemical enthalpy in the initial JP-8 feedstock. For 12 of the 13 total reformat samples analyzed, the chemical efficiency was over 60%. The highest chemical efficiencies (>80%) were measured at a total flow rate of 30 SLPM with ϕ ranging from 2.4 to 3.

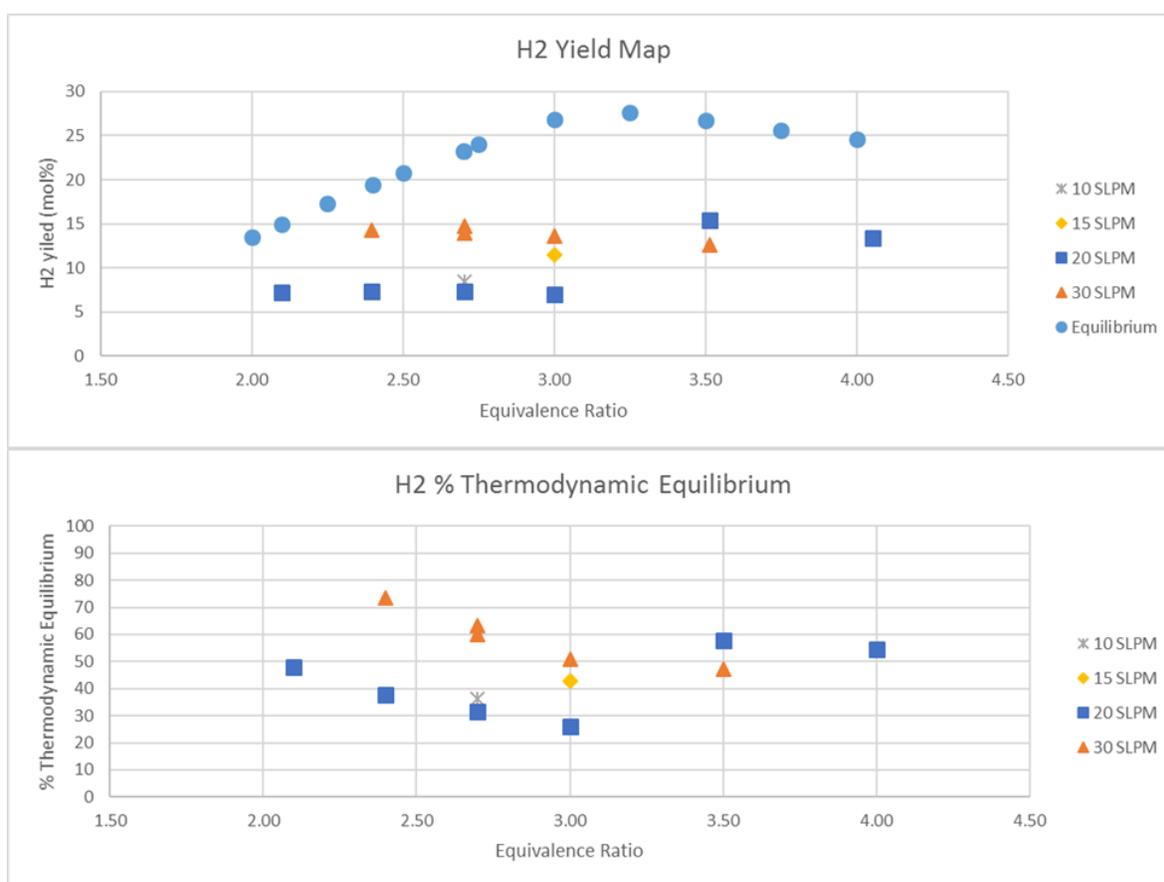


Figure 3: The hydrogen yield in the Swiss-roll reformat as a function of reaction equivalence ratio at different total flow rates.

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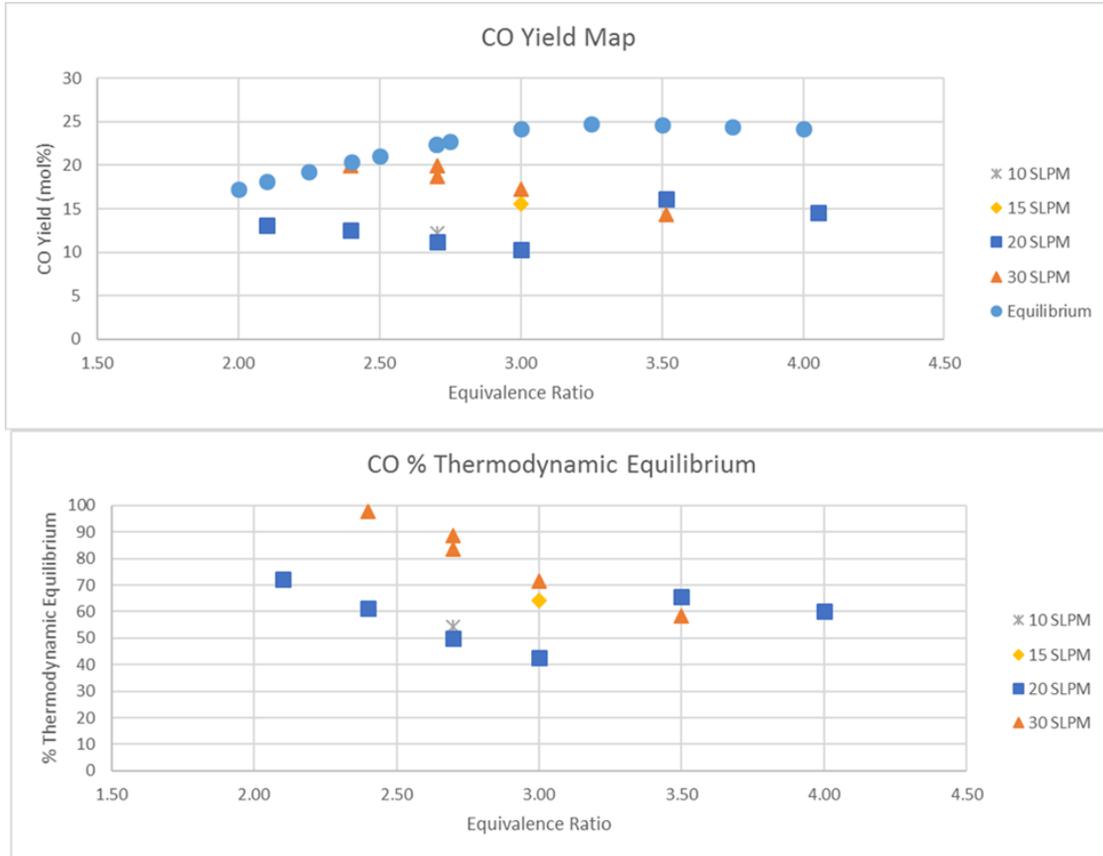


Figure 4: The carbon monoxide yield in the Swiss-roll reformate as a function of reaction equivalence ratio at different total flow rates.

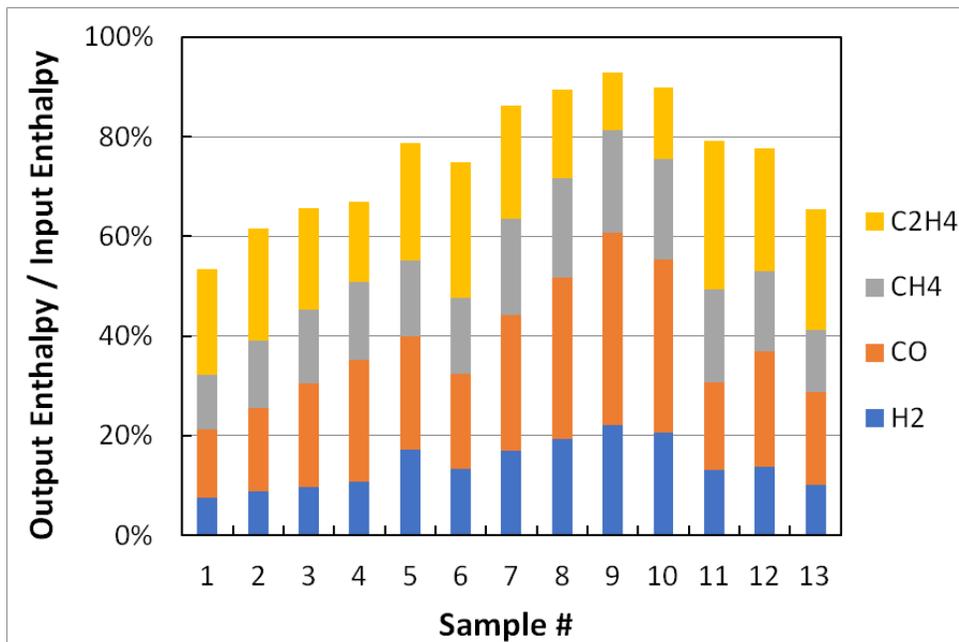


Figure 5: A large amount of the input chemical enthalpy from the JP-8 fuel is conserved in the Swiss-roll reformate after TPOX fuel reforming.

4. Conclusions

The Swiss-roll reactor tested in this work was able to successfully reform JP-8 fuel using TPOX with heat recuperation. Hydrogen and carbon monoxide yields at about 75% and 98% of thermodynamic equilibrium were demonstrated respectively, while retaining over 80% of the input chemical enthalpy. In addition, no significant soot accumulation was visibly observed during testing. Future work is needed to further characterize the device over a wider range of reaction conditions, with an emphasis on building and sustaining a higher temperature reaction zone to push the reformat toward thermodynamic equilibrium.

5. Acknowledgements

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6. References

- [1] S. Lloyd, F. Weinberg, A burner for mixtures of very low heat content, *Nature* 251 (1974) 47-49.
- [2] A. Jones, S. Lloyd, F. Weinberg, Combustion in heat exchangers, *Proceedings of the Royal Society of London Section A* 360 (1978) 97-115.
- [3] P. Ronney, Analysis of non-adiabatic heat-recirculating combustors, *Combustion and Flame* 135 (2003) 421-439.
- [4] C. Chen, P. Ronney, Three-dimensional effects in counterflow heat-recirculating combustors, *Proceedings of the Combustion Institute* 33 (2011) 3285-3291.
- [5] C. Chen, P. Ronney, Scale and geometry effects on heat-recirculating combustors, *Combustion Theory and Modelling* 17 (2013), 888-905.
- [6] C. Chen, P. Ronney, Geometrical effects on swiss-roll heat-recirculating combustors, PhD Thesis (2011).
- [7] Ryan Zelinsky et al., 10th U. S. National Combustion Meeting, College Park, MD, April 23-26, 2017, <https://www.1-act.com/wp-content/uploads/2017/05/Zelinsky-Swiss-Roll-Style-Combustion-Reactor-for-Non-Catalytic-Reformi....pdf>