

Fuel Reforming Using Counter-Current Heat-Recirculating “Swiss Roll” Combustors

Shrey Trivedi¹, Srusti Koli¹, Andrew Lawson¹, Chien-Hua Chen², Howard Pearlman², and Paul Ronney¹

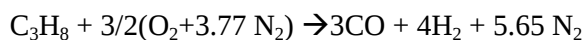
¹Department of Aerospace and Mechanical Engineering, University of Southern California
Los Angeles, California USA

²Advanced Cooling Technologies, Inc.
Lancaster, Pennsylvania USA

1 Introduction

The performance of a "Swiss Roll" heat-recirculating combustor [1, 2] as a self-contained and thermally self-sustaining fuel reformer was tested using very rich propane-air mixtures that cannot support combustion without heat recirculation. Since hydrocarbon fuels contain 50 times more energy per unit mass than batteries [3, 4, 5], reforming of hydrocarbon fuels into hydrogen and carbon monoxide which could be used in fuel cells [6] to generate much more electrical energy than batteries can be made possible using this scheme.

Fuel reforming is done by burning a very rich mixture which causes the partial oxidation of fuel and results in the formation of H₂ and CO instead of H₂O and CO₂. For example, oxidation of Propane at an equivalence ratio $\phi = 3$ is as follows:



This reaction gives us CO and H₂ which can be used as fuel in a Solid Oxide Fuel Cell (SOFC) to generate electric power. If this fuel reforming is done on a small scale, it could potentially replace batteries.

Figure 1 plots the graph of hydrogen production efficiency vs. equivalence ratio of a propane-air mixture at equilibrium at various fixed temperatures using the data obtained from GASEQ. It can be seen that burning 12% rich mixtures at a temperature of 1200°K or higher gives maximum hydrogen production efficiency which is defined as the ratio of amount of hydrogen produced to the maximum possible amount of hydrogen than can be produced in the given fuel-air mixture.

Hydrogen Production Efficiency = Number of mole of H₂ produced / 4 x Number of moles of C₃H₈

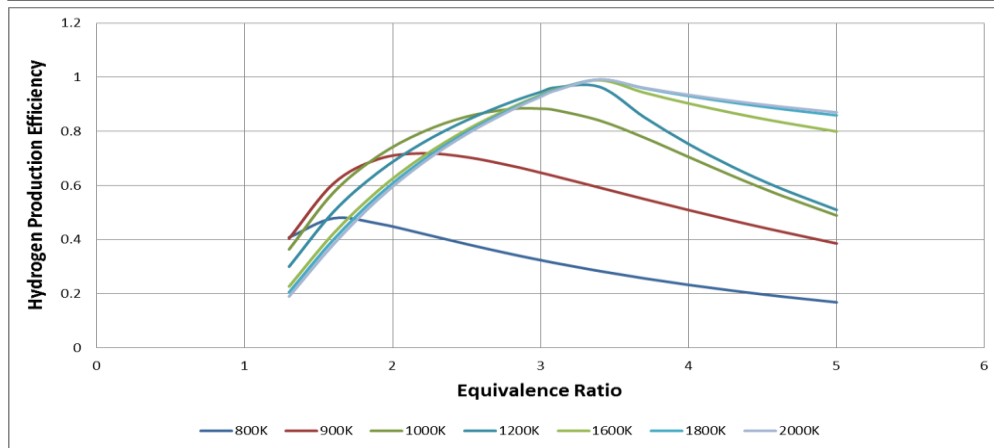


Figure 1. Hydrogen Production Efficiency vs Equivalence Ratio at equilibrium for propane-air mixture at different temperatures using GASEQ.

Figure 2 shows a graph of temperature of products vs. equivalence ratio. To achieve maximum hydrogen yield, we need to be in the grey zone which represents temperatures above 1200°K and a 12% or higher propane-air mixture would give us maximum hydrogen yield. However, at equilibrium conditions it is not possible to burn such rich mixtures as the extinction limit for propane is 9.3% (Figure 2a). One way to burn such rich mixtures is by preheating the reactants. Figure 2b shows the temperature of products vs. equivalence ratio plot for reactants preheated by 400° K. This preheating of the reactants can be achieved by using Swiss Roll combustors.

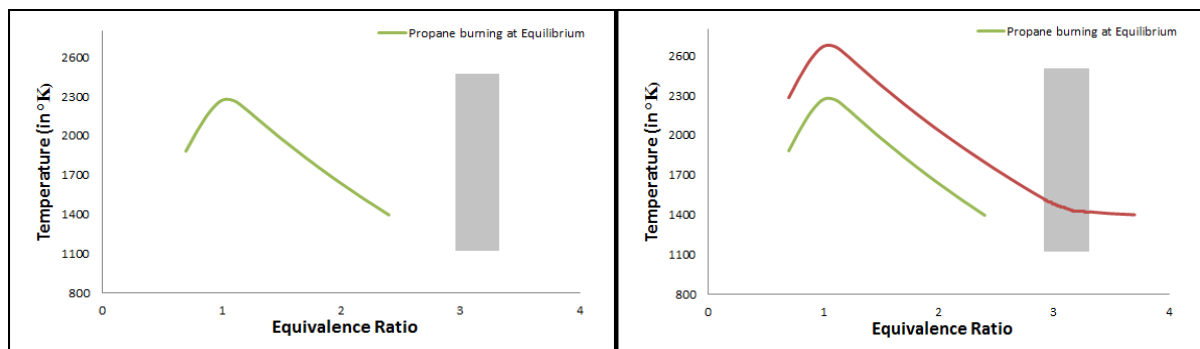


Figure 2. (a) Product Temperature vs Equivalence Ratio at equilibrium for a propane-air mixture without preheating; and (b) Product Temperature vs Equivalence Ratio at equilibrium for a propane-air mixture after 400°K preheating.

The biggest challenge in micro scale combustion is heat extinction via heat loss. A Swiss Roll combustor (Figure 3) recirculates the thermal enthalpy from the hot, burnt products to the cold reactants resulting in higher reaction temperature than the adiabatic flame temperature. This gives a Swiss Roll combustor the ability to sustain combustion for an extraordinary range from extremely lean to extremely rich combustion [7]. Also, due to its spiral design the internal heat transfer area to external heat loss area is high, making it extremely thermally efficient.

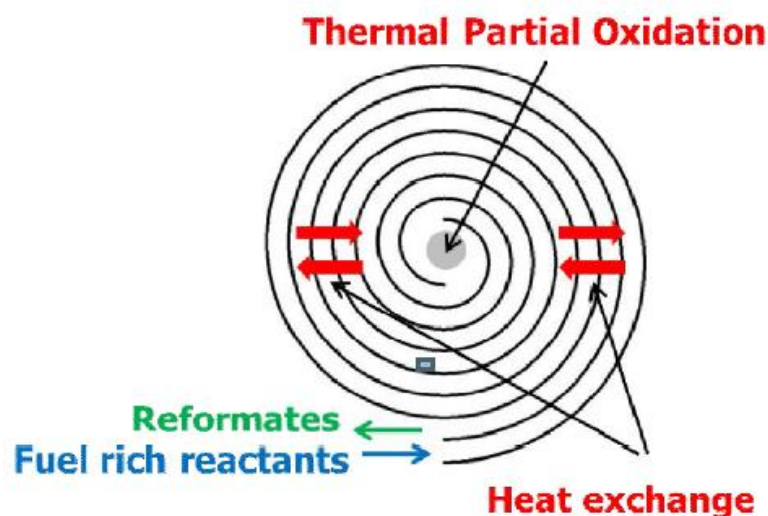


Figure 3. Schematic of a Swiss Roll Combustor

2 Experimental Setup

A 3.5-turn combustor was made with two Inconel sheets (0.05 mm thick) by rolling them manually. A constant channel width of 2.5 mm between adjacent windings was obtained by putting a temporary internal spacer (soft rubber strips 2.5 mm thick) between the two sheets. Ceramic adhesive (Cotronics Resbond 907GF) was then used to seal the end plate(s) which were made from ceramic board.

Figure 4 shows a schematic diagram of an experimental setup. Mass flow controllers connected to a data acquisition (DAQ) system are used to control the flow rates and the composition of the fuel-air mixture into the combustor. A K-type thermocouple is used to measure the temperature in the center. The exhaust is extracted using a syringe and analyzed with a SRI Gas Chromatograph (GC). An electrical igniter (Kanthal resistance wire) located in the center of the reactor was used for igniting the fuel mixture and was turned off once the combustion has started.

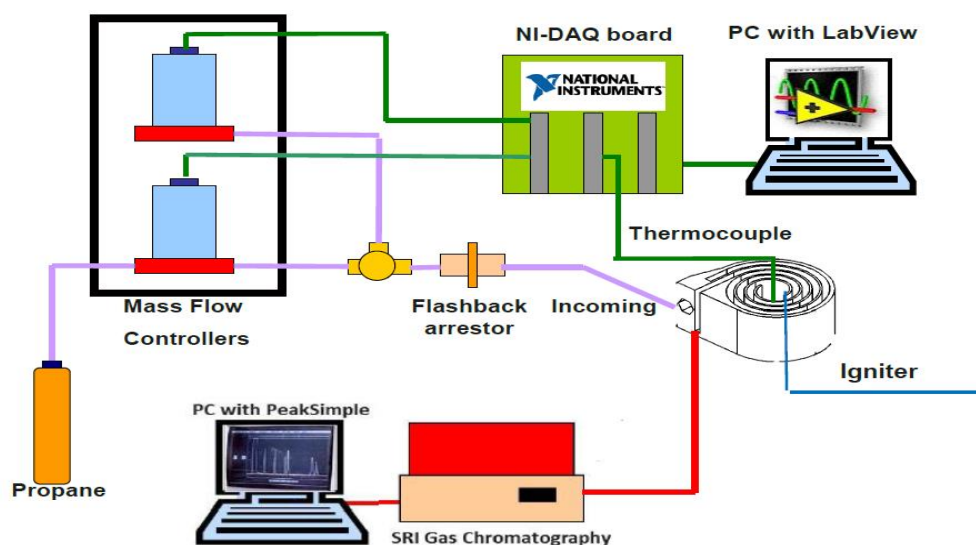


Figure 4. Experimental Setup

3 Results and Discussions

For the experiments, the baseline case was set to be 70cm/s flow rate ($Re \sim 120$) and exhaust gases output were recorded for various fuel-air mixtures. Figure 5 shows that the H_2 yield was around 11% for close to 8% fuel-air mixture and went down continuously on increasing the fuel %. The center temperature was close to 1150°K. Increasing the flow rate to 200cm/s ($Re \sim 330$) resulted in a temperature rise to around 1300°K. This is because increasing the flow rate results in a higher heat release to heat loss ratio and hence, provides more benefits of heat recirculation. This resulted in the rise of H_2 output to nearly 13%.

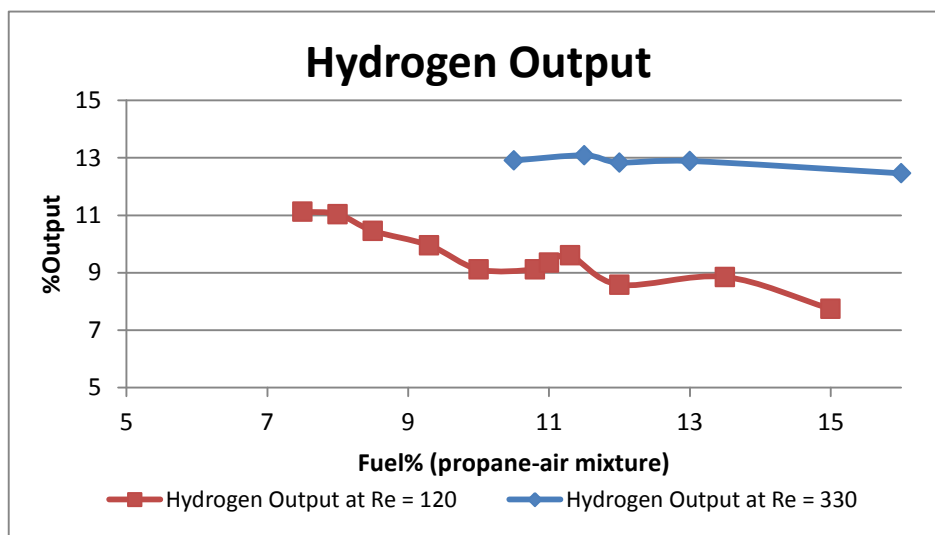
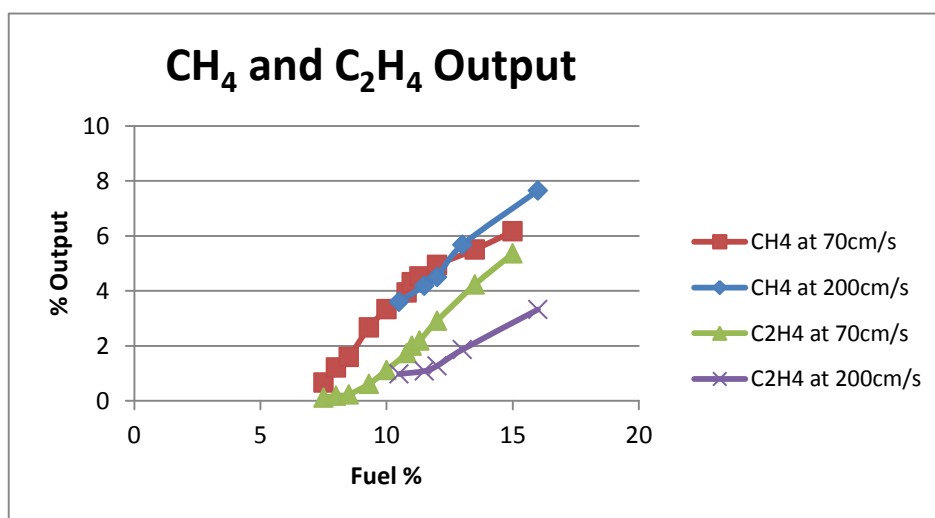


Figure 5. H_2 output at $Re = 120$ and $Re = 330$ for various fuel-air mixtures,

For both $Re = 120$ and $Re = 330$, less useful CH_4 and C_2H_4 were formed as well and their production increased as the fuel-air mixture was increased. However, their amount (particularly C_2H_4) dropped on increasing the Re to 330 (Figure 6), especially for richer mixtures.



. Figure 6. Methane and Ethylene output vs Propane-air mixture

4 Conclusion and Future Work

The effectiveness of a Swiss Roll combustor as a fuel reformer is demonstrated. Results suggest that for $Re = 120$, 8% fuel-air gives the best hydrogen output of around 11%. Increasing flow rate results in better reformer performance due to a higher heat generation to heat loss ratio – resulting in higher amount of useful hydrogen (upto 13%) and lower amount of less useful CH_4 and C_2H_4 . Testing at even higher flow rates may result in further improved performance.

Also, the products at the center show more hydrogen output but because of further reaction in the outlet channel, there is a drop in the output. To recover some of that hydrogen, a narrower outlet channel can be tried with same channel width on the inlet side in order to draw the products out faster for the same mass flow rate. Swiss Rolls with different sizes and number of turns are also to be tested in the future.

While the syngas yields have not as yet been optimized (as a function of mixture composition, flow conditions, reformer geometry), it is clear that the Swiss-roll reformer has several advantages. Not only is it compact, lightweight, non-catalytic, and, self-sustaining, it is also able to provide higher power density syngas output for portable applications.

References

1. Lloyd, S. and Weinberg, F., “A Burner for Mixtures of Very Low Heat Content,” *Nature*, 251, 47-49 (1974).
2. Jones, A., Lloyd, S., and Weinberg, F., “Combustion in Heat Exchangers,” *Proceedings of the Royal Society of London Section A*, 360, 97-115 (1978).
3. D. Dunn-Rankin, E. M. Leal and D. C. Walther, *Personal Power Systems*, *Progress in Energy and Combustion Science* 31 (2005), 422 – 465.
4. D. C. Walther and J. Ahn, *Advances and challenges in the development of power generation systems at small scales*, *Progress in Energy and Combustion Science* 37 (2011), 583-610.
5. K. Maruta, *Micro and mesoscale combustion: technology development and fundamental research*, *Proceedings of the Combustion Institute* 33 (2011), 125 - 150.
6. Roychoudhury, S., Lyubovsky, M., Walsh, D., Chu, D., Kallio, E., “Design and Development of a Diesel and JP-8 Logistic Fuel Processor,” *J. Power Sources*, 160, 510-513 (2006).
7. Chen, C., “Geometrical Effects on Swiss-roll Heat-recirculating Combustors,” PhD Thesis (2011).