Sub Topic: Micro-Combustion and New Combustion Devices

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An Innovative Volatile Organic Compound Incinerator

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Abstract: Volatile organic compounds (VOCs) are a byproduct of many processes across industrial sectors. Instead of venting VOCs to the atmosphere, many industries simply use flares, with supplemental fuel, to burn the waste. However, recent environmental regulations limit the amount of combustion products that can be vented to the atmosphere by incineration devices. A novel combustion device was developed to incinerate waste VOC streams with reduced harmful combustion products and supplemental fuel consumption. The device, termed a "Swiss-roll" incinerator, embeds a combustion chamber inside of a spiral heat exchanger. The heat exchanger recovers heat from the combustion exhaust stream to the premixed inlet reactant stream, thus increasing the adiabatic flame temperature of the combustion reaction and extending the flammability limits of the fuel. With efficient heat recuperation, a combustion reaction is stabilized at ultra-lean, super-adiabatic conditions, resulting in reduced supplemental fuel consumption and harmful emissions. In this work, a Swiss-roll incinerator was tested and ultra-lean combustion with reduced emissions was successfully demonstrated. The experimental results and potential applications for the Swiss-roll incinerator are discussed.

Keywords: Swiss-roll, Incinerator, Heat Recuperation, Volatile Organic Compounds

1. Introduction

In many industrial processes, such as natural gas storage or landfill biogas collection, there are waste volatile organic compounds (VOCs) that must be handled according to specific environmental guidelines, as defined by the Environmental Protection Agency (EPA), due to their ability to react with NOx to produce ozone, a known component of smog. Some recent research has focused on methods to recover waste VOCs for reuse [1], but more often the VOC-laden streams are incinerated using a flare or thermal oxidizer, with strict regulations on the resulting combustion emissions, for simplicity and economic reasons. However, these combustion processes require supplemental fuel if the chemical enthalpy of the waste VOC stream is below the lean flammability limit. Furthermore, non-premixed incineration systems operating at high temperature are prone to thermal NOx formation, which may be harmful for the environment. The fuel expense and environmental impact can be reduced if incineration systems were designed to address these specific challenges.

A unique heat recuperating combustor, termed a "Swiss-roll", can use efficient heat recuperation to reduce supplemental fuel consumption and emissions. The Swiss-roll combustor was first proposed by Dr. Felix Weinberg in 1974, and many studies since have demonstrated its unique performance capabilities [2-7]. Specifically, the Swiss-roll transfers thermal energy from the combustion reformate to the inlet reactants, raising the total enthalpy of the inlet stream, using a spiral heat exchanger, Figure 1A. With this excess enthalpy, the inlet reactants can self-sustain combustion in the center of the Swiss-roll at super-adiabatic conditions for a given equivalence ratio, as shown in Figure 1B. Since the reactants gain excess enthalpy from the reformate, they have sufficient thermal energy to combat heat losses for smaller chemical enthalpy inputs. In other words, the excess enthalpy reaction extends the flammability limits of the fuel and enables ultra-lean, self-sustained combustion, minimizing the amount of supplemental fuel needed to incinerate fuel-lean waste VOC streams. Also, the combustion temperatures of the ultra-lean, excess enthalpy reaction are much lower than typical non-premixed combustion reactions. At reduced temperatures, the thermal NOx formation time scale is increased and the exhaust does not have sufficient residence time in the hot combustion zone to form NOx.

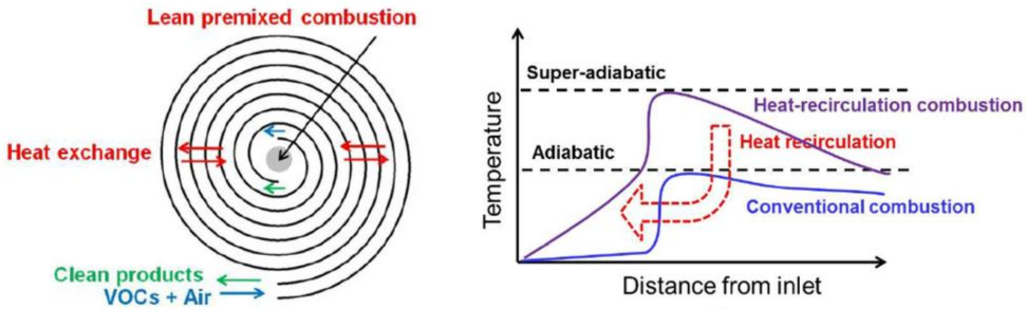

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Figure 1: (A) A schematic of Swiss-roll incinerator; (B) Temperature profiles of the combustor with and without heat recirculation.

2. Methods / Experimental

In this work, a large-scale prototype Swiss-roll was designed, fabricated, and tested to characterize the combustor for waste VOC incineration. Figure 2A shows the final prototype which was roughly 11” in diameter by 12” tall. The 3.5” diameter center combustion zone was defined by the innermost turns of the spiral heat exchanger as shown in Figure 2B. The spiral heat exchanger had roughly 3.5 turns with a 1/2” channel width for inlet and outlet spirals. The channels in the Swiss-roll were sealed using a ceramic blanket and a clamping force provided by the peripheral bolts. In addition, a metal honeycomb structure insulated the top and bottom faces of the Swiss-roll to prevent thermal losses.

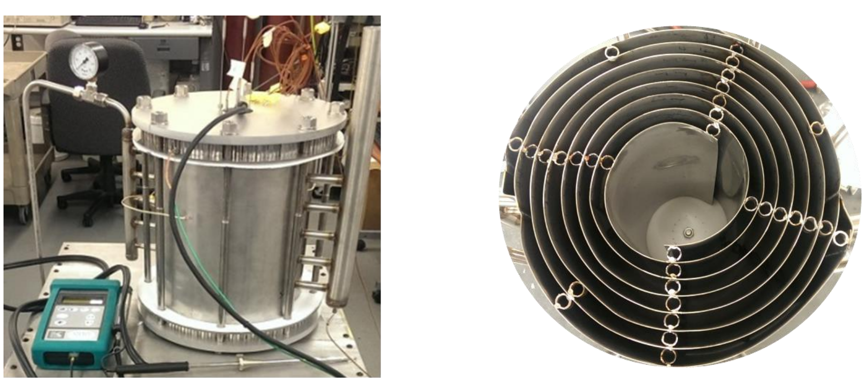

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Figure 2: (A) The fully assembled Swiss-roll incinerator prototype. (B) A cross-sectional view of the Swiss-roll incinerator showing the spiral heat exchanger and combustion zone.

Figure 3 shows a schematic of the experimental setup used to test the Swiss-roll incinerator. Combustion air and gaseous fuel were delivered to the Swiss-roll inlet spiral in precise quantities via mass flow controllers, controlled by LabVIEW software. A flashback arrestor was mounted directly after the fuel mass flow controller to prevent a flame from propagating back to the fuel source. For propane fuel, the inlet reactants were ignited with a diesel engine glow plug. Fuels that need more energy to ignite, such as methane, required a propane pilot flame. While the Swiss-roll was operating, strategically placed thermocouples measured the temperature at various points of interest and the measurements were displayed in real-time using LabVIEW software. The exhaust gas composition was measured using a portable KANE flue gas analyzer and a gas chromatograph.

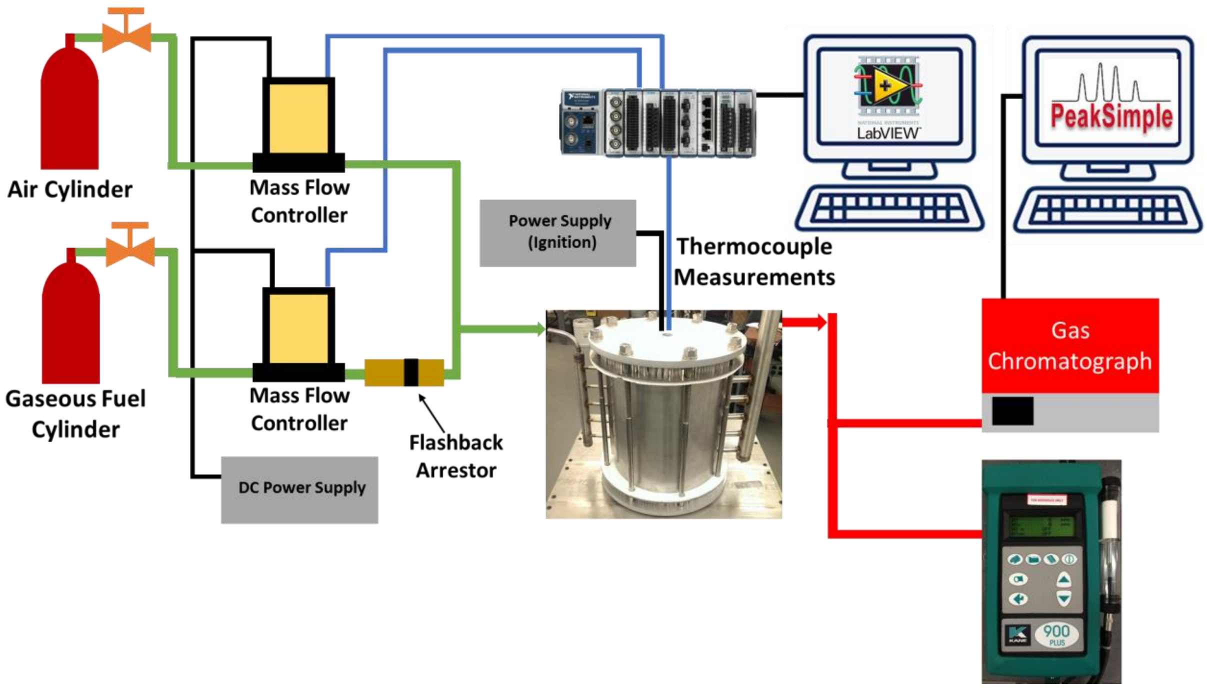

Figure 3: Schematic of experimental test setup used to test the Swiss-roll incinerator.

The Swiss-roll incinerator was tested repeatedly at steady-state for different flow rates to determine the lean flammability limit and subsequent emissions. Propane and simulated landfill biogas fuel, 55% methane and 45% carbon dioxide, were used for testing. For each test, a thermal profile of the incinerator showed the temperature of various parts of the Swiss-roll during operation. The thermal profile indicated key stages during the test cycle such as start-up, steady-state operation, and reaction extinction. For different flow rates, the lean flammability limit was determined by decreasing the fuel percentage until the temperature readings from the center thermocouples drastically dropped or the CO levels began to rise significantly, indicating incomplete combustion. The portable flue gas analyzer collected real-time measurements of oxygen percentage, carbon dioxide percentage, carbon monoxide emissions, and NOx emissions. A more in-depth flue gas composition was provided by the gas chromatograph. The important test metrics pertaining to the flue gas composition were the fuel percentage present and the NOx emissions, both of which were directly measured. The NOx emissions were further characterized in more transparent units by converting the part per million measurement to nanograms of NOx per joule of chemical enthalpy input using Eq. 1

$$NO_x \text{ emissions (ng/J)} = (C_{ppm} \cdot \rho \cdot V_{out} \cdot 10^{-9})/(10^{6} \cdot 60 \cdot E_{in}) \quad (1)$$

where C_{ppm} is the NOx measurement from the combustor in volume parts per million (ppm), ρ is the density of NOx in g/L, V_{out} is the volume flow rate of the exhaust gas leaving the Swiss-roll in L/min, and E_{in} is the chemical enthalpy input from the fuel in Watts (W).

3. Results and Discussion

The Swiss-roll incinerator met performance expectations during testing by self-sustaining, ultra-lean combustion in the center of the Swiss-roll with low NOx emissions. Figure 4 shows the temperature, total inlet flow rate, and inlet fuel percentage versus time during an experiment with propane fuel. At startup, the first 1000 seconds, the diesel glow plug was heating up to ignite the reactants flowing at 50LPM with 3.0% propane. At around 1500 seconds, the flow ignited and entered unsteady operation while the Swiss-roll heated up in order to self-sustain the reaction. Once the Swiss-roll was self-sustaining, the glow plug was turned off. As the Swiss-roll continued to heat up, the combustion reaction could propagate into the inlet channel if the flame speed was higher than the inlet reactant speed. This phenomenon was observed from 2500 to 3000 seconds as the thermocouple mounted on the inlet wall heated up while the center thermocouples slightly decreased in temperature. While the reaction can stabilize in the inlet channel, this position is not ideal since the flow speed through the channel is quite high and the reaction residence time in that region is short. To push the reaction to the center of the Swiss-roll, the flow speed of the reactants in the channel must be higher than the flame speed associated with the combustion reaction. The reactant flow speed can be increased by increasing the total volume flow rate entering the Swiss-roll. Also, the flame speed of the reaction can be reduced by decreasing the equivalence ratio to reduce the flame strength. By using these two techniques, the reaction eventually became self-sustained in the center combustion zone at around 6000 seconds. At this point, the Swiss-roll reached steady-state operation and a lean limit test was conducted by adjusting the volume flow rate to the desired set point and slowly reducing the fuel percentage until the reaction extinguished.

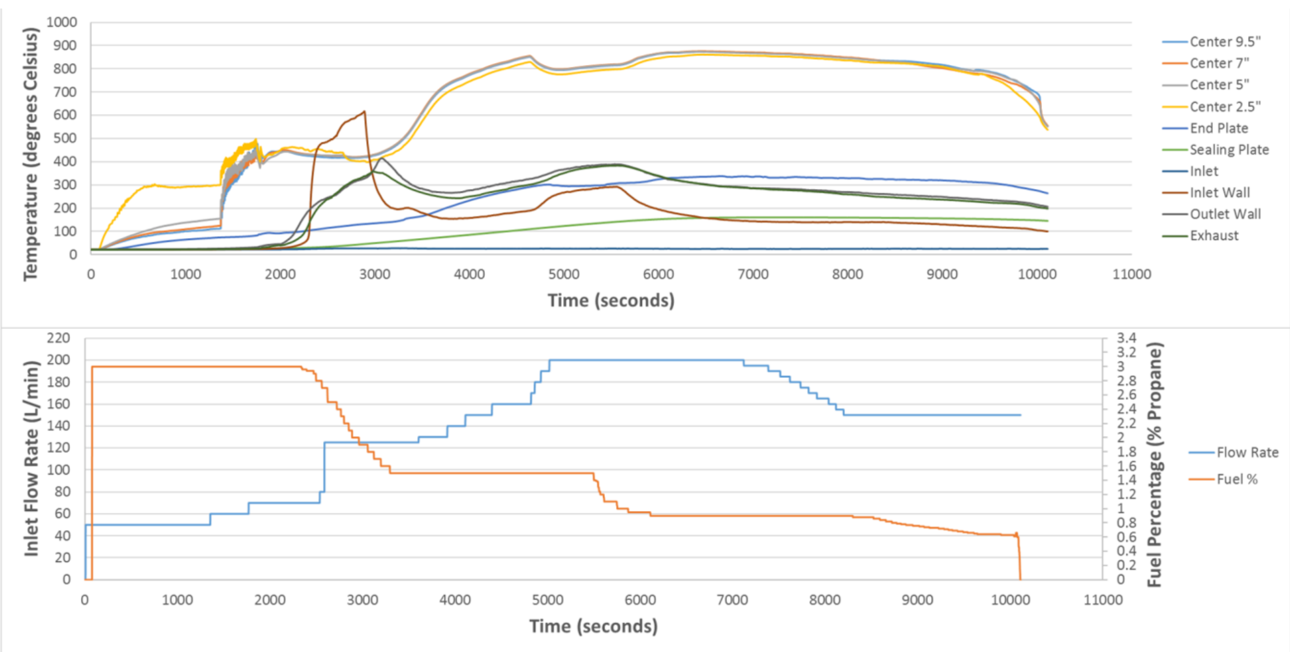

Figure 4: A thermal profile of the Swiss-roll during a propane lean limit experiment.

Figure 5 shows the lean operating limits for the Swiss-roll incinerator using propane and biogas fuel for a range of flow rates. As predicted, the Swiss-roll effectively extended the lean flammability limits of the fuel and self-sustained combustion below the conventional lean limit, typically equivalence ratio (Φ) ≈ 0.5 for hydrocarbon fuels, thus reducing the amount of supplemental fuel input required. For propane fuel, the data shows a slight trend upwards in equivalence ratio for increasing volume flow rates, this phenomenon is expected because the flame speed must be increased as the inlet flow speed is increased to prevent extinction due to blow-out. In contrast, the biogas lean limit curve shows a slight decrease in equivalence ratio as flow rate increases. The experimental testing did not include high enough flow rates to capture the blow-off mechanism for simulated biogas fuel.

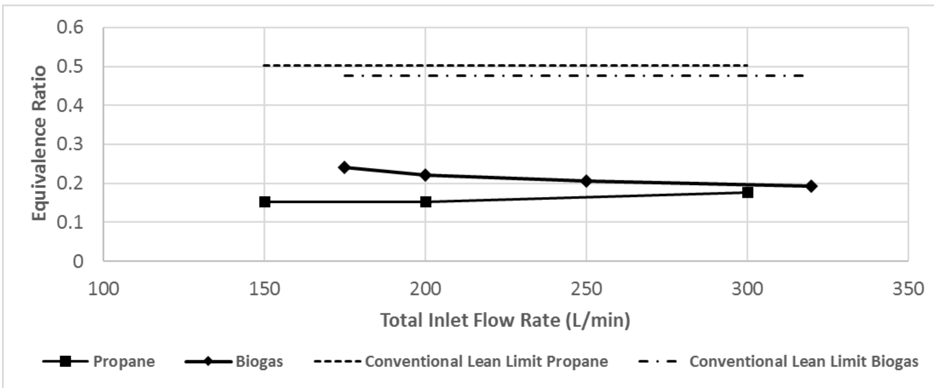

Figure 5: Lean Limit Plot

The flue gas samples analyzed by the gas chromatograph did not show any propane in the exhaust when the channels were adequately sealed, as shown in Figure 6. However, the ceramic gasket seal was eventually compromised and channel leaking did occur as evidenced by consistent percentages of fuel measured in the exhaust during operation. To reach the high destruction efficiency potential of the Swiss-roll, the channels must be adequately sealed. In addition, the Swiss-roll incinerator did not produce high levels of NOx as evidenced by the portable flue gas analyzer. The NOx level on the flue gas analyzer typically read between 0-1 ppm NOx during steady-state operation, with an analyzer resolution of 1 ppm. Using Eq.1 and assuming realistic operating parameters, a NOx density of 2.05 g/L, an outlet volume flow rate of 391 L/min, and a chemical enthalpy input of 2294 W, the Swiss-roll only emits 5.84 ng/J of NOx for every part per million.

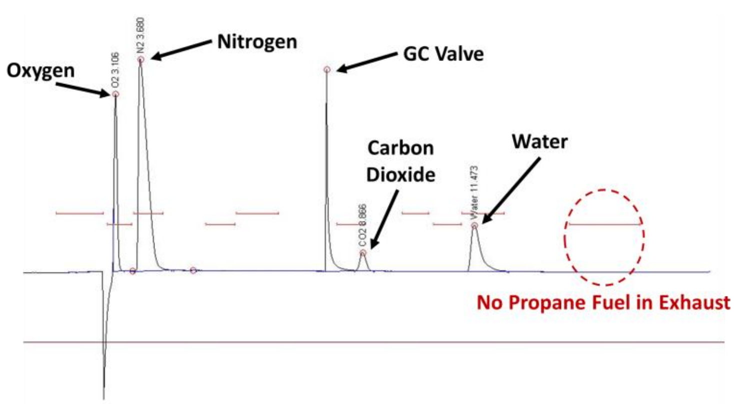

Figure 6: A gas chromatograph result showing complete combustion and high destruction efficiency.

4. Conclusions

This Swiss-roll VOC incinerator proved successful during this development effort. A large-scale Swiss-roll combustor was designed, fabricated, and testing using propane and simulated landfill biogas fuel. The experimental results show the flammability limits of the fuel are significantly extended, proving the Swiss-roll incinerator's advantage of reduced supplemental fuel consumption. Also, the flue gas from the incinerator contained ultra-low NOx at steady-state showing the clean combustion capabilities of the Swiss-roll. With further development efforts, the Swiss-roll combustor is a promising application for waste VOC incineration.

5. Acknowledgements

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6. References

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