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 the raw waste to the atmosphere, many industries must first use incineration systems to convert the VOCs to less harmful combustion products. However, in order to ensure a high degree of VOC destruction, incineration systems often require a significant amount of supplemental fuel added to the waste stream. In this work, a novel combustion device was developed to incinerate waste VOC streams with reduced supplemental fuel consumption. The device, termed a “Swiss-roll”, 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 addition, the preheated reactants enable the combustion reaction to be stabilized at a temperature where the NOx emission is negligible. In this work, a Swiss-roll incinerator was fabricated and experimentally tested to demonstrate self-sustained, ultra-lean incineration with low harmful emissions. The experimental results and potential applications for the Swiss-roll incinerator are discussed.

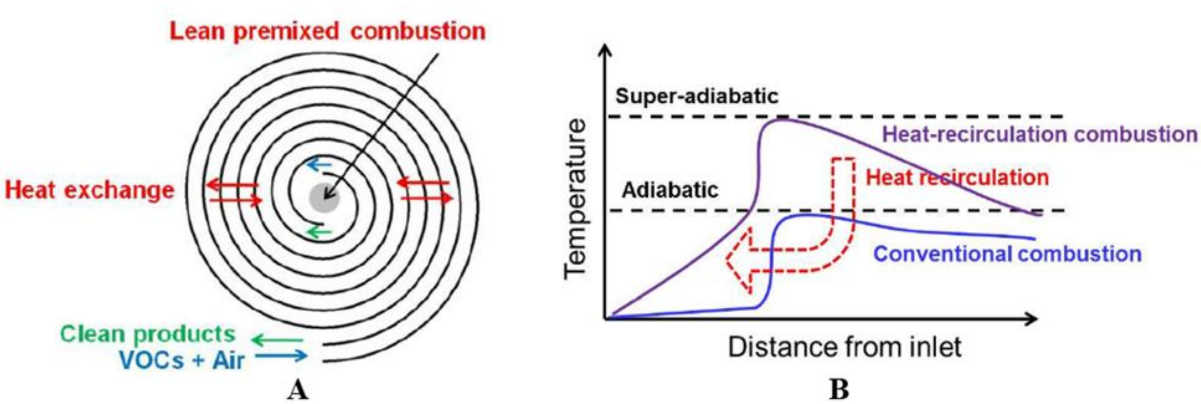
INTRODUCTION

In many industrial processes, 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, 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.[1] 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 common approach to reduce supplemental fuel consumption, is to use heat recuperation to extend the flammability limits of the original VOC-laden waste stream. Many commercial incineration systems, such as regenerative thermal oxidizers (RTOs), recuperative thermal oxidizers (RECUPs), or catalytic thermal oxidizers (CATOXs), employ high temperature heat exchangers in an attempt to recycle any wasted thermal energy. RTOs are a popular choice for incineration systems due to their high thermal efficiency, but they are often limited to high flow rate operation due to the large capital and maintenance costs associated with the flow cycling required to regenerate the ceramic heat exchanger beds. RECUPs do not have oscillating flow patterns, which make them more economical for low flow rate applications, but the thermal efficiency of the system is limited since the heat exchanger is not directly integrated with the combustion chamber. CATOX systems compete with RECUPs in low flow rate incineration applications, but the maintenance and deactivation challenges associated with catalysts limit the capabilities of the systems. For low flow rate applications, there is a need for highly thermally efficient incineration systems that are not subject to the maintenance, operational, or capital costs associated with current technologies.

A unique heat recuperating combustor, termed a “Swiss-roll”, can use efficient heat recuperation to reduce supplemental fuel consumption and emissions by directly integrating the combustion zone inside the heat exchanger. 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 exhaust 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.

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

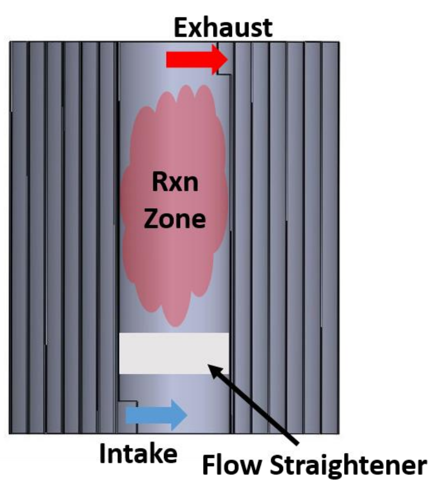


Since the reactants gain excess enthalpy from the combustion products, they have sufficient thermal energy to build a stable combustion zone with smaller chemical enthalpy (fuel) inputs. In other words, the excess enthalpy reaction extends the flammability limits of the fuel and enables ultra-lean, self-sustained combustion, minimizing the amount of supplemental fuel needed to incinerate fuel-lean waste VOC streams. Also, the combustion temperatures inside the Swiss-roll are lower than typical combustion temperature without preheated reactants. 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. The Swiss-roll design is extremely thermally efficient since the reaction zone, which is most prone to heat loss, is surrounded by the heat exchanger. The compact, thermally efficient design, with no moving parts, makes the Swiss-roll potentially feasible for waste gas incineration applications.

EXPERIMENTAL METHODS/MATERIALS/PROJECT APPROACH

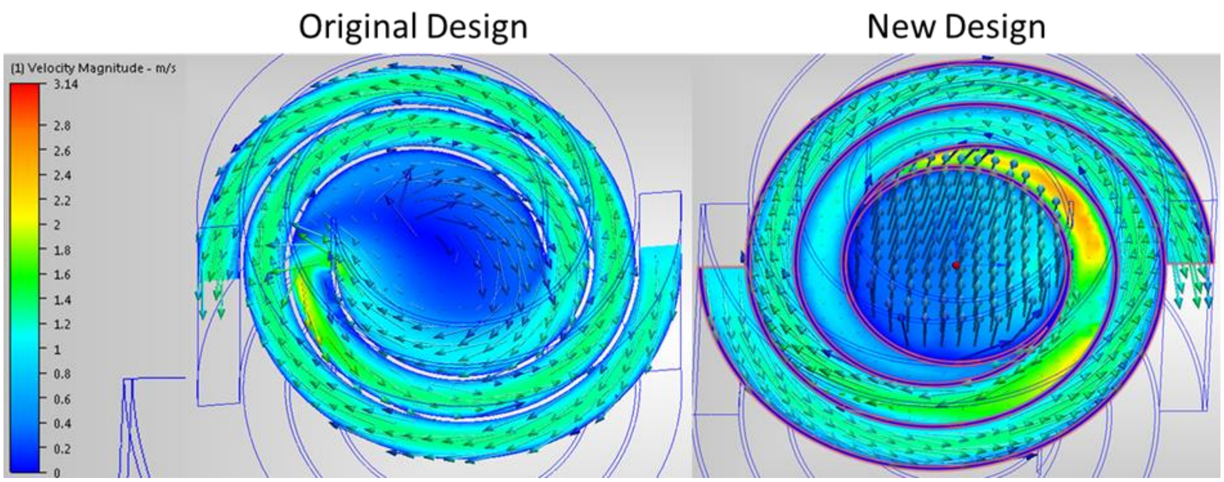
As a proof of concept exercise for the Swiss-roll incineration technology, a prototype combustor was designed, fabricated, and experimentally tested at the Advanced Cooling Technologies, Inc. (ACT) facility. The prototype constructed in this work includes a unique center combustion zone in an attempt to improve upon conventional Swiss-roll designs. A standard Swiss-roll's combustion zone is defined by the open region in the center of the device, where the inlet channel ends and the exhaust channel begins. In this design, both the inlet and exhaust channel are open to the combustion zone along the entire height of the channel, leaving a large recirculation zone in the center of the device due to the swirling flow mechanics. While this design is easier to construct, ideally the flow would utilize the entire combustion zone volume, without a recirculation zone, to reduce flow velocity and maximize residence time. With this in mind, ACT redesigned the center combustion zone to operate with a more ideal, plug flow reactor type, flow pattern. The innovative design forces preheated reactants from the inlet channel to enter the combustion zone at one end, turn 90 degrees to flow axially along the reactor height, and the leave center combustion zone at the opposite end as shown in, as shown in Figure 2. When this flow pattern in used in conjunction with a flow straightener, such as a metal mesh screen, the reacting flow more evenly fills the entire volume of the combustion zone.

Figure 2. Schematic of the Swiss-roll combustion zone design to improve uniformity in the reacting flow.



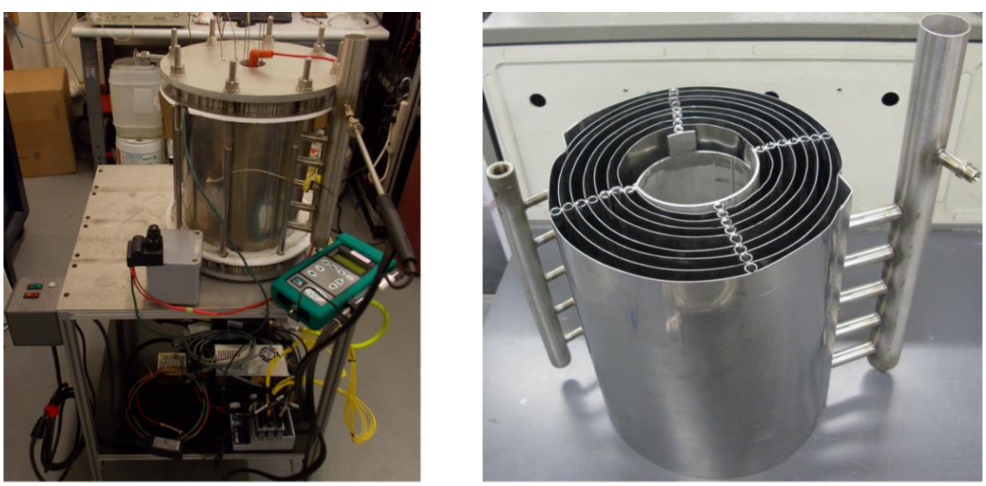
Two cold flow CFD models, with no chemical reaction or heat transfer, were generated by ACT to simulate the performance of the new center design and compare the flow pattern to the standard design. The results in Figure 3, validate the predicted theory as the center velocity vectors in the new design are more uniform in magnitude and direction than the conventional design.

Figure 3. Non-reacting CFD flow modeling of the Swiss-roll designs to compare flow patterns. The center combustion zone flow uniformity is improved in the new design.



ACT incorporated the new center design into a working prototype Swiss-roll incinerator for experimental testing. The entire prototype, Figure 4A, stands roughly 15.5 inches tall and is 14 inches in diameter. The device is comprised of a cylindrical center combustion zone, about 4 inches in dimeter by 11.75 inches tall, surrounded by a 3.5 turn, countercurrent spiral heat exchanger with 3/8-inch-wide by 11.75 inches tall channels, Figure 4B.

Figure 4. (A) The entire experimental test bench, including the fully assembled Swiss-roll. (B) The Swiss-roll incinerator body, without sealing/insulating layers, fabricated by ACT.



A **B**

The top and bottom faces of the device body are sealed and insulated using successive layers of wire-reinforced ceramic blanket, ceramic board, stainless steel plate, stainless steel honeycomb, and an aluminum plate. Threaded rods are inserted through alignment holes on the periphery of the aluminum plates to clamp the layers together and provide an airtight seal between the channels.

Figure 5 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. Using propane fuel, the inlet reactants were ignited with a spark plug. While the Swiss-roll was operating, strategically placed thermocouples measured the temperature at various points of interest, Figure 6, 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 5. A schematic of the experimental setup used to test the Swiss-roll incinerator prototype at ACT.

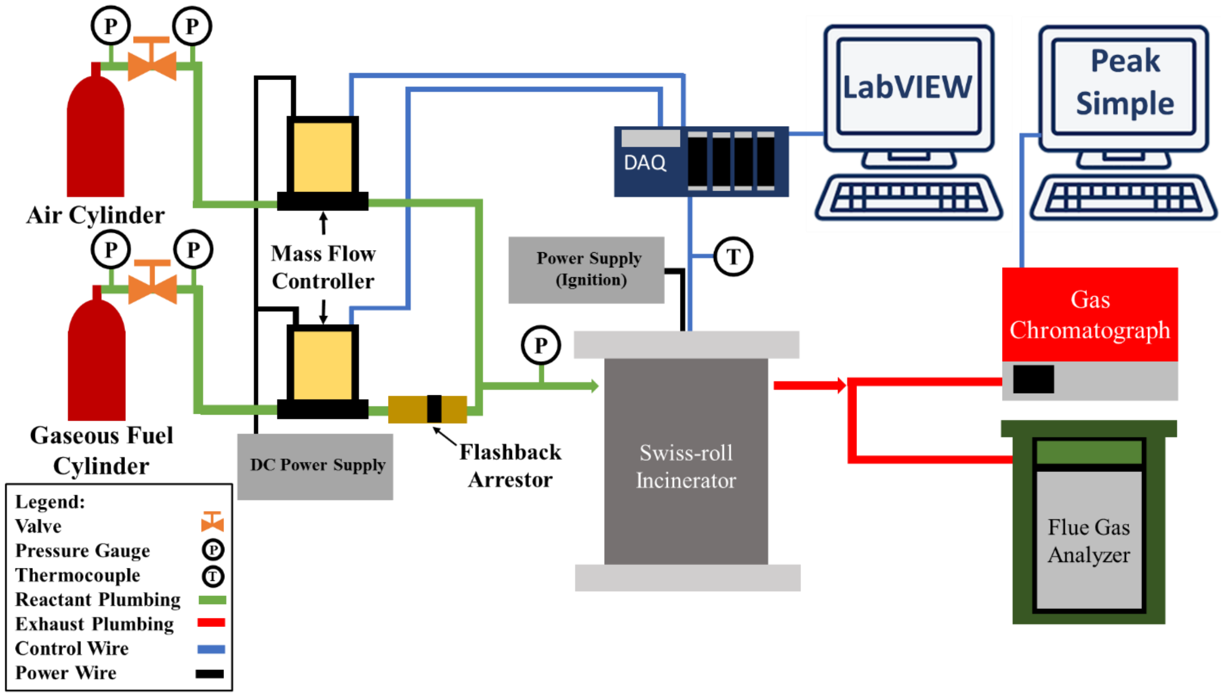
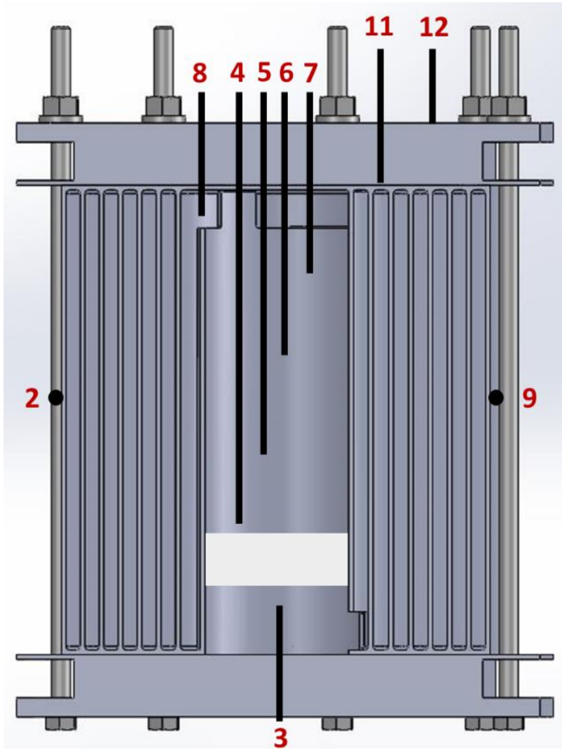


Figure 6. A schematic of the thermocouple placement during experimental testing of the Swiss-roll incinerator prototype.

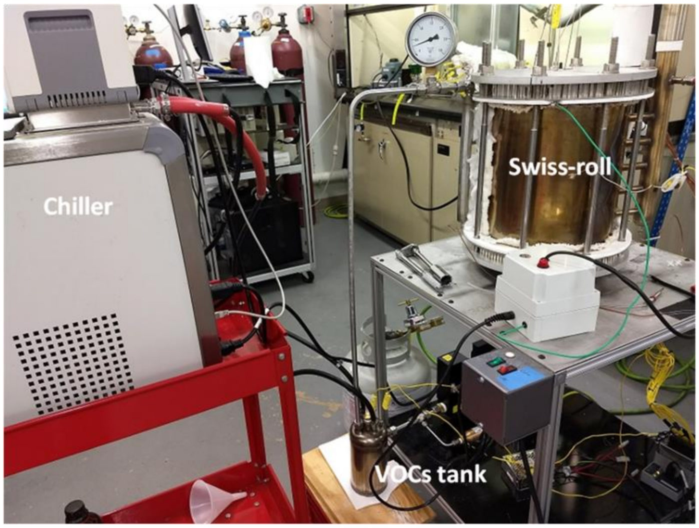


Experimental testing of the prototype focused on completely characterizing the device operational range to set a baseline for sizing the Swiss-roll incinerator. Specifically, the lean operating limit, destruction efficiency, and emissions were evaluated up to 800 SLPM (28 SCFM) total process flow rates.

To test the lean operating limit, the combustion reaction was ignited in the Swiss-roll center using the spark plug ignition system. Once ignited, the reaction was completely self-sustained by its own heat release from the chemical reaction and the thermal energy recycled to the reaction zone by the heat exchanger. A stronger mixture is used for ignition. As the device heated up to reach steady state, the reactant fuel percentage was consistently lowered to match the amount of amount of energy that was recuperated. At steady state, the flow rate was set to the desired operating condition. For a given constant total flow rate (air and fuel) the lean limit was found by slowly reducing the fuel percentage until the reaction extinguished, or the carbon monoxide level began to rise significantly. The lowest fuel percentage that could self-sustain a combustion reaction in the device, marked the lean limit operating condition for a given flow rate. Repeating this test procedure over a range of flow rates, created a lean limit operating curve for the device. During testing, the carbon monoxide and nitrogen oxide emissions were measured using a KANE flue gas analyzer to observe their respective trends across the lean operating limit of the device.

ACT measured the VOC destruction efficiency by adding toluene vapor to the inlet reactant stream using a temperature-controlled storage canister, Figure 7.

Figure 7. The experimental setup used to test the destruction efficiency of the Swiss-roll with toluene and propane supplemental fuel.



Liquid toluene, held at 10°C by a recirculating chiller, released vapor into the reactant stream, which passed through the vapor head space in the storage canister. The amount of toluene vapor injected can be assumed by the vapor pressure of toluene at a given temperature. Gaseous samples were taken from the inlet and exhaust manifolds of the Swiss-roll during operation and the gas composition was evaluated by a gas chromatograph using a flame ionization detector (FID). By making the rough assumption that the total number of moles in the system is conserved, the destruction efficiency was calculated using the ratio of toluene mole percentages between the exhaust and reactants.

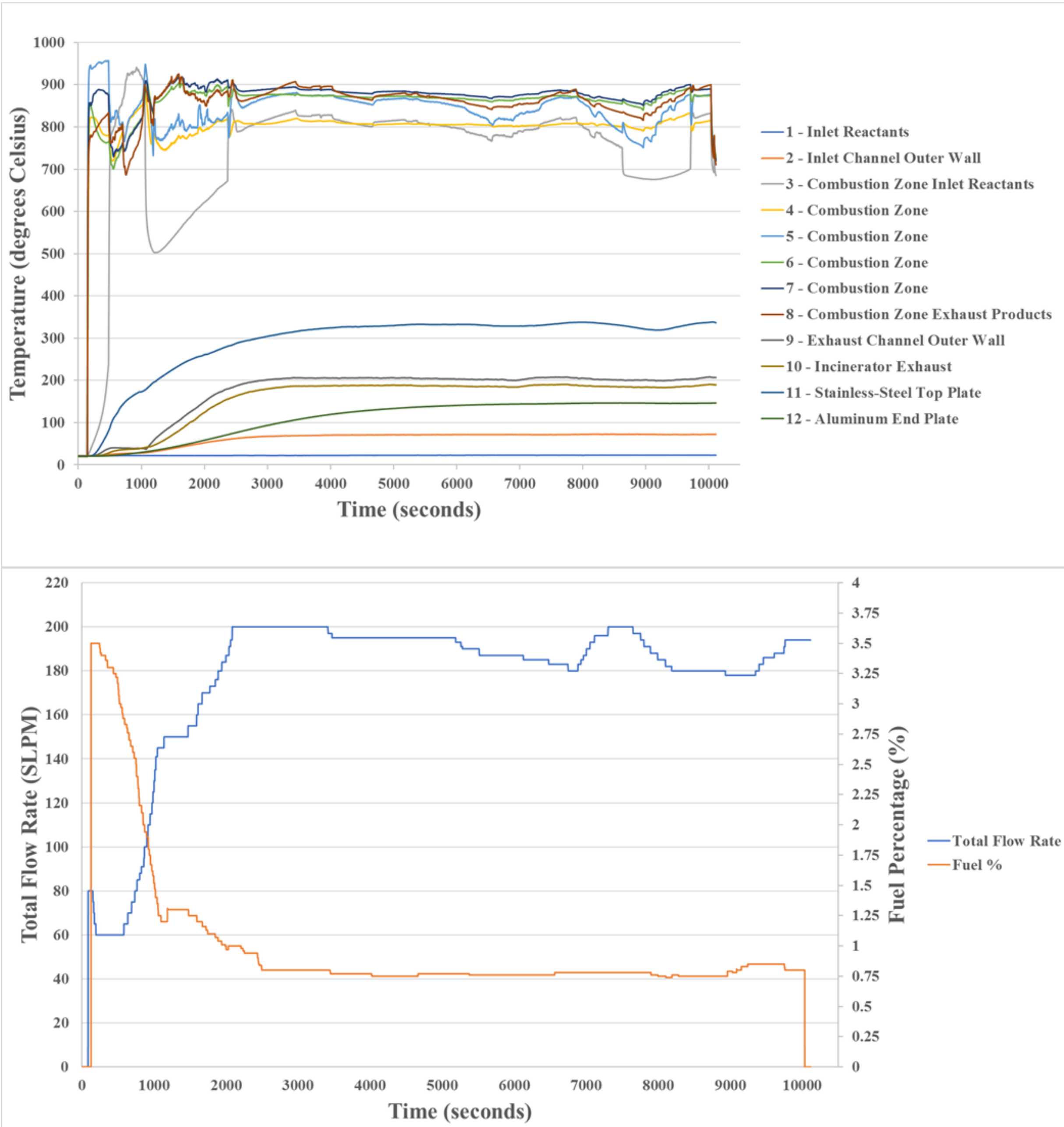
RESULTS AND DISCUSSION

The Swiss-roll incinerator prototype performed well during repeated testing using propane fuel, showing significantly extended flammability limits, high destruction of toluene VOCs, and low harmful emissions. The quantitative results for each test class are discussed in detail in the following sections.

Thermal Profile

The temperature of the combustion zone is a key performance metric for the Swiss-roll incinerator since the reactants will need sufficient residence time in a high temperature region in order to be completed destroyed. The thermocouple arrangement, shown previously in Figure 6, provided valuable thermal profile data for the device during testing. Figure 8 shows the thermal profile from a representative experimental test of the Swiss-roll prototype, proving self-sustained high-temperature combustion. At steady state, the center combustion zone was steady at nearly 900°C, with the inlet reactants preheated to about 800°C, while only 0.77 vol% of propane was added to the 195 SLPM total flow rate. This example proves the Swiss-roll incinerator is capable of using efficient heat recuperation to self-sustain even with reactant flows of low heating value.

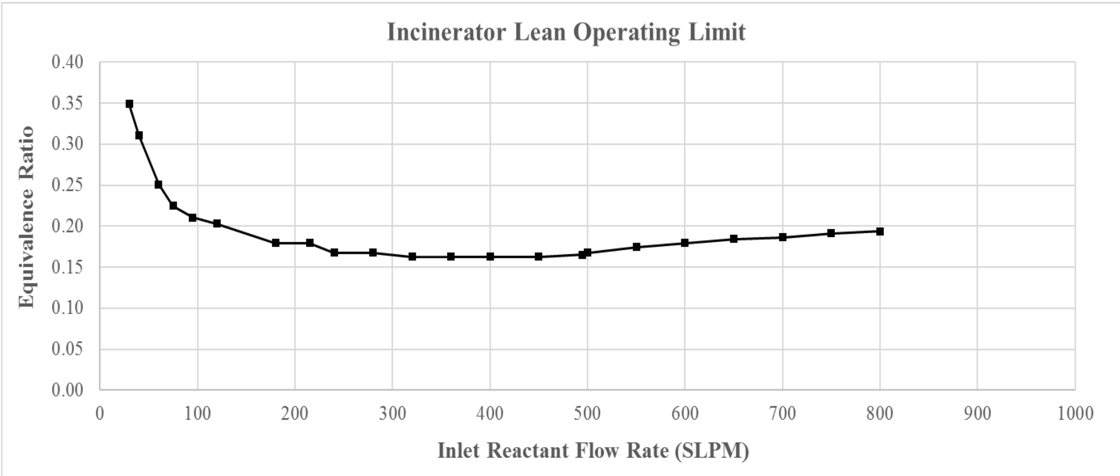
Figure 8. The thermal and flow profiles of the Swiss-roll incinerator during experimental testing.



Lean Operating Limit

Due to its high heat recuperation capability, the Swiss-roll incinerator is capable of significantly extending the flammability limit. The results of the lean limit testing are shown in Figure 9 in terms of equivalence ratio versus inlet volume flow rate**.**

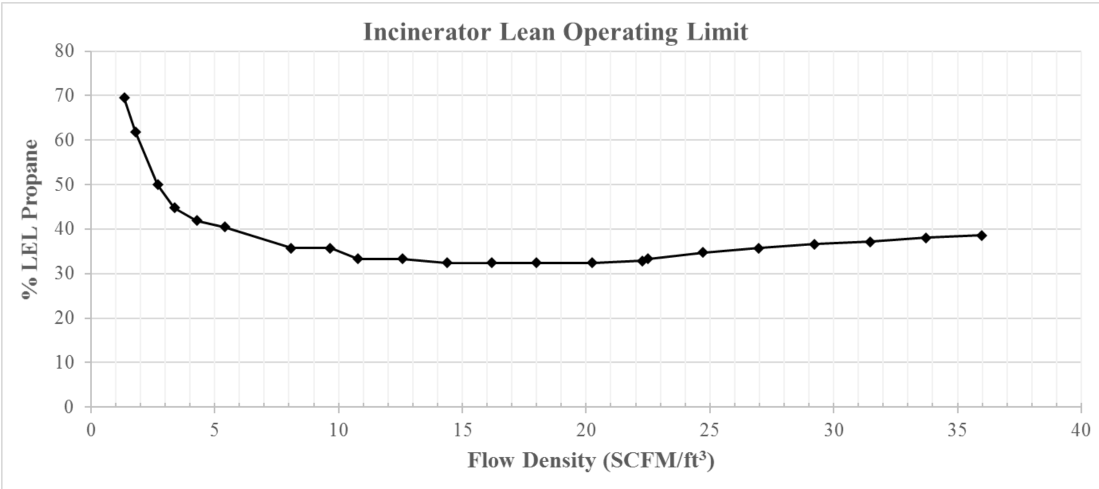
Figure 9. Lean operating limit for the prototype Swiss-roll incinerator with the lean limit significantly extended when compared to previous designs.



For the majority of the operating range, the Swiss-roll self-sustained combustion below equivalence ratio (ϕ) = 0.2, less than half the conventional lean limit for propane fuel of roughly ϕ = 0.5. The lean limit curve followed a parabolic shape, similar to findings in the previously referenced research, since more fuel (higher equivalence ratio) is required at the extremes of the range to combat heat loss (low flow rate regime) and the blow-off limit (high flow rate regime). However, the blow-off limit was not reached in the tested operating range evidenced by the gradual, instead of sharp, increase in equivalence ratio as the inlet flow rate increases. This phenomenon can be attributed to the improved end-to-end center design which reduced the velocity, and Reynolds number, of the flow in the center combustion zone, allowing the device to operate a higher flow rates than its predecessors without reaction extinction. This result is significant because for commercial applications it is desirable to process the largest flow of waste VOCs possible while still meeting emissions regulations, which means the blow-off limit in the Swiss-roll incinerator will control the process flow rate the device can handle.

Since most applications could require much higher flow rates (> 1000 SCFM), it is important to estimate the size and performance for Swiss-roll incinerators that are scaled-up even further. Based on the previous scalability study, similar lean limit behavior is expected for Swiss-rolls of geometrical similarity but different scale.[6] The lean limit data here is presented in more practical terms by scaling the percentage of the lean explosive limit (% LEL) with specific flow rate, which is the inlet flow rate divided by the incinerator total volume. Figure 10, shows the lean limit data expressed in these terms. By using the specific flow rate, the required incinerator size can be predicted for a given application if the total inlet process flow conditions are known. For example, if a proposed application required 1000 SCFM of total inlet flow ACT could choose an operating point on the plot in Figure 10, and calculate the approximate incinerator volume necessary for the application. In that case, if the operation point was chosen to be 35 SCFM/ft^3 at roughly 39% LEL, the estimated incinerator volume would be 28 ft^3. Presenting the results in this way, will serve as a good initial design tool when evaluating the incinerator for new commercial applications.

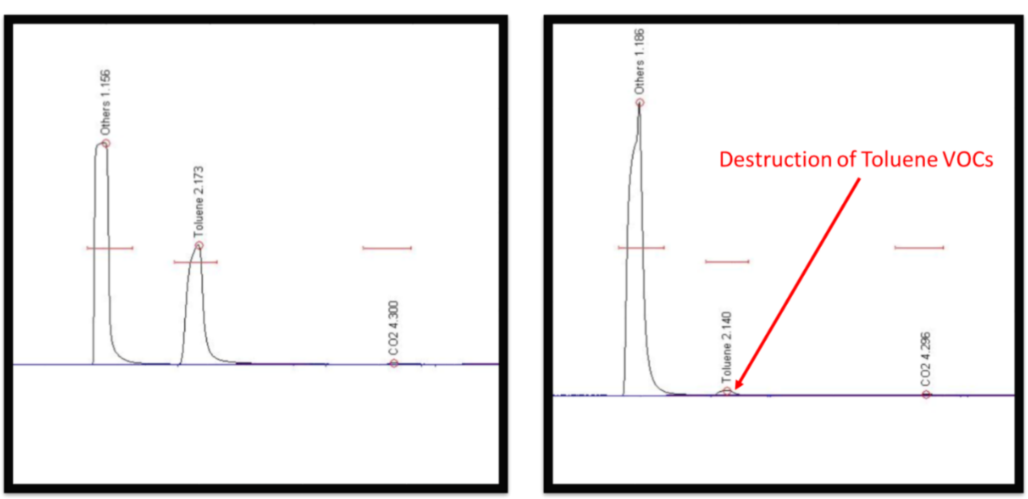
Figure 10. Lean operating limit presented in terms of % Lean Explosive Limit (LEL) vs. Flow Density to use as a prediction tool for future Swiss-roll product designs.



Destruction Efficiency

Toluene was used as a sample VOC to examine the destruction efficiency of the Swiss-roll incinerator. Due to toluene's high vapor pressure at room temperature, the liquid sample was cooled to 10°C. The resulting vapor pressure yielded an estimated 0.4 mol% of toluene vapor in the reactant stream. Experimental testing was performed at a 200 SLPM total reactant flow rate with 0.52 vol% supplemental propane fuel addition, while holding the liquid toluene temperature constant. At steady state, gas chromatograph samples were taken at the reactor inlet and exhaust along with ambient air samples to use as a control. The gas chromatograph results are shown in Figure 11 showing high toluene concentration before incineration, and very low concentration after treatment.

Figure 11. LEFT – GC sample taken upstream of the Swiss-roll incinerator indicating high toluene concentration. RIGHT – GC sample taken downstream of the Swiss-roll incinerator indicating low toluene concentration resulting from VOC destruction.



Using the calculated inlet toluene vapor mol% to scale the measured toluene peak in the exhaust, the resulting toluene composition was nearly 0.004 mol% after incineration. Assuming the number of moles in the system was conserved, a destruction efficiency of less than 99% is calculated to roughly estimate the waste VOC destruction performance. This result is comparable to current incineration technologies which vary in destruction efficiency from 90% to nearly 100% depending on the emission regulation required.

Emissions

Carbon monoxide was measured and recorded during testing to analyze combustion performance. Since carbon monoxide concentration is very low as an equilibrium product in complete combustion, measuring its emission from the device shows the completeness of the reaction. Because of this, ACT used the carbon monoxide measurement to identify the incinerator's lean limit during testing. An extremely high carbon monoxide level (> 100 ppm) is a good indication that the reaction is nearing extinction, even if the temperature has not begun to reduce drastically. Figure 12, quantifies the carbon monoxide emissions across the tested range of flow rates for the incinerator. The carbon monoxide emission at stable lean limit operating conditions was often near 25 ppm for the prototype device.

Figure 12. Carbon monoxide emissions from the 2nd Generation Swiss-roll incinerator prototype during lean limit testing.

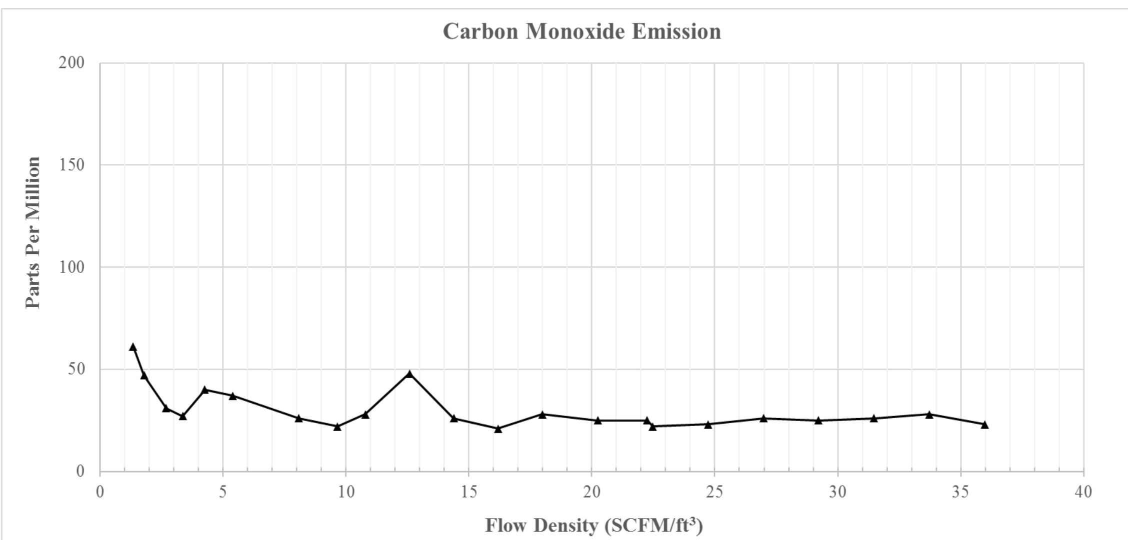
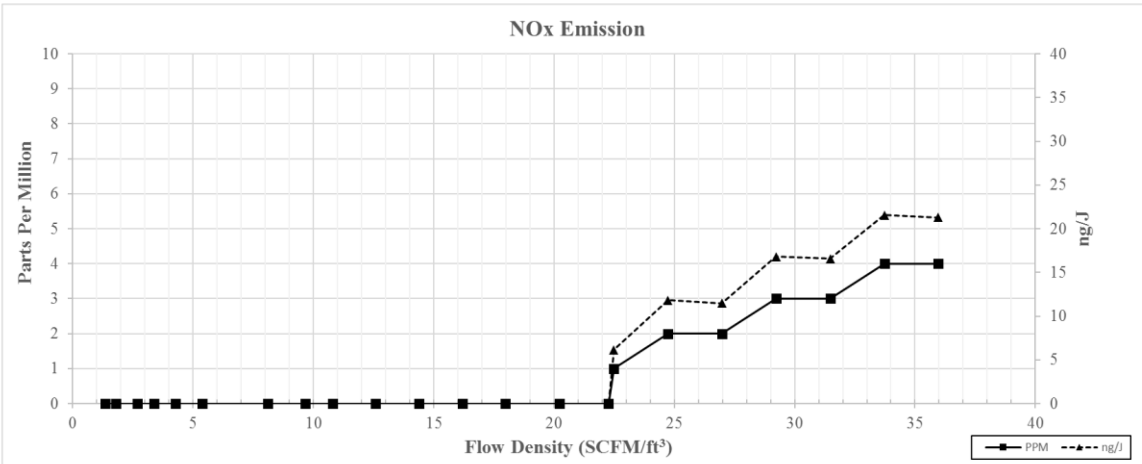


Figure 13, shows real NO_x emission data recorded at the lean operating limit in the second-generation scaled-up Swiss-roll prototype. For the lower part of the incinerator operating range, NO_x (NO and NO_2) was not detected by the KANE flue gas analyzer. The NOx analyzer was calibrated via the calibration gas before the testing. Since, the resolution of the measurement device is 1 ppm, the NO_x emission can be assumed to be between 0 and 1 ppm. Towards the upper end of the operating range, NO_x begins to be regularly detected by the flue gas analyzer due to the temperature rise from the increased chemical enthalpy input into the device. In this regime, the peak reaction temperature in local regions is large enough to create a small amount of NO_x. ACT estimates the NO_x emission to be slightly larger than 20 ng/J at the highest flow rate tested.

Figure 13. Nitrogen oxide emissions from the 2nd Generation Swiss-roll incinerator prototype during lean limit testing.



SUMMARY

A Swiss-roll incinerator prototype was designed, fabricated, and experimentally tested in this work. The results prove the innovative device can achieve extended flammability limits of the input fuel, high destruction efficiency, and low harmful emissions. These attributes make the Swiss-roll technology as ideal candidate for low flow rate incineration applications, where current technologies lack in thermal efficiency. While many previous studies have focused on small-scale applications for the Swiss-roll technology, where even small heat losses drastically impact combustion performance, this work proves the scalability of Swiss-roll and its applicability to large-scale applications such as waste gas incineration. This technology can be directly applied to any process which requires tight remediation of low-heating value waste VOC streams such as, but not limited to, chemical/pharmaceutical plants, landfills, or natural gas storage systems.

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KEYWORDS

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