Sub Topic: Coal, Biomass, and New Devices

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A "Scale-up" Swiss-roll Combustor and Its Application in Waste Gas Incineration

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Abstract: Waste Volatile Organic Compounds (VOCs) from a variety of processes can be incinerated, often with supplemental fuel, to convert the VOCs to less harmful combustion products before being vented to the atmosphere, to meet emission regulations. 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 to recover heat from the combustion exhaust stream to the premixed inlet reactant stream. With efficient heat recuperation, a combustion reaction is stabilized at ultra-lean, super-adiabatic conditions, resulting in reduced supplemental fuel consumption and harmful emissions. While Swiss-roll combustors are typically applied in small-scale combustion, this work emphasizes advantages even at larger scales, due to exceptional thermal efficiency and the associated fuel savings. In this work, a relatively large-scale prototype incinerator, roughly 1ft. tall by 1ft. in diameter, was designed, fabricated, and tested. Experimental results include promising scalability, a significant extension in the fuel's lean flammability limit beyond conventional limits, high destruction of toluene VOCs, and low carbon monoxide and nitrogen oxide emissions. The results of this work and potential commercial applications in waste VOC incineration are discussed in detail.

Keywords: Swiss-roll, Heat Recuperation, Volatile Organic Compound, Incineration

1. Introduction

In a variety of industrial processes, there are waste volatile organic compounds (VOCs) that can not be directly vented to the atmosphere due to their ability to react with NOx to produce ozone, a known component of smog. Some recent research has focused on innovative vapor recovery units (VRUs) to recover waste VOCs for future reuse [1]. In applications where vapor recovery is not feasible or economical, the VOC-laden streams are simply incinerated using a flare or thermal oxidizer, with strict regulations on the resulting combustion emissions. 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 is a harmful environmental pollutant. The fuel expense and environmental impact can be reduced if incineration systems are designed to address these specific challenges.

A unique combustor, termed a "Swiss-roll", embeds a combustion chamber inside of a spiral heat exchanger to extend the flammability limits of the input fuel using efficient heat recuperation. The Swiss-roll combustor was first proposed by Dr. Felix Weinberg in 1974, and many studies since have demonstrated its unique performance capabilities [2-8]. Specifically, the Swiss-roll transfers thermal energy from the combustion exhaust to the inlet reactants, raising the total enthalpy of the inlet stream (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.

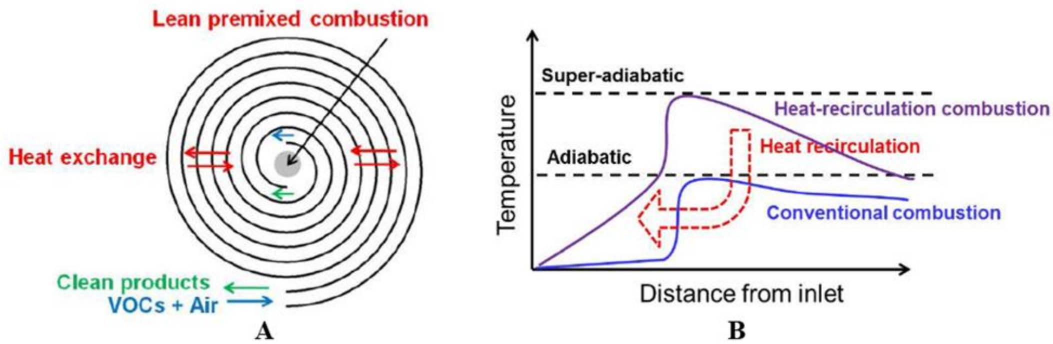


Figure 1: (A) A schematic of Swiss-roll incinerator. (B) Temperature profiles of the combustor with and without heat recirculation.

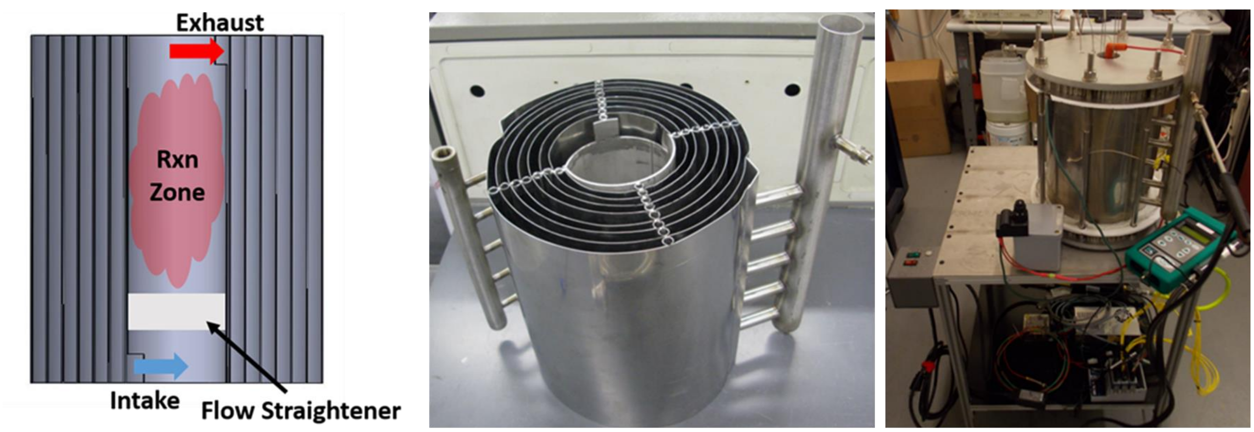
Since the reactants gain excess enthalpy from the combustion products, they have sufficient thermal energy to build a stable combustion zone with smaller chemical enthalpy (fuel) inputs. In other words, the excess enthalpy reaction extends the flammability limits of the fuel and enables ultra-lean, self-sustained 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 temperatures 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.

Past Swiss-roll research has been predominately focused on small-scale combustion applications, where heat losses can have a dramatic effect on reaction stability and performance. However, most waste gas incineration applications would require a much larger Swiss-roll combustor than previously studied. This work attempts to scale-up the Swiss-roll combustor and characterize performance of larger devices.

2. Methods / Experimental

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 during operation. While the standard design is easier to construct, ideally the flow would utilize the entire combustion zone volume, without a recirculation zone, to reduce flow velocity and resist the blow-off extinction limit. 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 Figure 2A. When this flow pattern is used in conjunction with a flow straightener, the reacting flow evenly fills the entire volume of the combustion zone.

ACT incorporated the new center design into a working prototype Swiss-roll incinerator for experimental testing. The entire prototype, Figure 2C, 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 2B. The top and bottom faces of the Swiss-roll body were 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 were inserted through alignment holes on the periphery of the aluminum plates to clamp the layers together and provide an airtight seal between the channels.



A **B** **C**

Figure 2: (A) A schematic of the end-to-end center design used to eliminate recirculation zones in the center combustion zone. (B) The Swiss-roll prototype body, without sealing/insulating layers, which was built with the end-to-end combustion zone flow path. (C) The entire Swiss-roll prototype assembly integrated with the experimental test setup.

Experimental testing of the prototype focused on completely characterizing the device's 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. A schematic of the experimental test setup is shown in Figure 3.

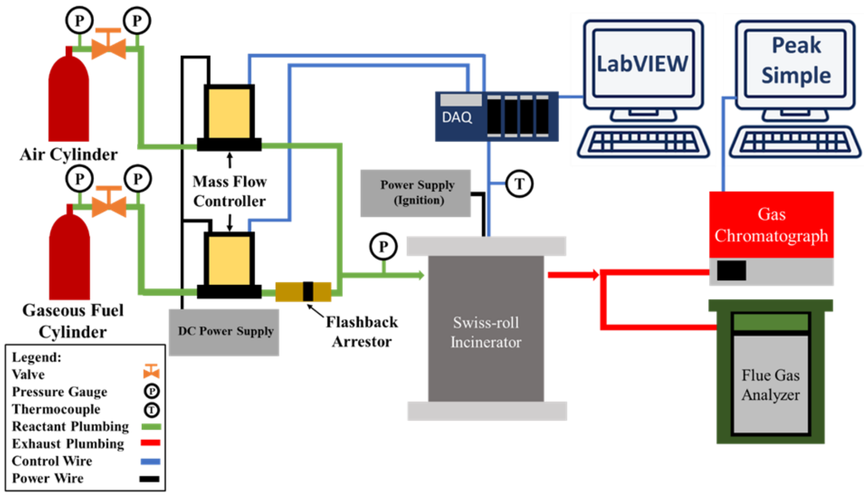


Figure 3: A schematic of the experimental setup used to test the Swiss-roll incinerator prototype.

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. 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 was estimated using 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.

3. Results and Discussion

Experimental testing proved the scaled-up Swiss-roll incinerator prototype extended the lean flammability limit of the input fuel for a wide range of flow conditions while maintaining high destruction efficiency and low emissions. The experimentally generated lean extinction limit plot, using propane fuel, is shown in Figure 4. Like previous studies, the Swiss-roll lean extinction limit curve in this work takes a parabolic shape, since more chemical energy is needed to combat heat losses in the low Reynolds number regime and the blow-off limit in the high Reynolds number regime.

While the performance of the scaled-up device is similar to previous experimental and computational findings at smaller combustor scales, the results in this work show an extended blow-off limit capability enabled by the end-to-end center combustion zone design. Since the flow velocity in the center combustion zone is reduced by eliminating the traditional recirculation zone, the device can operate at larger inlet Reynolds number flow conditions while avoiding the blow-off extinction limit. This result is important for potential large-scale applications, such as waste gas incineration, where high (>1000 SCFM) process flow rates are commonplace.

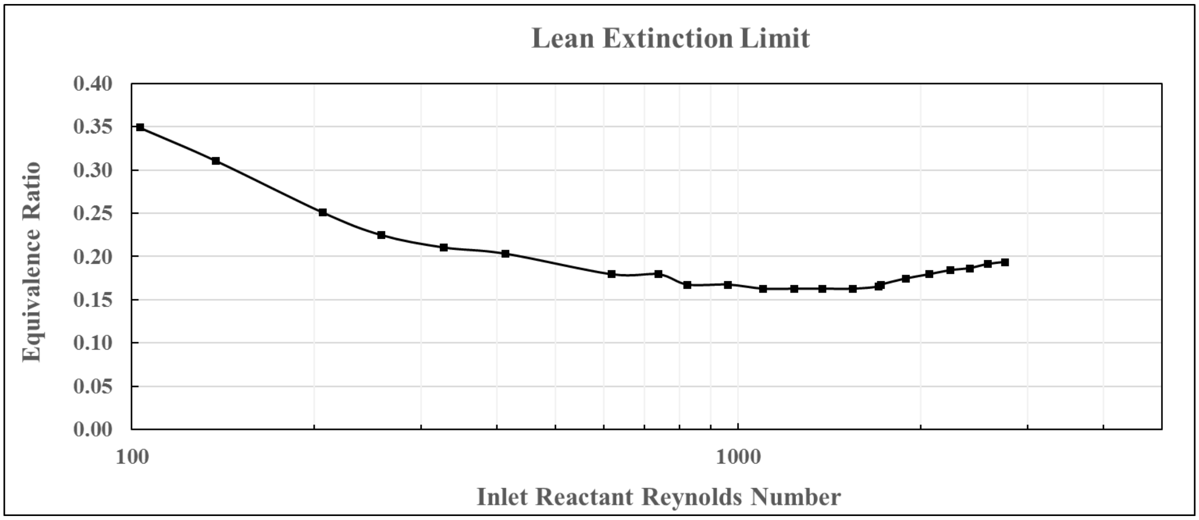


Figure 4: The lean extinction limit curve for the Swiss-roll incinerator prototype.

When considering the Swiss-roll combustor for waste gas incineration applications, the destruction efficiency and resulting emissions from the device are the most important performance metrics. The gas chromatograph results in Figure 5 show the Swiss-roll incinerator's high destruction efficiency during testing with toluene vapor and propane supplemental fuel. Based on the GC measurements at the inlet and exhaust of the combustor, the prototype demonstrated a destruction efficiency of just less than 99%. In addition, the measured carbon monoxide and nitrogen oxide emissions at the lean extinction limits across the entire tested flow range were less than 75 ppm and 5 ppm respectively.

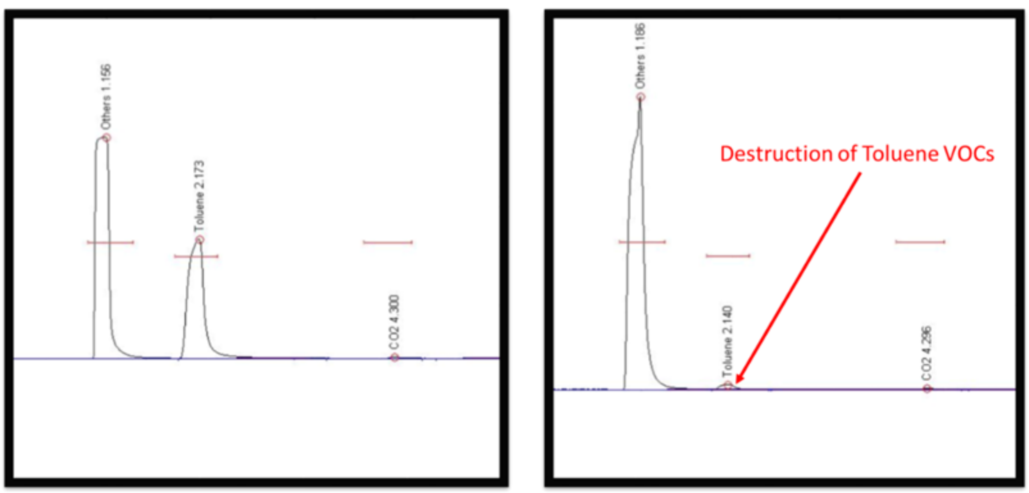


Figure 5: LEFT – The GC species composition measurement from the Swiss-roll inlet reactant sample showing toluene. RIGHT – The Swiss-roll exhaust sample GC measurement showing a significant reduction in toluene after thermal incineration.

4. Conclusions

The scaled-up Swiss-roll prototype fabricated and experimentally tested in this work demonstrated extended lean flammability limits, high destruction efficiency, and low harmful emissions. The combustion performance is similar to traditional smaller Swiss-roll devices, proving the scalability of the technology for large-scale applications. In addition, the end-to-end center design developed in this work effectively extended the blow-off extinction limit in Swiss-roll combustors, allowing the device to operate a higher inlet Reynolds number conditions. These developments are important for potential waste gas incineration applications, where large flow rates are often used to treat large amounts of waste VOCs with the least amount of supplemental fuel possible. A large-scale Swiss-roll can potentially excel in this application with an extremely thermally efficient combustion system.

5. Acknowledgements

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