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DEMONSTRATION OF AN EXTERNAL COMBUSTION MICRO-HEAT ENGINE

Jeong-Hyun Cho, ChienShung Lin, Cecilia D. Richards, Robert F. Richards, Jeongmin Ahn
School of Mechanical and Materials Engineering, Washington State University,
Pullman, WA 99164-2920 USA

Abstract: The integration of an external combustion micro heat engine with a Swiss roll combustor to produce power is presented in this work. The micro heat engine, a Micro-Electro-Mechanical-Systems (MEMS) based engine fabricated with standard micro-fabrication techniques, consists of a cavity filled with a saturated, two-phase working fluid, and bounded on the top and bottom by thin membranes. The engine is coupled to the combustor through a thermal switch which controls heat conduction from the combustor to the engine. The engine can utilize heat over a wide range of temperatures to produce power. The Swiss roll combustor utilizes the high energy density of hydrocarbon fuels in order to provide the necessary heat transfer required to power the engine. The overall feasibility of this integration as well as the results of this endeavor are explored.

Key words: Micro heat engine; Micro-combustion; Micro-Electro-Mechanical-Systems (MEMS); Micro power generation; Heat-recirculating combustors;

1. INTRODUCTION

There have many attempts over the last decade to produce a dynamic MEMS heat engine [1-3]. Unfortunately, while macro-scale heat engines have achieved both high power densities and high conversion efficiencies, the development of power dense, efficient micro-scale heat engines has proven very challenging. Because of the challenges these groups have faced in realizing micro heat engines based on rotating components we have focused on developing a micro heat engine base on flexing components [4-9]. The engine, an external combustion engine, consists of a cavity filled with a two-phase fluid bounded by top and bottom membranes. The bottom membrane acts as an evaporator. The top membrane acts as an expander. A thermal switch controls the timing and duration of the heat addition and heat rejection. Mechanical power is produced as the top membrane alternately expands and compresses the working fluid. Electrical power is produced by depositing a thin film piezoelectric on the top membrane. Work in our group has focused on optimizing components for the engine, including the thermal switch responsible for controlling heat transfer into and out of the engine [8], the wicking evaporator on the bottom membrane that controls the liquid-phase working fluid [6], and the top membrane that functions as the expander [5]. The engine and components have been integrated to demonstrate net mechanical power production when operating from a constant temperature heat source at 60 °C [9].

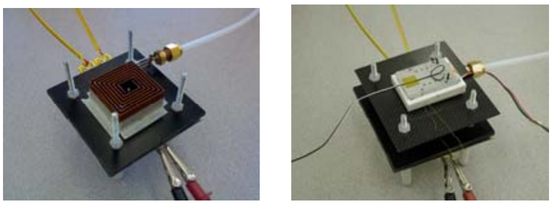
The engine is an external combustion engine and so a heat-recirculating combustor is an attractive candidate for integration. Heat-recirculating or “excess enthalpy” combustors were first studied 30 years ago [10,11]. In such combustors, thermal energy is transferred from the combustion products to the reactants without mass transfer and thus without dilution of reactants. As a consequence, the total reactant enthalpy is higher than that of the incoming cold reactants enabling sustained combustion under conditions that would extinguish without recirculation. This feature renders combustor designs such as the counter-current, spiral “Swiss roll” heat exchanger and combustor particularly attractive for micro-scale power generation applications.

In particular, our experiments and modeling [12-14] have shown that heat-recirculating combustors require thin walls with low thermal conductivity for maximum performance at small-scales. Combustors were constructed from polyimide plastics, which have far lower thermal conductivities than metals (typically 100 times lower) or even ceramics (typically 10 times lower). Plastics have the additional advantages of low cost, ease and variety of fabrication techniques, durability and electrical insulation properties.

Based on previous testing, temperatures in range of 60 ~ 80 °C are sufficient for the micro heat engine operation. At these low temperatures combustion heat losses and reaction quenching may be problematic in small-scale devices. Our previous work [12] has shown, however, that Swiss roll combustors can mitigate quenching at low Reynolds numbers (Re), where produces low reaction temperatures. In light of those results, the objective of the present work is to assess the feasibility of integrating the micro heat engine with a Swiss roll combustor.

2. EXPERIMENTAL APPARATUS

Experiments were performed by placing the micro-engine immediately on the top of the center of a 3-turn, spiral, counterflow Swiss roll combustor (Fig. 1). Appropriate micro-engine operating temperatures are maintained via combustion at the center of combustor. The Swiss roll combustor was made from commercially available DuPont™ Vespel™ polyimide (k ≈ 0.29 W/m˚C). The combustor (Fig. 1a) was milled automatically from SolidWorks™ CAD files. The outside dimensions of Vespel™ combustor are 44 mm wide by 44 mm deep by 16 mm tall with 0.7 mm wall thickness. The gap-width for each inlet and exhaust channel is 2 mm. The top of the combustor is sealed with approximately 0.5 mm of fibrous ceramic blanket, backed by 1.5 mm carbon fiber plate. A hole was cut in the center of the ceramic blanket and carbon fiber plate in order to have a direct thermal path between the reaction zone in the Swiss roll and the micro heat engine. The performance of this combustor was tested using propane fuel and Pt foil catalyst specially treated with NH_3, which we have found yields far superior performance at lower temperatures [12], were placed along the walls at the center of the combustor. The fresh fuel-air mixture is plumbed through a manifold attached to the inlet of the Swiss roll. An electrically heated Kanthal wire wrapped around a ceramic post located at the center of the combustor is used for ignition. The combustor was instrumented with thermocouples located at the center and in each inlet and exhaust turn. Mass flow controllers were used to regulate the flow rate of fuel and air through the combustor. LabView data acquisition software was used to record the response of each thermocouple and to control the mass flow controllers.



(a) (b)

Fig. 1: (a) CNC-milled Swiss roll combustor; top plate removed for clarity, and (b) micro-engine mated with Swiss roll combustor in experimental stand.

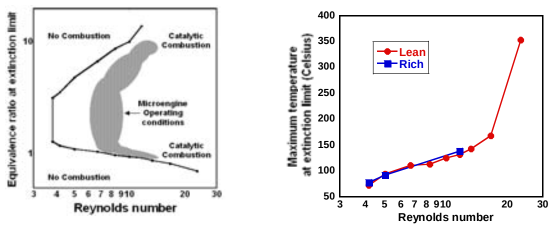
The engine, described in detail in [4,7,9], consists of four major components; a cavity, an evaporator, an expander/compressor, and a thermal switch. The evaporator is fabricated on the inner surface of the bottom membrane. Use of a wicking structure on the lower membrane provides control over the liquid location and thickness; as well as, the rate at which the wicking structure pumps liquid from the liquid reservoir into the heat addition region [6,7].

The thermal switch controlling heat transfer to/from the micro-engine takes the form of a liquid-metal micro-droplet array deposited on a silicon die. It is important to note that the thermal switch is not activated by heat. It is a device, actuated by a piezoelectric here, to control heat transfer by making and breaking thermal contact between two contacts to quickly alternate between a low thermal resistance state and a high thermal resistance state. An array of liquid-metal micro-droplets is fabricated on a silicon die using preferential vapor deposition on patterned gold. A second silicon die is used to make and break contact with the micro-droplet array. When the die makes contact, squeezing the liquid-metal micro-droplet array between them, the thermal switch is in its "on" state with increased heat transfer by conduction through the droplets [8]. When the die breaks contact, leaving a gas gap between the die, the thermal switch is in its "off" state with reduced heat transfer by conduction across the gas gap. The micro-droplet-array die is bonded on the tip of a piezoelectric cantilever actuator [7]. The cantilever thermal switch is then mounted immediately below the engine so that as the cantilever flexes the micro-droplet array makes contact with the bottom evaporator membrane.

The indicated power produced by the engine was calculated from measurements of the deflection of the top membrane. A laser vibrometer (Polytec OFV-5000, OFV-511) was used to measure the deflection of the top membrane. The engine cavity pressure was determined from the top membrane deflection using an experimentally determined pressure-deflection curve. The indicated mechanical power is the area under the pressure-volume curve for the micro-engine cavity divided by the time per cycle. This boundary work is the upper limit on useful mechanical work.

3. RESULTS AND DISCUSSION

The lean and rich extinction limits and thermal behavior of the polymer Swiss roll were thoroughly mapped prior to micro-engine testing. Fig. 2a shows the extinction limits obtained with the Vespel™ Swiss roll. Self-sustained reactions with Pt foil catalyst specially treated with NH_3 could be maintained within the Swiss roll at Re as low as 3.8. For Re < 8, the lean catalytic extinction limit is actually rich of stoichiometric. Also, rich limits could be extremely rich. Propane-air mixture compositions ranging from equivalence ratios of approximately 0.7 to 20 could be burned and a range of temperatures from approximately 72 °C to 500 °C could be sustained within the Vespel™ Swiss roll. Previous characterization of the micro-engine showed that operating temperatures of 60 °C to 80 °C were sufficient for power generation by the micro-engine. It was also found that Swiss roll should maintain the higher reaction temperature to obtain the operating temperature of the micro-engine due to the heat losses from micro-engine. Swiss roll required a reaction temperature of 150 °C to 230 °C for micro-engine operation. Fig. 2a shows the wide operating conditions of micro-engine in conjunction with Swiss roll combustor. It was therefore determined that the Vespel™ Swiss roll could readily provide the conditions necessary for micro-engine operation.

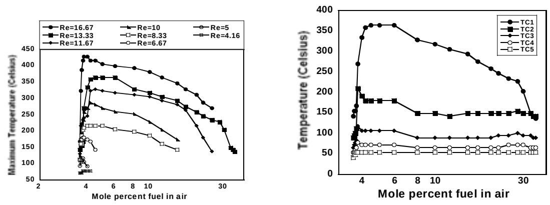


(a) (b)

Fig. 2: (a) Extinction limit map for catalytic combustion, (b) Maximum combustor temperatures (T_{max}) at lean and rich extinction limits.

Fig. 2b shows the maximum temperatures recorded in the Vespel™ combustor (T_{max}) at the extinction limits as a function of Re for catalytic combustion. The minimum reaction temperature of propane-air mixtures observed is 72 ˚C at Re = 3.8. Note that the maximum temperatures obtained for both the lean and rich extinction limits are in good agreement with each other. Note too that the minimum temperature required to sustain combustion exceeds Vespel™ material limit at Re around 20 and higher. Therefore, polymers are not suitable material for the combustor for high Re, however, polymers are suitable for the combustor for low Re that meso- or micro-scale devices should be more concerned.

The maximum temperature recorded by thermocouple in the center of Vespel™ combustor is shown for a range of fuel concentrations in Fig. 3a. Continuous, sustained operation of the Vespel™ combustor at temperatures up to 500 ˚C was demonstrated. Fig. 3b shows temperatures at all 5 thermocouples located in the center and each inlet and exhaust turns of Swiss roll for the entire range of mixture compositions at Re = 13.33. The reaction is centered for the entire range of mixture compositions, thus TC1 (located at the center) recording the highest temperature (T_{max}). Fig. 3b shows TC5 (located at the most outlet turn) recorded slightly higher than 50 ˚C, however, the external wall temperatures of combustor were below 50 ˚C in practically all cases even with over 400 ˚C internal reaction temperatures, which leads to minimal thermal signature and touch-temperature hazards.

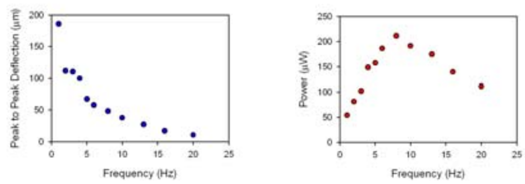


(a) (b)

Fig. 3: (a) Maximum combustor temperatures (T_{max}) as a function of Re and mixture strength, (b) temperature profiles recorded over a range of mixture compositions at Re = 13.33.

The operation of the micro heat engine with heat addition from the Swiss roll combustor is illustrated in Fig. 4 and 5. In these experiments, only one thermal switch was employed and so heat rejection from the engine was by passive cooling to the surroundings at 20 °C.

Fig. 4a shows the dynamic deflection of the top expander membrane of the engine as a function of engine cycle speed. The maximum expander membrane deflection is seen to be 180 microns when the engine cycles at 1 Hz. As the cycle speed is increased, the peak-to-peak deflection of the membrane falls. This decline in peak-to-peak membrane deflection with increasing engine cycle speed is a result of passive heat rejection from the engine. That is, the heat rejection rate is not adequate and the engine 'heats up' causing the membrane to bulge out and no longer return to a zero deflection for its minimum. Active heat rejection with a second thermal switch is expected to ameliorate these effects and lead to significantly higher power output [9].



(a) (b)

Fig. 4: (a) Peak to peak deflection versus engine speed, (b) engine power versus speed.

The mechanical power output of the micro-engine versus engine cycle speed is shown in Fig. 4b. The engine power is seen to rise to a maximum of 220 μW at a cycle speed of 8 Hz and then decline. The primary reason for the decline in engine output is the rise in average engine temperature as engine cycle speed and thermal power into the engine increases.

The voltage and power requirements of the cantilever actuator have been previously measured [9]. At peak power output from the engine the power required to actuate the switch, 10 μW, is a relatively small fraction of the power produced by the engine, 220 μW. Thus, these experiments demonstrate net power out from this system consisting of a micro-combustor and micro-engine.

Electric power production is shown in Fig. 5. A thin film of piezoelectric material (PZT) is deposited on the expander membrane to obtain mechanical to electrical energy conversion. The expander membrane had 3 microns of PZT sandwiched between Pt electrodes. Details on the fabrication and performance of the thin film piezoelectric membranes are given in [15,16]. The figure shows a peak to peak voltage of 400 mV is produced at 2 Hz.

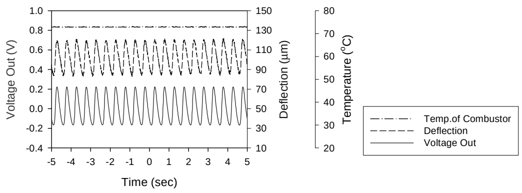


Fig. 5: Voltage produced by integrated system.

4. CONCLUSION

Experiments performed at low Re indicate that an integrated power generation system consisting of a micro-engine coupled to a Swiss roll combustor is feasible. Detailed mapping of both thermal and extinction limit behavior of a polymer Swiss roll in (Re, Φ) parameter space revealed that appropriate operating conditions for the micro heat engine could be maintained via self-sustained reactions in Swiss roll. Overall, the results suggest that this micro heat engine incorporated with a Swiss roll combustor may provide a solution for achieving high energy density in portable power applications.

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