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Mesoscale Microdroplet Based Combustion Power Generation using an Ultrasonic Droplet Generator

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Abstract

In this paper, we present the first micro-droplet based combustion power source using an ultrasonic fuel droplet generator. This paper addresses the challenging problem of achieving stable and self-sustaining combustion, while generating electrical energy from released heat in a cm3 package. A novel composite single droplet actuator is used to inject high velocity microdroplets of fuel, which can have terminal distances as long as 1 meter, that impact a burner, where the droplet is burnt. The heat from the burner is converted into electricity using a commercial Peltier device. A fuel-to-electricity conversion efficiency of 2% has been achieved, with 600mW power output across a 6Ω load. The fuel droplets ejected onto the combustor provide thermal-isolation between the fuel ejector and the hot zone, enabling independent design of thermal isolation of the burner for higher efficiency combustion,. We also demonstrate low-voltage and low-power fuel droplet ejection regulated by a microcontroller with nonlinear control schemes, suitable for power-on-demand applications that maximize energy conversion efficiency.

Keywords: Ultrasonic, Droplet, Combustion, PZT, Thermoelectric

1 - INTRODUCTION

Power-on-demand using combustible fuels in a cm^3 package has the potential to increase the lifetime of portable equipment such as laptops, unattended sensor networks, and cell-phones. The efforts to achieve this goal have centered around combustion engine on a chip [1,2]. In these approaches, the combustion zone is relatively closed and requires delivery of fuel and air from the outside, with concomitant heat loss from the hot zone to the package and the fluidic interconnects. Droplet based combustion solves this problem by shooting droplets of fuel onto a thermally-isolated combustion zone. Furthermore, the heat-to-electricity converter can also be placed remote to the hot zone maintaining thermal isolation for the burner and allow adjustable high temperature at the converter surface. If the droplets and ignition can be realized on-demand, one can obtain a hot zone and electric power as needed. In this paper droplets are generated using a low-voltage ultrasonic droplet generator, and heat is converted to electricity using commercial Peltier devices, enabling power output as high as 600mW, at a fuel flow rate of 27µL/min, with a total fuel to electricity conversion efficiency of 2%.

Different atomization (droplet generation) techniques have been implemented including thermal, mechanical, electrostatic and piezoelectric methods [3]. Although thermal droplet generation is widely used in application areas, such as ink-jet printing, thermal actuation for fuel atomization is less efficient and more power hungry compared to other methods. For mechanical-impulse driven atomization, where fuel or a co-flowing jet is accelerated, miniaturization of moving parts and pumps is technically challenging for sustained reliability due to high mechanical stresses generated. Electrostatic atomization using electrospray methods, on the other hand, require high voltages and prone to arcing. Most pulsed piezoelectric approaches also require high voltage excitation to deform a mechanical structure, again prone to reliability and arching problems. Although there are piezoelectric ejectors that use lower voltages, such as the capillary wave-based atomizers, these methods produce a mist rather than a directed jet [4], which generates a diffuse combustion zone.

A novel resonant piezoelectric droplet generation technique has been developed by our group to obtain single droplets in contrast to existing mist producing ultrasonic actuators [5]. In this study, this composite single droplet actuator is used to inject high velocity microdroplets of fuel to impact a platinum-mesh burner 1-cm away from the droplet ejecting orifice. The distance between the actuator and the combustor provides thermal-isolation between the fuel and the hot zone. This eliminates heating of fuel, increases thermal isolation for the burner for more efficient combustion, and enables low-flow resistance transport of air needed for combustion to the hot zone.

Our composite droplet generator is able to work with drive voltages as low as 1.5Vpp and actuation frequencies in the range of 100-200 kHz. This enables the use of compact low-power microcontroller based actuator regulation, and

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conducive to chip-scale based drive circuits for portable power generation systems.

2 - ULTRASONIC DROPLET GENERATOR

2.1- Device Structure

The ultrasonic ejector (Fig.1) is composed of a micro-pulled glass capillary bonded adhesively to a PZT (lead zirconate titanate-oxide) plate. The capillary has inner and outer diameters of 0.75 and 1 mm respectively with a pulled tip diameter ranging from 0.1 to 30μm. The PZT was diced with appropriate dimensions to co-resonate longitudinally with the capillary. One side of the PZT was tapered 0.4 mm deep for a better mechanical coupling with the glass capillary (Fig.1B) and aligned bonding.

The resonance frequency of the composite actuator in the longitudinal direction can be estimated assuming ½-wavelength resonance in the PZT bar, using the relationship:

$$f = \frac{c_P}{2L_p} \qquad (1)$$

where L_p is the length of the PZT along the capillary, and c_p is the velocity of the compressive waves in PZT.

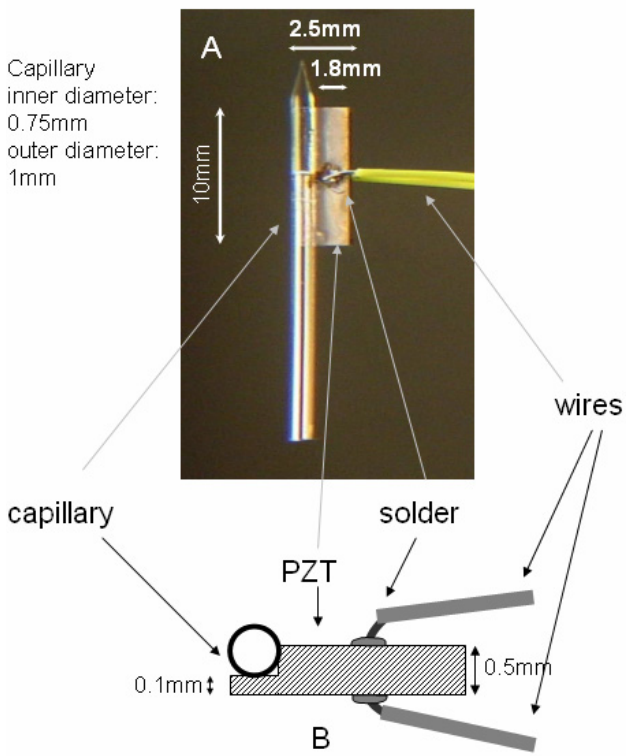

Figure 1 – Picture of the composite actuator (A) with the schematic drawing of the side view (B).

Equation (1) in conjunction with a detailed theoretical model gives a resonance frequency of $f = 165kHz$ which is in very good match with the experimental values measured between 162 and 167kHz. For a typical device, a quality factor of 420 and an electromechanical coupling of 0.057 have been calculated using the following expressions:

$$Q = \frac{energy\_stored\_in\_resonator}{energy\_dissipated\_each\_cycle} = \frac{\omega_{res} \cdot L_m}{R_m} = \frac{1}{\omega_{res} C_m R_m} \qquad (2)$$

and

$$K_{eff}^2 = \frac{mechanical\_energy\_stored}{total\_energy\_stored} = \frac{\frac{1}{2} C_m V^2}{\frac{1}{2} C_d V^2} = \frac{C_m}{C_d} \qquad (3)$$

where ω_{res} is the resonance frequency, C_m, L_m and R_m are the electrical analog of the equivalent mechanical spring, mass and damping constants of the resonator respectively, C_d is the parallel capacitance of the piezoelectric ceramic (i.e. the blocking capacitance) and V the applied voltage. In Figure 2 the numerical parameters of the equivalent electrical circuit, measured by means of the frequency spectrum analyzer HP4194A, are reported.

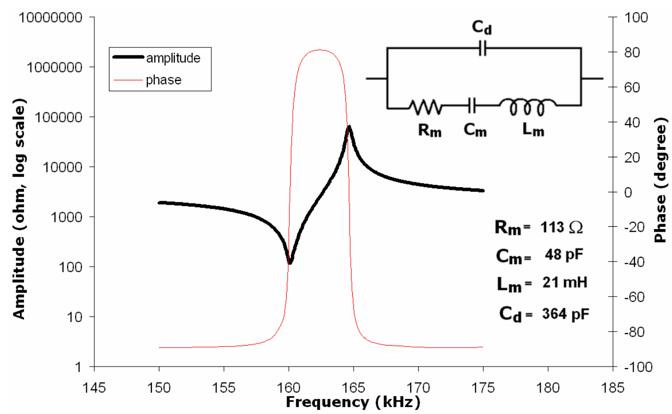

Figure 2b – The input impedance amplitude and phase of the overall actuator Q:420 $Keff^2$:0.057 and equivalent electrical circuit of a typical PZT/capillary resonator.

2.2- Droplet Elector Working Principle

The microdroplet ejection phenomenon is based on the volume change of a tapered-end glass capillary subject to longitudinal motion induced by PZT. Ultrasonic actuation at resonance causes expansion and compression of the liquid in the capillary. The elongation and compression of the neck volume results in a net body force on the liquid in the neck (Fig. 3).As a compressive. Since the distance of the tip to the squeezing volume is smaller than the acoustic wavelength, the liquid is ejected outside the capillary as droplets [5].

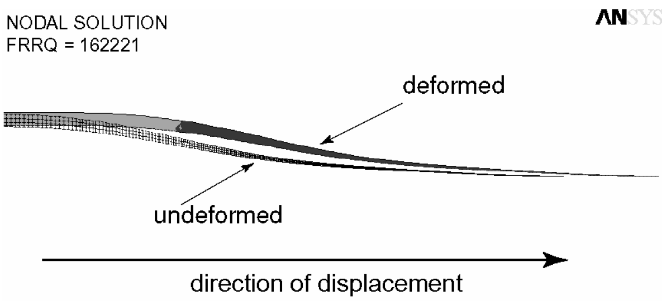

Figure 3 – The compression and expansion in the neck of the actuator responsible for droplet ejection [5], as simulated in ANSYS, with an axisymmetric model of the actuator.

3 - EXPERIMENTAL SETUP

3.1- Thermoelectric Power Generation

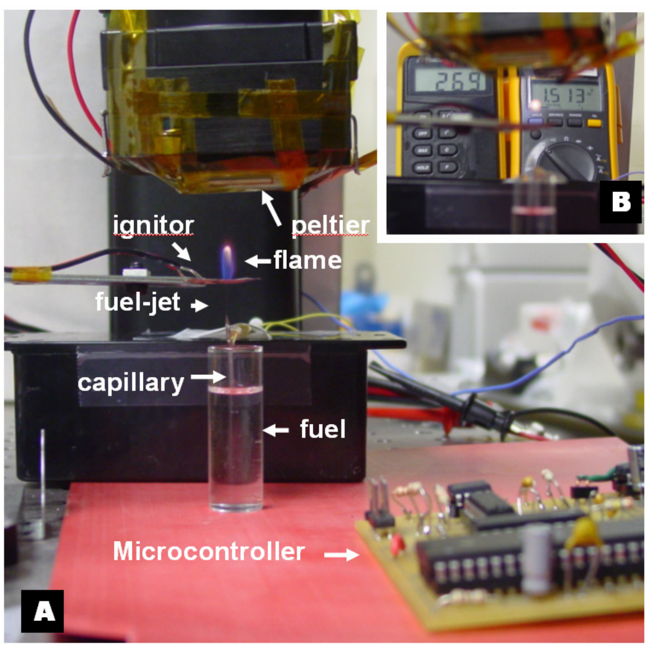

Figure 4 – Description of the experimental setup for power generation (A) with open circuit voltage reading of 1.5V at 270°C (B).

An experimental set-up was built to generate electrical power using ejected fuel droplets (Fig.4). The shank-end orifice of the glass capillary was placed into a small tube containing isopropyl alcohol. Capillary action pulls the fuel along the capillary to the ejection orifice. A platinum metal mesh (mesh hole size and wire diameter, both, 25µm) was located 1-cm above to thermally isolate the fuel from the mesh. A 1.5V induction coil based battery-operated igniter (QD1.5-4 from Quanglong, Ltd.) was located just over the mesh. A thermocouple (Omegaclad® from Omega Engineering, Inc.) was placed above the burner to measure the temperature above the hot zone for feedback to the microcontroller. A thermoelectric (Peltier) device was positioned on a moving stage to be able to adjust the distance to the combustion zone and the resulting flame. A heat sink ($12 \times 6 cm^2$) with a miniature fan (Sunon,Inc.) was attached to the cool side of the Peltier to keep the cool side at room temperature. The Peltier device was connected to a matching resistive load and the voltage across the load was measured to calculate the power output using a multimeter. The fuel ejection rate was also monitored during combustion by using the measurement marks on the fuel containing tube and a watch-clock.

3.2- Microcontroller Based Adaptive Drive Circuit

As a result of the ultrasonic focusing at the neck of the pulled capillary, and the high Q of the resonant actuator, drive voltages as low as 1.5Vpp at relatively low actuation frequencies (150-170kHz) can be used to eject the fuel droplets. A challenge to resonant actuator operation is the shift in resonance frequency due to time varying temperature, fuel level changing shifting the length of the capillary shank in contact with fuel, aging of the actuator, and possible ejecting tip occlusions. Although a simple phase-locked loop control of this resonator is feasible, it usually cannot take into account for events such as occlusion and excessive temperatures. Hence, a microcontroller based controller was implemented, providing control of the actuator, using information from the thermocouple and PZT current. A control system was built on a printed-circuit-board using the commonly used Atmel Mega32-16PC microcontroller.

The microcontroller sweeps the drive frequencies from 145 to 175-kHz in one-second sweep-time, and measures the actuator's output current (Figure 5). At the end of the sweep, it determines the resonance frequency by locating the frequency at which the PZT draws the maximum current, and drives the PZT for some time at that frequency. The output is fed to a DAC that latches the value, allowing the microcontroller to be put in sleep mode, saving on operating power. Input from the thermocouple can serve as an interrupt to force the microcontroller to wakeup and adjust the fuel ejection rate by controlling the duty cycle and drive amplitude. The microcontroller also can be used to control the electrical igniter in case the flame dies out. The entire system consumes 350mW during sweep and 60mW during sleep periods, and has much potential for power reduction by ASIC design.

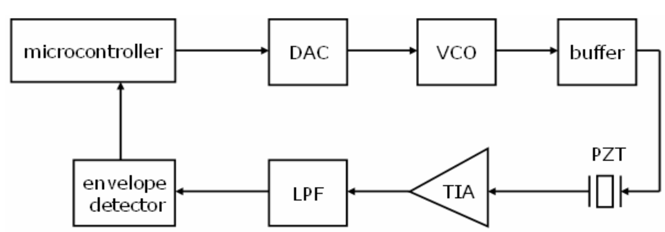

Figure 5 – Block diagram of the microcontroller based lock-in circuit (µ-controller:Atmel-Mega32 Buffer:MCP601).

4- ENERGY GENERATION RESULTS

Flow rate of the fuel ejection depends on the tip diameter size, actuation frequency, and PZT drive voltages. Flow rates obtained as a function of orifice size, while operating at resonance is shown in Figure 6.

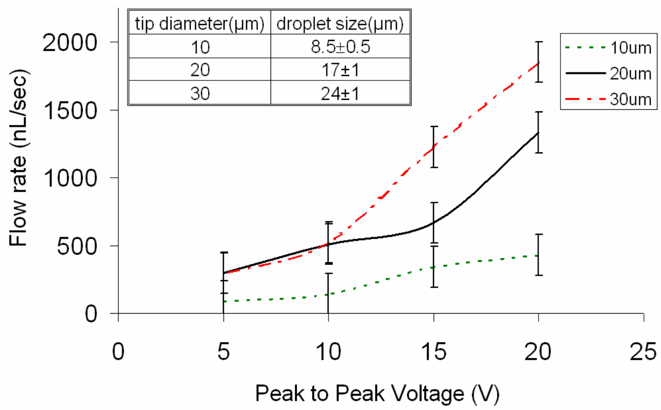

Figure 6 – Flow rate with driving voltage for different tip diameters.

When the flame was started using the igniter, the power output of the thermoelectric generator is proportional to the temperature difference between its hot and cold sides. The cool side was kept constant with the heat sink, never increasing above 45°C. In order to find the hot side temperature, a flame was obtained with peak-to-peak drive voltage of 20V with a function generator and temperature was measured at different distances to the flame with the help of the moving stage (Figure 7).

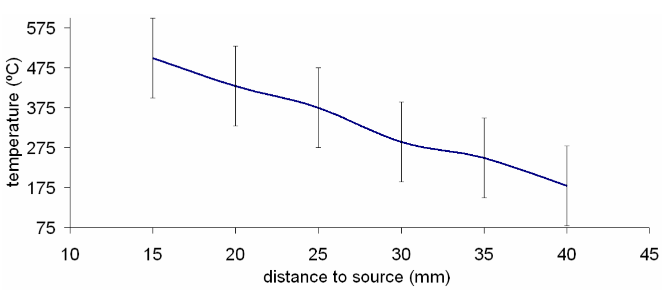

Figure 7 – The obtained temperature vs. distance to flame.

Flame durations of more than 30 minutes were observed, and were quenched only when the fuel ran out. For a drive voltage of $5V_{pp}$, drive amplitude generated by the microcontroller control loop, the Peltier device was positioned 15mm away from the flame, where the temperature was measured to be 230°C. This resulted in 600mW at the output, measured across a 6Ω resistive load. An efficiency of 2% is obtained by dividing the output power (600mW) by the fuel energy density and flow rate (24.3 kJ/cc * 12.3×10^{-4} cc/s = 29 W) [6]. The 600mW power is also well in access of the 60mW needed to maintain generator operation, and also above the 350mW needed to retune the actuator operation, at a low duty cycle.

5- CONCLUSION

This paper presents an implementation of a cm-scale droplet based combustor that is amenable to power-on-demand applications using combustible fuel sources. The ultrasonically generated droplets are generated in a controlled manner such as they impact a small combustion zone, the heat from which is converted to electricity using a Peltier device. The fuel droplets ejected onto the combustor enable thermal-isolation between the fuel and the hot zone, enabling independent thermal isolation of the burner for high efficiency, a major problem in mesoscale combustion systems where heat is lost to surrounding fuel and package. We also demonstrate low voltage fuel droplet ejection implemented in a microcontroller allowing complex control algorithms utilizing various sensors monitoring the generator operation. The 600mW power output (@2% efficiency) exceeds the 60mW power needed to sustain the control electronics, enabling access power that can be used to charge an energy storage battery or a super-capacitor, as power is needed.

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