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Non-equilibrium microsecond pulsed spark discharge in liquid as a source of pressure waves

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ABSTRACT

The present study investigated the ability of non-equilibrium microsecond pulsed spark discharge in liquid to generate pressure waves and the application of these waves as a source of small-scale compression. The spark pressure wave generator utilized the pressure waves produced by high energy pulsed spark discharge in water to produce usable pressure output in the form of a piston. Pin-to-pin spark generated inside of distilled water was observed in experiments to determine the spark temperature, pressure wave speed and pressure, water displacement, and piston output pressure and frequency. Pressure of 1.87 atm was produced by the piston from a pressure wave pressure of 6.15×10^5 atm generated by the 5500 K temperature spark. These results indicate that spark in water can be used as a source of small-scale compression.

1. Introduction

The size limitations of currently available small-scale reciprocating compressors present an opportunity to explore fundamentally new methods of pressure generation with a goal of serving the needs of mobile applications where the pressure requirements are on the order of 1–10 atm. Portable devices which require compression can be reduced in size in part by reducing the size of the compressor but the compressor size is limited by its mechanical components. Comparable size piston and diaphragm pumps produced by G.D. Thomas, KNF, and Hargraves original equipment manufacturers produce pressures of 1–8.2 atm and weigh 200–2132 g [1–3]. The markets for these pumps and compressors as stated by Hargraves and KNF, include in part, environmental monitoring, medical devices, patient monitoring, and medical therapy [4,5].

One potential solution to reducing the size of these compressors are microfluidic valves and micropumps. These devices use microelectromechanical systems (MEMS) technology for application in a variety of fields that include drug delivery, microelectronic cooling, and blood transport [6,7]. In a review of micropumps by Laser and Santiago, the max pressure change possible out of the 47 devices reviewed was 3 atm and the average pressure change was 0.25 atm [7]. Based on this pressure generation, micropumps are not capable replacing existing small-scale compressors but instead serve to fill the needs of newly developed MEMS technologies.

Microsecond spark discharge produces temperatures near the spark channel of 10,000–20,000 K at atmospheric pressure in less than 5 μs that result in the production of intense pressure waves outward from the channel [8,9]. Studies into using spark discharge in water as a source of pressure waves have been previously conducted for the inactivation of bacteria, gallstone fragmentation, removal of calcium carbonate in water, and the formation of sheet metal, but has never been utilized as a method of compression before [10–13]. The study presented here is focused on studying the pressure waves generated by spark in water and the development of a device to produce usable pressure of 1–20 atm from a system that uses limited mechanical components.

2. Materials and methods

Experiments were conducted in a plastic discharge chamber that housed the electrodes and water. This chamber was connected

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to a resistor–capacitor (RC) circuit to generate the spark pulses. Fig. 1 shows a schematic diagram of the testing configuration which consists of an RC circuit, adjustable spark gap, discharge chamber, voltage probe, current probe, and oscilloscope. The RC circuit contains a Bertan 205A-50R 50 kV DC power supply, 100 kΩ resistor, and 6800 pF capacitor bank. To monitor the spark discharge electrical parameters, the voltage and current were measured using a Tektronix P6015A 1:1000 75 MHz high voltage probe, Pearson 4100 1 V/A current probe with 10 ns usable rise time, and a 1-GHz Tektronix DPO4000B digital phosphor oscilloscope with an impedance of 1 MΩ ±1%.

Sparks were generated within the discharge chamber shown in the schematic in Fig. 2. This chamber was 3D printed out of ABS plastic using a MakerBot Replicator 1 and Servometer metal bellows were attached to the top. The electrodes entered through the chamber walls and were held in place by threaded metal inserts. The internal volume of chamber that contains the water is a cylinder with final dimensions of 9.88 mm diameter and 17.25 mm depth.

The bellows were used to provide a means of observing the pressure output in place of a typical piston which would be used in a reciprocating compressor. The bellows are hollow inside, sealed on one end, and open to the chamber on the other end. The bellows are electroformed nickel and have a spring rate of 1033 N/m, inner diameter of 3.81 mm, and a maximum stroke length of 2.82 mm as specified by the manufacturer [14]. The chamber and bellows were filled with approximately 2 ml of distilled water and sealed so that no air bubbles were present. Distilled water was used as opposed to tap water to reduce the mineral content in the water to prevent mineral fouling inside of the device. Throughout testing with distilled water, no mineral fouling was observed.

The water was changed before and after each experiment so that any effects caused by changing water chemistry were minimized. The changes in water chemistry were not measured during this study but products generated by plasma in water have been observed by Mededovic and Locke to produce stable H_2O_2, H_2, and O_2 [15]. Over time these chemical products will increase the acidity and chemical composition of the water enough to change the breakdown conditions of the water. Long duration tests were not conducted but during experiments over 1 h at a pulse frequency of 1 Hz would produce noticeable changes in spark frequency. To run the system continuously at a consistent pulse frequency, the water should be changed approximately every 10 min.

The electrodes were constructed out of 316 stainless steel bolts to provide adjustability and were machined to a tip diameter of 0.6 ± 0.1 mm to provide electric field enhancement. The distance between the electrodes was set to 0.9 ± 0.1 mm which was the largest distance possible with the most consistent discharge pulses observed. The gap between the electrodes changes the amount of energy which is deposited into the water because a smaller gap requires less voltage to reach breakdown conditions. As the distance between the electrodes increases, more energy is required to ionize the water between the electrodes. It was observed experimentally that as the circuit operates at higher discharge voltage, the frequency of the spark being generated by the circuit become less consistent.

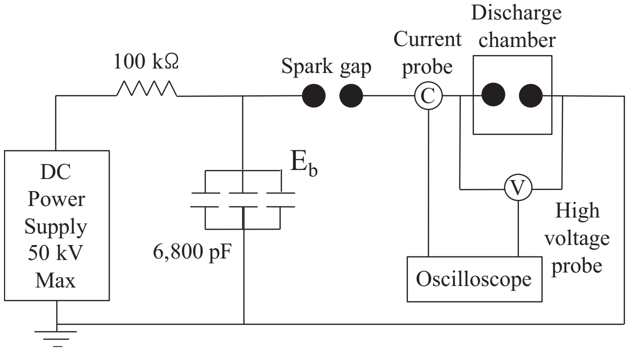

Fig. 1. Schematic diagram of the spark generation testing configuration.

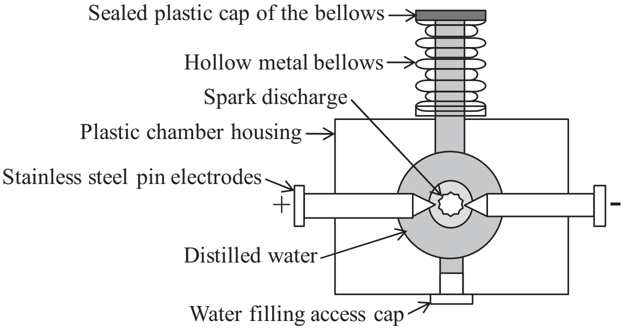

Fig. 2. Schematic diagram of the discharge chamber.

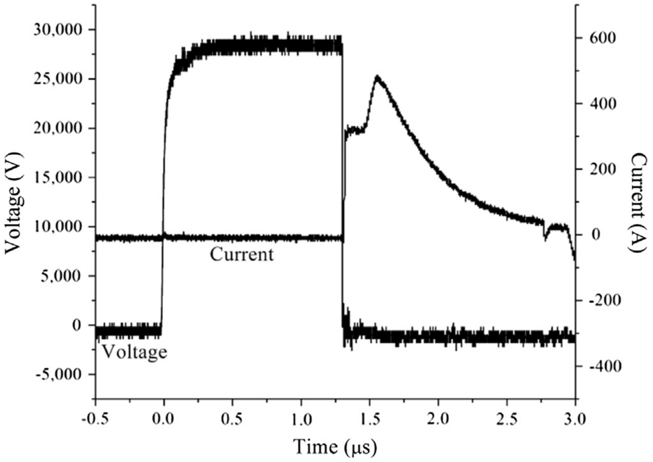

Fig. 3. Oscillogram of the voltage and current for a typical spark discharge in water.

Fig. 3 shows an oscillogram of the voltage and current of a typical spark discharge pulse. The peak-to-peak voltage and current ranged from 25 to 40 kV and 400 to 900 A respectively. The pulse width ranged from 1 to 5 µs and the voltage rise time was approximately 40 ns. The pulse energy was calculated by integrating the voltage and current over the pulse width.

2.1. Pressure output tests

The metal bellows were used to measure the average volume displaced by the spark, the pressure output of the device, and to determine the potential piston stroke generated. Measurements of the bellows were conducted using high speed imaging with a Phantom Miro M310 high speed video camera with a 1 µs exposure time. Images were extracted from the videos and the displacement of the bellows were measured with ImageJ software using a known pixel length.

2.2. Pressure wave observation tests

Schlieren imaging was utilized for imaging the spark discharge and pressure wave formation. Fig. 4 shows a schematic of the Sch-