Effects of improving current characteristics of spark discharge on underwater shock waves

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ABSTRACT

We have been developing a food-processing device that uses underwater shock waves generated by spark discharges at an underwater spark gap. Underwater shock waves can be used in food processing for softening, fracturing and sterilization. These technologies are attracting attention because the food is not heated during processing, so it does not change flavour. In this study, we develop a rice-powder manufacturing system using the fracturing effect provided by underwater shock waves. Because rice grains are very hard, the process must be applied repeatedly using a momentary high pressure to fracture the grains. The fast repeated generation of shock waves should provide high pressures from low energies. Therefore, we aim to achieve higher pressures from low energies expended by the underwater gap discharge. We increase the pulse compression rate by decreasing the circuit impedance of the device and increasing the charging voltage. Using optical observations and a pressure sensor, we measure the high pressure developed by the underwater shock wave and the rise time of the discharge current. We find that we can decrease the rise time of the discharge current by 17% while maintaining the peak current, and simultaneously increase the high pressure of the underwater shock wave by 135%.

Keywords: Shock wave, Pulse power, High pressure, Food processing

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1. INTRODUCTION

We have been developing a food-processing device that uses underwater shock waves [1] These waves offer some advantages to food processing; for example, use of shock waves can replace heating and reduce processing time. They can be used in food processing to fracture, soften, extract and sterilize food [2]. We are developing a shock-wave generator that fractures rice for manufacturing rice powder [3]. When an underwater shock wave passes through a grain of rice, differences in density separate the wave into a penetration wave and a reflection wave. When the shock wave leaves the rice grain, the grain surface gets crushed; this is called a spall fracture [4]. Figure 1 shows the mechanism by which a rice grain is crushed by a spall fracture. Since one shock wave only fractures the surface, grains must be repeatedly subjected to shock waves to achieve the desired product. Therefore, the purpose of this study is to enhance the underwater shock wave generator by improving current characteristics of the spark discharge.

2. CHANGES IN CURRENT CHARACTERISTICS BY IMPROVING IMPEDANCE

Figure 2 shows the RLC equivalent circuit for the discharge circuit and the relations among current characteristics. When the circuit of the device is analogous to that in Figure 2 and the RLC circuit obeys (1), the current of the discharge is a damped oscillation, as shown in Figure 3, while the oscillation frequency and peak current are given by (2) and (3), respectively. According to (2) and (3), we can increase the frequency and peak current by decreasing the inductance L [5]. Furthermore, we can increase the frequency by decreasing the capacitance C, but then the peak current of the discharge would also decrease.

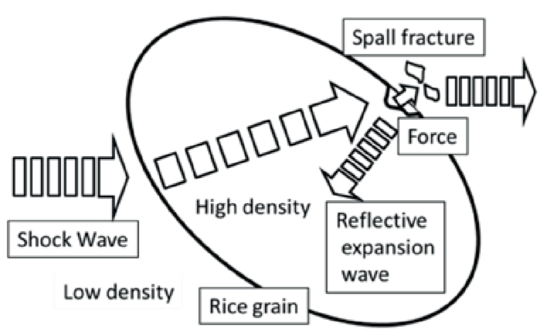
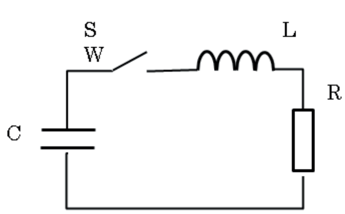


Figure 1: Mechanism of spall fracture created by an underwater shock wave



$$R < \sqrt{\frac{4L}{C}} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

$$f = \frac{1}{2\pi\sqrt{LC}} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

$$I_{peak} = V_C\sqrt{\frac{C}{L}} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

Figure 2: RLC equivalent circuit for the discharge circuit and relations among current characteristics

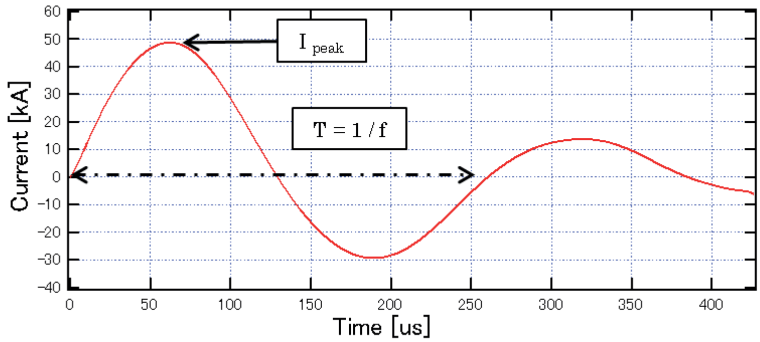


Figure 3: Current from the spark discharge as a damped oscillation

3. EXPERIMENTAL METHODS

3.1. EXPERIMENTAL DEVICE

Figure 4 shows the experimental device used to measure high pressures created by underwater shock waves. The shock-wave generator includes a high-voltage capacitor bank, switching circuits and a high-voltage power supply. Electrical energy from the generator is discharged at the underwater gap in the pressure vessel, which is filled with water. When a spark discharge forms at the gap, a shock wave is generated at the interface between the discharge and water. In the pressure vessel, a pressure sensor (Muller-Platte Needle Probe 100-100-1) is positioned at the bottom, which is at a distance of 150 mm from the gap, as shown in Figure 5. The discharge current and electrode voltage are measured by a Rogowski coil (Power Electronic Measurement Ltd, Rogowski Current Waveform Transducer and Type CWT 1500B) and a high-voltage probe (TESTEC, HPV-15HF and 50 MHz) using an oscilloscope (Tektronix, TDS2024C and 2 GS/s).

3.2. DECREASING INDUCTANCE

To reduce the inductance of the discharge circuit, we replaced single-line cables in the discharge circuit with a coaxial cable (Figure 6). Then we examined the response of discharge characteristics and peak pressures to the decrease in circuit inductance.

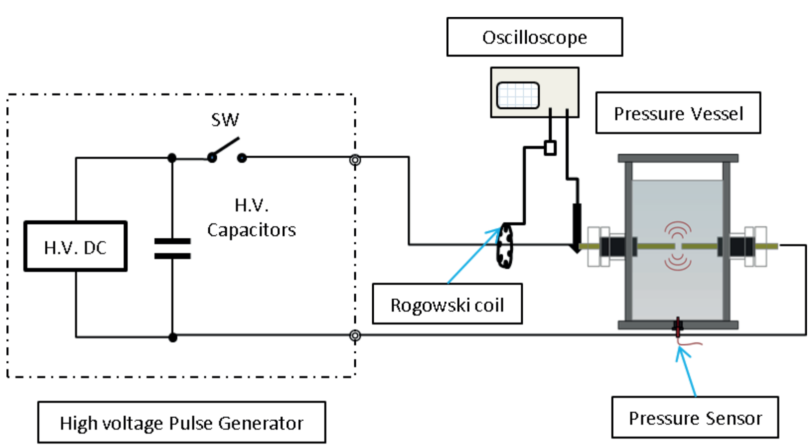


Figure 4: (left) Underwater shock-wave generator and (right) setup to measure high pressure caused by the underwater shock wave

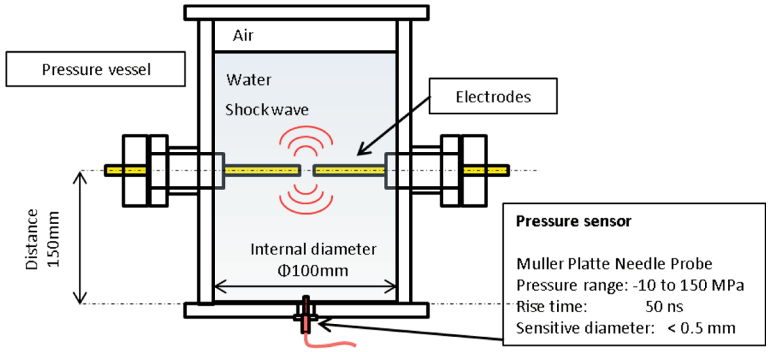


Figure 5: Detail of the pressure vessel and position of pressure sensor

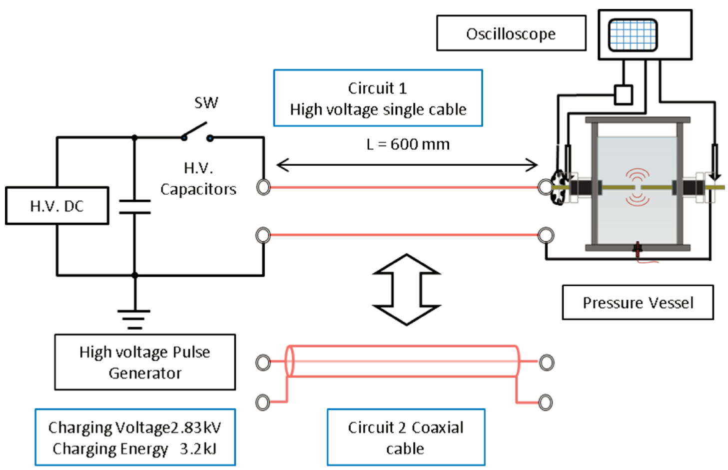


Figure 6: Reducing inductance by changing the discharge cable from a single-line cable (Circuit 1) to a coaxial cable (Circuit 2)

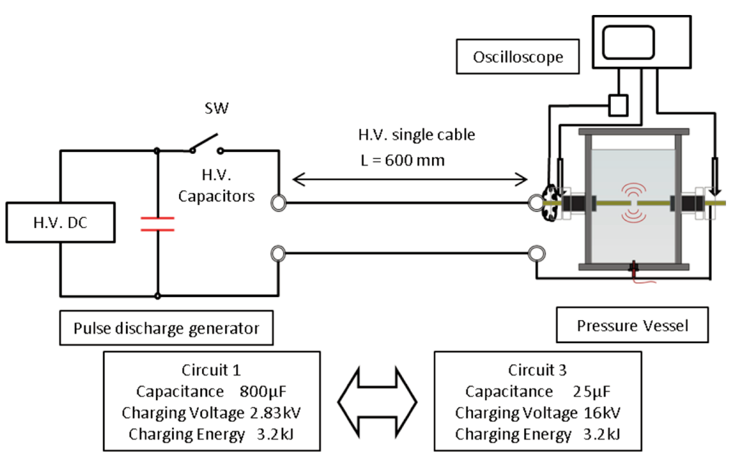


Figure 7: Reducing circuit capacitance from Circuit 1 to Circuit 3 for the same charging energy

3.3. DECREASING CAPACITANCE

We also examined the response of the high pressure to shortening the oscillation wavelength by decreasing the circuit capacitance, as shown in Figure 7.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Changes in pressure, voltage and current due to reduction in inductance are obtained by comparing the plots in Figure 8 (for Circuit 1, which used the single high-voltage cables in Fig. 6) with those in Figure 9 (for Circuit 2, which used the coaxial cable in

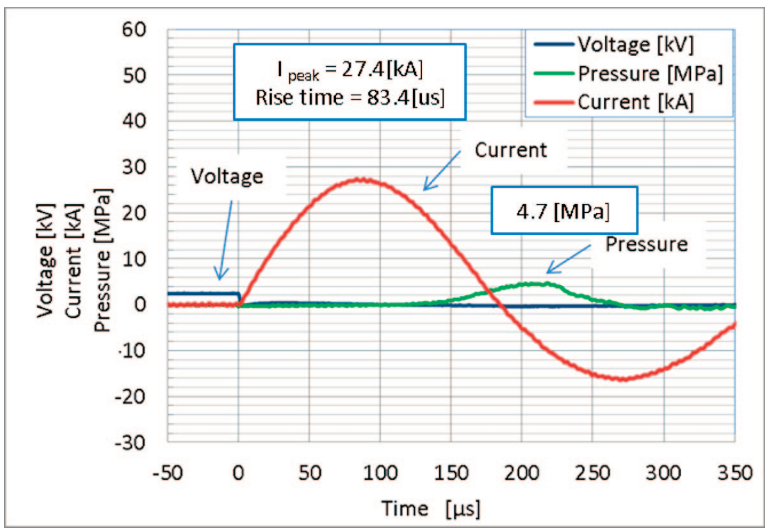


Figure 8: Voltage, current and pressure characteristics measured for Circuit 1

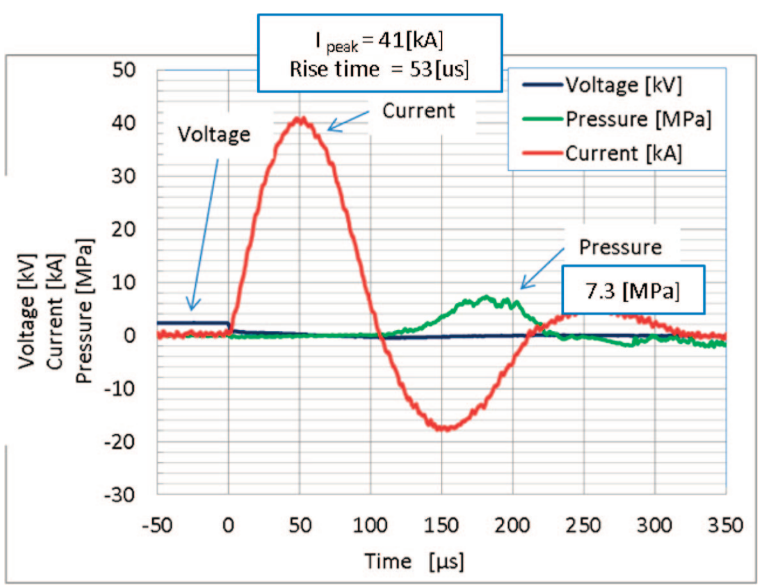


Figure 9: Voltage, current and pressure characteristics measured for Circuit 2

Fig. 6). For Circuit 1 (Circuit 2), the oscillation frequency, calculated from the rise time of the current, was 3 kHz (4.7 kHz) and circuit inductance was 3.52 μH (1.43 μH). For Circuit 1 (Circuit 2), the peak current was 27.4 kA (41 kA) and occurred at 83.4 μs (53 μs) after the discharge; the maximum pressure created by the underwater shock wave was 4.7 MPa (7.3 MPa). For Circuit 1 (Circuit 2), the pressure started to increase at 121 μs (111 μs) after the electric breakdown, and the average propagation velocity of the underwater shock wave was calculated to be 1232 m/s (1351 m/s). So, the average velocity and maximum pressure of the shock wave were increased by reducing circuit inductance.

Changes in pressure, voltage and current due to reduction in capacitance were obtained by comparing the plots in Figure 8 (for Circuit 1 in Fig. 7) with those in Figure 10 (for Circuit 3 in Fig. 7). For Circuit 3, the current rise time calculated from the size of the capacitor bank was 14.7 μs, which was 0.18 times the value for Circuit 1. The measured value of the maximum current for Circuit 3 was 30.8 kA at 12.2 μs after the discharge. The measured current rise time agreed with the calculated value. For Circuit 1 (Circuit 3), the pressure started to increase at 121 μs (109 μs) after the electric breakdown, the average propagation velocity of the underwater shock wave was calculated to be 1232 m/s (1376 m/s) and the maximum pressure was 4.7 MPa (29.2 MPa). So, the average velocity and maximum pressure of the shock wave were increased by decreasing circuit capacitance.

Figure 11 shows the relationship between the peak pressure and I_{peak}/T_{peak} obtained from the experiments. Here, I_{peak} is the peak current, and T_{peak} is the rise time for the current to peak. We anticipated that the peak pressure increases for faster, higher peaks in the current. Decreasing both inductance and capacitance enhanced the underwater shock wave compared to the behaviour of Circuit 1; however, Figure 11 shows that decreasing capacitance is more effective.

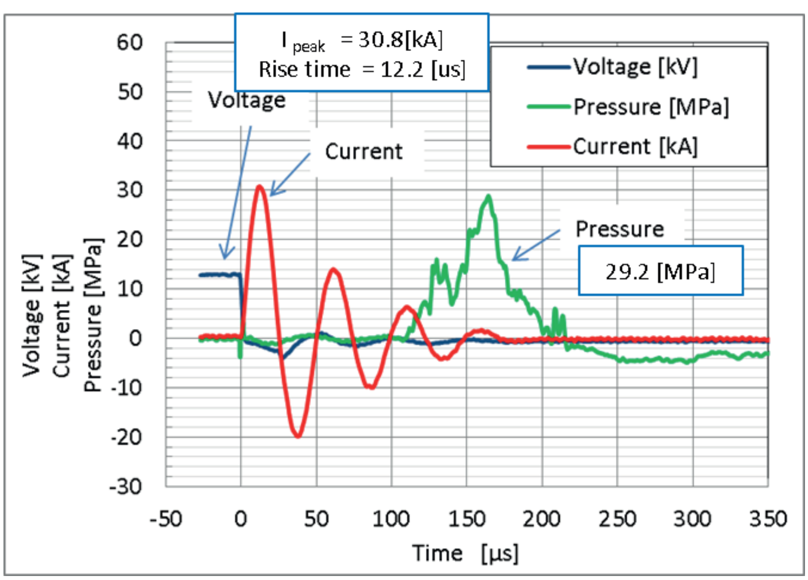


Figure 10: Voltage, current and pressure characteristics measured for Circuit 3

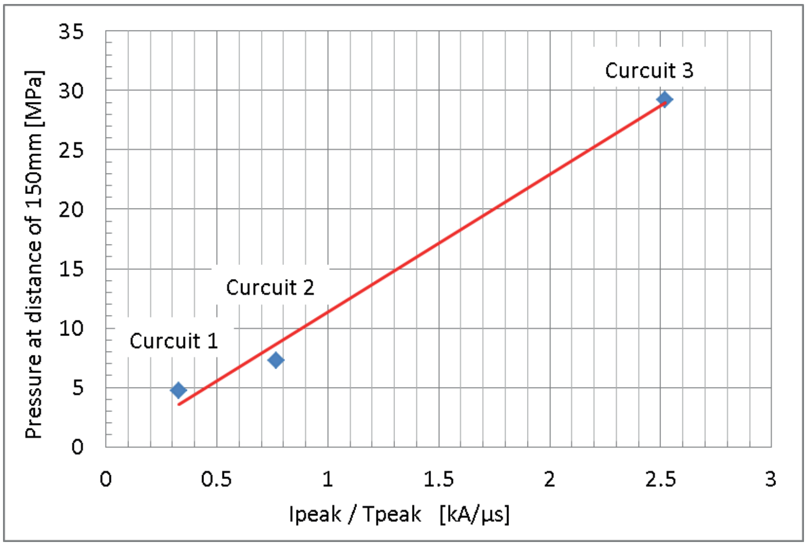


Figure 11: Relationship between peak pressure and ratio of peak current (I peak) to rise time to peak current (T peak) from measurements for Circuits 1–3

5. CONCLUSIONS

We are developing an underwater shock-wave generator using underwater spark discharge for a rice-powder manufacturing system. In this study, we measured the increase in pressure from the underwater shock wave by decreasing the impedance in the discharge circuit of the wave generator. We examined two methods for decreasing impedance. One was to decrease the inductance of the circuit by replacing the high-voltage single-wire discharge cable with a coaxial cable. The other was to decrease the capacitance by decreasing the capacitance of the capacitor bank and increasing the charging voltage. Before and after these changes, we measured the high pressure created by the underwater shock wave. Our results showed that the underwater pressure increased by a factor of 6.21 compared to the original circuit using low capacitance and high voltage. This shows that desirable features of the underwater shock wave can be improved by improving circuit impedance in the shock-wave generator.

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REFERENCES

[1] K. Simojima, Y. Miyafuji, K. Naha, O. Higa, R. Matsubara, K. Higa, Y. Higa, T. Matsui, A. Takemoto, S. Tanaka, H. Maehara, S. Itoh:, "Development of the rice-powder manufacturing system using underwater shock wave", *The International Journal of Multiphysics*, Vol.6 No.4 pp.355–364 (2012)

[2] A. Oda, N. Okamoto, S. Itoh: "Study on the Relationship between Some Foods and Underwater Shock Wave Using the Explosion of the Detonation Fuse", *Materials Science Fouram*, Vol.566, pp.197–202 (2008)

[3] O. Higa, R. Matsubara, K. Higa, Y. Miyafuji, T. Gushi, Y. Omine, K. Naha, K. Shimojima, H. Fukuoka, H. Maehara, S. Tanaka, T. Matsui, S. Itoh: "Mechanism of the Shock Wave Generation and Energy Efficiency by Underwater Discharge", *The International Journal of Multiphysics*, Volume 6, Number 2, pp. 89–98 (2012)

[4] Y. Miyafuji, K. Shimojima, S. Tanaka, K. Naha, T. Aka, H. Maehara, S. Itoh: "Development of The Pressure Vessel for Manufacturing the Rice-Powder using Underwater Shock Wave", *ASME 2011 Pressure Vessels and Piping Conference*, PVP2011-58033, pp. 53–56 (2011)

[5] R. Hanaoka: "*High Voltage Engineering*", Morikita Publishing Co., Ltd. (2007)