

EFFECTIVE COUPLING OF PULSED POWER TO CHEMICALLY REACTIVE METALLIC SYSTEMS*

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Abstract

The pulsed electrical excitation of reactive metals like aluminum in water triggers a fast and highly energetic chemical reaction generating gaseous products. For applications such as fuses, safe explosives or fast gas generation, it is desirable to maximize the ratio of conductor mass to stored electrical energy while rapidly attaining a high resistive state. Various techniques have been used to partly meet this requirement. These techniques included double pulse application, pre-dispersion of metallic material prior to pulse application, and coaxial metallic system in which a metal of lower boiling point is surrounded by a metal of higher boiling point. The preliminary test results demonstrated that the efficiency of the pulsed power in deriving the chemical action can be greatly improved by these techniques.

Introduction

Fast electrical activation of light metal conductors in a water environment has potential applications in fields such as underwater shock wave generation, fuse opening switches, and fast gas generation. Electrical, chemical, and pressure measurements on such system show that fuse operation, efficiency of chemical conversion, and shock wave generation are all interrelated [1-3]. Normally the performance in such applications depends on the ratio of total electrical energy to conductor mass. If the ratio is not high enough and the distance between electrodes is not short enough to form a plasma channel, then the effectiveness depends on time rate of the energy dissipation through the dissipating medium. The chemical reaction between the conductor and water during the electrical discharge increases the rate of dissipation [4].

The contribution of the reaction to the increase in the rate is mainly attributed to the surface effect originating from the oxide film on the metal surface. In other words, the extent of the reaction during discharge is limited near the surface of the dispersing metal particles. Due to the inherent time lapse for transport of water molecules and chemical interaction of the reacting molecules, completion of the chemical reaction lags behind the electrical explosion triggered by the pulse. Although an increase in electrical power can narrow the time gap, the chemical process is not strongly coupled to the electrical pulse (Figure 1). In the aluminum-water system most of the exothermic chemical energy produced from their interaction is the outcome of an after effect of the electrical pulse.

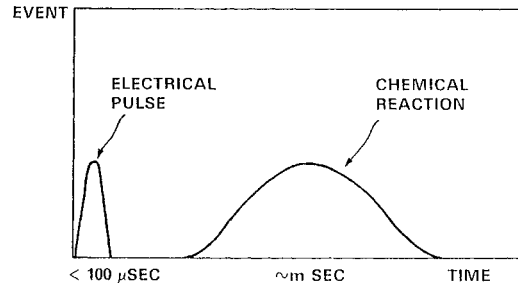


Fig. 1. The chemical reaction of the dissipating medium occurs as a consequence of an electrical pulse, with a time delay.

Reactive metal in water goes through two distinct physical phases, one after another in time sequence, during the pulse application. The first phase represents the metallic conductor maintaining the physical integrity until it starts to explode. During this phase the metallic conductor acquires the energy for dispersal within water. The second phase appears when the metal and water are thoroughly being mixed. The energy dissipation rate in the second phase is much greater than in the first phase. Efficient dissipation of the stored energy requires that the reacting medium carries the current to its peak value without dissipating much energy. Most of the stored energy needs to be dissipated immediately after the peak current. This type of dissipation, discharge of inductive stored energy [1], results in a maximized chemical reaction between the metal and water.

However, these conditions constraint the mass of the reacting metal when it is to discharge a given amount of the stored energy. The mass becomes the only adjustable variable for ensuring good coupling. Once the 'right' mass is determined, the ratio of the energy dissipated through the two phases is fixed. Even with such a coupling the ratio of the primary stored energy to the mass of reactive metal is high, in the order of 5 - 10 KJ/gm of metal [1]. To reduce the ratio the medium should undergo some modifications.

Extra energy provided by a source other than the primary energy storage during the pulse application can certainly augment pulsed power efficiency. For example, fuse action of aluminum wire in water was clearly improved when its dispersal in water was helped by another exploding wire placed nearby [2]. The extra energy does not necessarily come from an

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external source. The pulse application through the medium can trigger exothermic chemical reactions in it or generate an expanding force inside the medium. This kind of internal action can greatly contribute to the pulse power efficiency if the chemical and electrical events are carefully matched to each other.

We have made several efforts in this regard. First, a pyrotechnic type of reaction was induced in addition to the metal-water reaction during pulse application. To maximize the effect of such chemical action a multiple pulse technique was also employed. Second, a premixed aluminum-water system was used to save the energy required to activate the metal and to disperse it. Third, two reactive metals of different boiling point were used as the current carrier in water. Preliminary results obtained by using these methods will be described in this paper. Finally an electrochemical combustion model will be introduced which explains the coupling between electrical pulse and chemical reaction.

Double Pulse Applied to Reactive Metal System

In this method two new features were added to ordinary aluminum-water reaction triggered by an electrical pulse. These included an incorporation of another chemical component, copper oxide (CuO) to the system and application of double pulses to it. The pyrotechnic reaction between aluminum and CuO contributed most to the initial increase in the temperature of aluminum. The reaction was triggered by applying a small precursor pulse through an aluminum wire embedded in the pellet made of the powder mixture of aluminum and CuO . Careful selection of the mass ratio of aluminum to CuO sustains the reaction, raising the Al temperature far above its melting point. Then a delayed (over one millisecond) and much larger pulse further activated the system. During the delay the pyrotechnic reaction should complete and the reaction products partly mix with water. A delay more than 10 milliseconds was necessary to advance the reaction. The schematic experimental setup is shown in Figure 2. The stored energy for the precursor was 15 % of the energy for the main pulse. For single pulse application the stored energy was just the sum of these two energies. The amount of water used was slightly in excess of the stoichiometric quantity based on its reaction with aluminum. The distance between the brass electrodes was 7 cm. Pressure of the generated gas was measured using PCB 108A03 gauge.

The effect of this technique on the energy dissipation rate and on gas generation is shown in Figures 3 and 4. For the case of single pulse application the current oscillated a few cycles indicating a low rate of energy dissipation. The rate was much greater during the second pulse application for the case of double pulse method. Apparently during the 20 milliseconds delay after the precursor pulse the mixture pellet underwent the reaction, ready to accept the second pulse with a higher dissipation rate. The pressure rise of product gases is shown in Figure 4. For the double pulse case the rise was much faster.

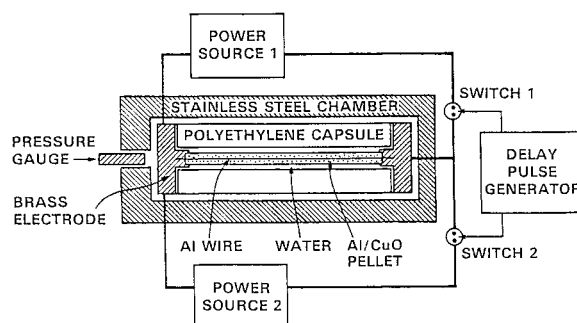
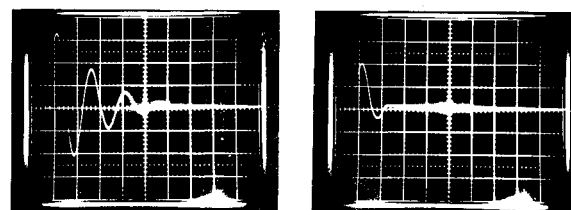


Fig. 2. Schematic diagram of the experimental setup used in the tests.



(a)

(b)

I : 12.5 KA/DIV TIME : 0.2 mSEC/DIV

Fig. 3. Current profiles through the dissipating medium. (a): Single pulse test. (b): Double pulse test. Time zero is the start of the second pulse.

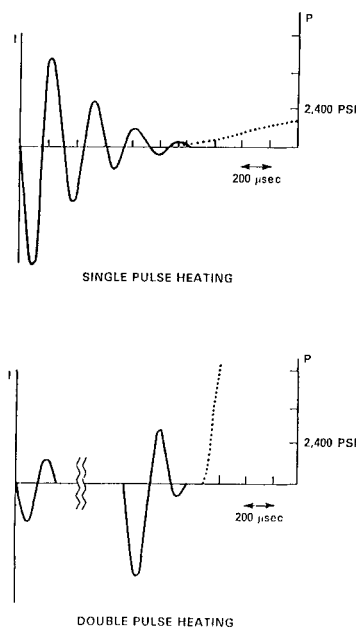
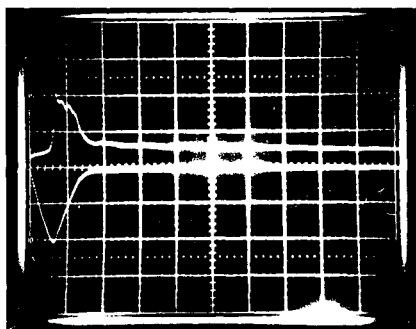


Fig. 4. Pressure rise (dotted line) in single and double pulse heating.

The purpose of this method was to save the electrical energy needed to disperse the metal conductor into water. A paste made of fine aluminum particles (50 micron) and water was used as the dissipating medium. A small aluminum wire going through the center of the paste column carried the initial current pulse from the power source (4.8 kJ stored energy). Weight of the aluminum in the paste was over twenty times weight of the wire. The role of the wire was to provide necessary energy for igniting the reaction in the paste.

Typical current and voltage profiles are shown in Figure 5. The wire was not able to carry the current to the peak value estimated from other parameters of the circuitry. The peak current was reached at 30 microseconds after triggering, 30 microseconds earlier than the characteristic peak current time. After the wire opened, the dissipation mode followed that of over damped dissipation in which $R > 2(L/C)^{1/2}$. The current did not die until almost one millisecond after the trigger. This type of decay appeared to be prerequisite for a strong pressure wave that followed (Figure 6). The pressure rise was found out to be an indication of the chemical reaction occurring in the premixed system. Analysis of the solid products can give an estimate of the extent of the reaction.



V: 3 KV/DIV I: 20 KA/DIV TIME: 50 microsec/DIV

Fig. 5. Voltage (upper) and current (lower) profiles of the pulse applied through premixed Al-water system.

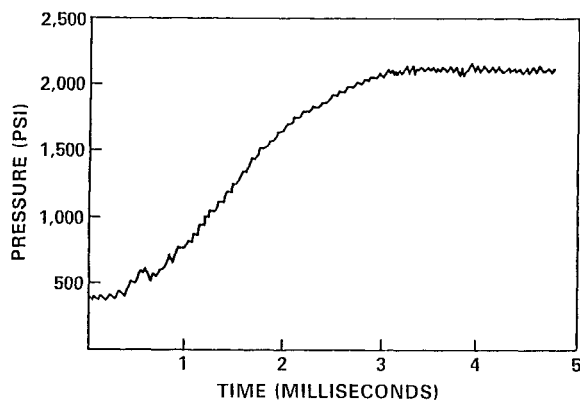


Fig. 6. Pressure rise curve for the same test as in Fig. 5.

It was attempted to reduce the energy required for the metal activation and its mixing with water by including magnesium inside the aluminum conductor. This method was to take advantage of the large difference in boiling point between the two metals, 1,107°C for Mg and 2450°C for Al (their melting point is almost the same, 650°C for Mg and 660°C for Al). During the pulse application through the metal system, the magnesium should boil first generating a force to push the molten aluminum into water. However, the real picture of the process would not be that clear-cut because the two metals could form a liquid alloy solution before magnesium starts to vaporize.

The physical arrangement of the metals was such that thin (0.5 mil) Al foil wraps fine magnesium particles (180 micron) forming a coaxial configuration with Mg inside. The weight of the Mg powder and the foil was 0.3 and 0.13 gm, respectively. For comparison, a similar test was made using aluminum particles wrapped with Al foil. The current profiles of the energy dissipation through these systems are shown in Figure 7 (the stored energy was 2.4 kJ for each case). The current profile shown in Figure 7 clearly shows the faster collapse of the current for Mg-Al system, about 20 microseconds earlier than for Al-Al system. Apparently the self-dispersing Mg-Al system attained high resistive state using much less amount of electrical energy per unit mass. However, it has to be pointed out that such sample arrangement makes it difficult to have a uniform explosion along the current path. The contact between the metal system and electrode is critical to assuring the uniformity.

If the chemical reactivities of Al and Mg with water are assumed to be the same, Mg-Al system should have higher chemical conversion per unit discharged electrical energy than Al-Al system. But the fact that it reaches high resistive state readily prevents the effective discharge coupled to the chemical reaction. The problem could be circumvented by changing the physical dimension of the metal-water medium.

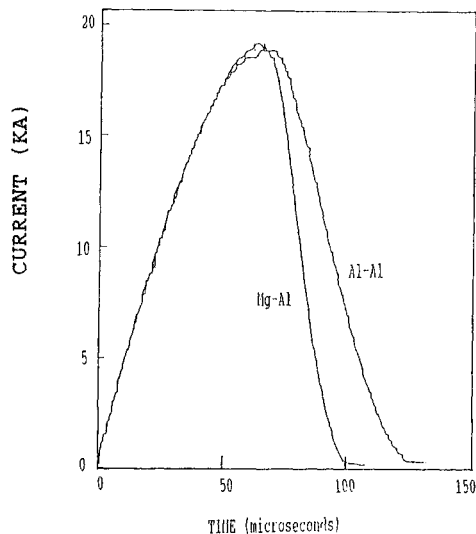


Fig. 7. Current profiles of the pulse applied through (a) Al-Al system and (b) Mg-Al system.

Electrochemical Combustion Model

The ideal use of stored electrical energy would be to consume only a small fraction of the energy for activating the metal and for its mixing with water. Most of the energy needs to be saved for the use for accelerating actual chemical reaction between the activated metal and water. The relationship between the events occurring in the conducting medium and partition of the pulse into them is illustrated in Figure 8. This study showed that the electrical energy needed for the first process can be saved by various methods. The next step is how to make most efficient use of the pulse for maximizing the chemical reaction. As pointed out earlier, inductive discharge is one way to make an efficient use of the pulsed energy for driving the chemical action. If the conducting medium already reaches a well mixed state having fairly high resistivity, the discharge can be made by a resistive decay, a rather long Joule heat dissipation, as seen in Figure 5. In the inductive discharge the coupling is weak, but the rate of the electrical dissipation is so high that the chemical reaction is sustained even after the pulse is gone. In the other mode of dissipation, the coupling lasts longer although the rate is low. Which mode is more efficient remains to be seen, but it should depend on the physical arrangement and the chemical nature of the conducting medium.

In either mode of the discharge, the microscopic details of the process occurring in the dissipating medium (for example, aluminum in water) between the electrodes can be depicted by the model shown in Figure 8. The medium can be described as a serial connection of many electrolysis cells, two aluminum particles with water between them constituting a cell. At one side of each cell hydrogen generation is the dominant process (cathode) while at the other side aluminum oxidation the major process. This process might be called an electrochemical combustion. It differs from an ordinary combustion in which the electrons taking part in the reaction are not subject to any external field. It also differs from an ordinary electrolysis because a steam bracket surrounds each metal particle that affects mass transport process as well as the double layer structure at the metal-water interface.

Since the electrons involved in the electrochemical combustion are aligned with the field direction, the reaction is under the control of external field. Based upon this model a systematic study might be attempted regarding the efficiency of the pulsed power in driving the chemical action.

Conclusion

Electrical pulsed power can be an effective tool for triggering and enhancing reactive metal-water reaction. The effectiveness is defined as how much and how fast chemical action can be driven per unit stored electrical energy. It critically depends on the pulse shape and on the physical configuration of the metal-

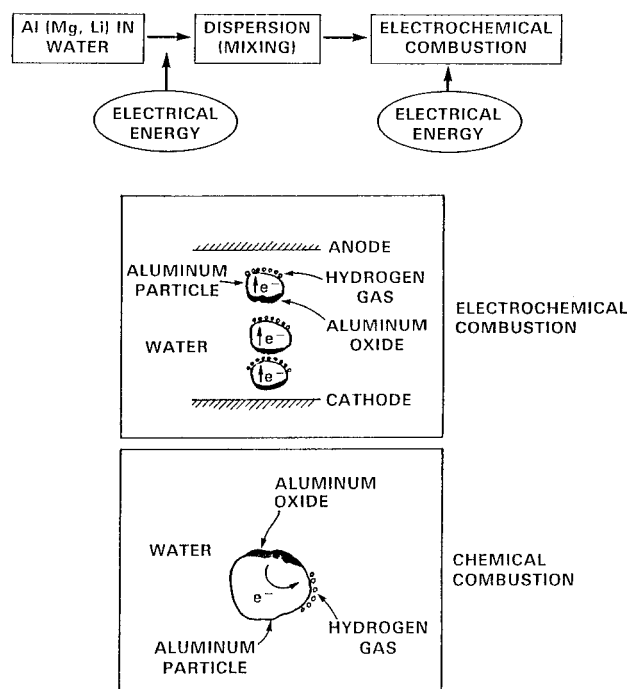


Fig. 8. Electrochemical combustion model.

water system. To ensure good coupling the metal-water system should attain highly mixed state almost by itself with using only a small portion of the stored electrical energy. Most of the stored energy should be saved for boosting the chemical reaction. Some techniques such as multiple pulse application and incorporating different kind of metal are proven to be promising for good coupling.

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