"Do water arc explosions release internal water energy? If so, what is the source of the released energy?"

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Section I: Abstract and Research Motivation

Abstract

This paper presents the results of an investigation into the phenomenon of "water arc explosions," in which an electrical arc is used to trigger the violent expansion of a small amount of water. Prior research has suggested that firing a high-current pulse through liquid water releases energy stored within the water. This manifests as kinetic energy and results in a veritable explosion, tearing the water apart into tiny fog droplets. Empirical measurements have shown that the explosions are much stronger than expected and that an explosion's kinetic energy can even exceed the electrical energy of the pulse that initiates it. Neither the source of the explosions' energy nor the mechanism by which it is released is well understood.

The purpose of this project was to verify that stored potential energy is liberated during a water arc explosion and to determine the nature and source of this liberated energy. Water explosions were created by discharging a high-voltage capacitor bank through 3-8 mL of water. The explosions' energies were measured by using them to launch a projectile into the air and extrapolating the explosion's average velocity from the height to which the projectile ascended. It was found that water explosions do in fact release energy and can have efficiencies of greater than unity; the energy released during the explosions is likely due to the difference between the heat capacities of bulk water and fog. These results allude to the possibility of harnessing water explosions to perform useful work.

Research Motivation:

A better understanding of water arc explosions and their causes may pave the way for the development of a novel new renewable energy source. Several recent papers (Hathaway et al., 1996; Hathaway et al., 1998; Graneau et al., 2000) have reported that rapidly dissociating liquid water into tiny fog droplets using a high-current, high-voltage pulse can release energy stored within the water. The released energy is supposedly "made up by atmospheric heat - that is, essentially by solar energy" when the fog droplets re-agglomerate into bulk water (Graneau et al., 2000, p. 116). Water explosions could therefore represent a method of converting atmospheric heat into directed kinetic energy, and since the explosions do not alter the water chemically (Hathaway et al., 1996; Graneau et al., 2000), the conversion process would be renewable. The prospect of harnessing clean, renewable bond energy in water is certainly noteworthy, especially since the world's carbonaceous energy resources are finite and their consumption is harmful to the environment.

Section II: Historical Context

In 2000, physicist Peter Graneau of Northeastern University published several extraordinary findings on water arc explosions. His paper, titled "Arc-Liberated Chemical Energy Exceeds Electrical Input Energy," presents evidence demonstrating that the kinetic energy of a water arc explosion can exceed the electrical energy of the current pulse used to initiate it (Graneau et al., 2000). These unanticipated results, if accurate, clearly require that the explosions release internal water energy.

To create a water arc explosion, a short, high-current pulse, on the order of several kiloamps over a duration of a few microseconds, is shot through a small quantity of water, which is usually, but not necessarily, distilled. The pulse imparts kinetic energy to the water and results in a veritable explosion. Previous research (Graneau et al., 2000; Hathaway and Graneau, 1998) has shown that the water is ionized and torn into tiny fog droplets (1-100 μm in diameter) during the explosion process.

Little research on water arc explosions and their energy efficiencies has been done since Graneau's 2000 paper, and no independent experimenters have yet confirmed Graneau's results. This paper presents a more in-depth analysis of the input and output energies of water arc explosions, providing needed accreditation for Graneau's results. Additionally, this paper proposes a theory on the source of the energy released during a water explosion and presents experimental evidence supporting this theory.

Section III: Summary of Past Research

Water arc explosions were first described in 1907 by John Trowbridge of Harvard University, though the phenomenon was not studied in detail until it caught the interest of Peter and Neal Graneau in the mid-1980s (Graneau and Graneau, 1985). By discharging a high-voltage capacitor through around 100 mL of water, the Graneau team was able to expel the water from a dielectric cup. At the time, the Graneaus conjectured that the arc discharge generated high-pressure steam within the water which expanded rapidly and resulted in the observed explosions. Measurements in Graneau and Graneau (1985) and Hathaway and Graneau (1996) indicated that water arc explosions were unusually strong.

Photographic evidence procured by George Hathaway and Peter Graneau in the mid-90's revealed that water arc explosions do not expel high-pressure steam (Hathaway and Graneau, 1996; Hathaway et al., 1998). They found that the water jet produced by an explosion is visible in air as a uniformly grayish cloud. Steam, on the other hand, does not scatter light and is invisible in air. Additionally, they observed that the water jet did not expand laterally as it left the barrel as a steam jet would (see Fig. 2). To explain these observations, Hathaway and Graneau hypothesized that water explosions tear the water into a multitude of tiny fog droplets and launch the droplets into the air. They described the phenomena as *cold fog explosions* to distinguish them from the adiabatic expansion of steam. Hathaway and Graneau believed that Ampere forces associated directly with the current pulse were responsible for tearing the water into droplets (Hathaway et al., 1998). However, if even a small amount of water is vaporized during a water explosion, the steam generated could also supply the mechanical forces for creating the fog.

In 1986, Azavedo et al. established that water explosions can accelerate the fog to supersonic speeds and that the explosions are highly current dependent (as cited in Graneau et al., 2000, p. 125). Then in 2000, Peter Graneau et al. published experimental results demonstrating that the kinetic energy of a water arc explosion can exceed the electrical energy of the current pulse used to initiate it. Graneau conjectured that "the most likely source of the explosion energy is that stored by hydrogen bonds between the water molecules. This bond energy is said to be equal to the latent heat of evaporation, and therefore could contribute up to 2200 J/g" (Graneau et al., 2000, p. 116). Graneau's paper did not provide any experimental evidence to support his theory, however.

Peter Graneau's son, Neal Graneau, demonstrated in 2011 that the internal water energy released in a water explosion can be also liberated by "electrospraying" (Graneau et al., 2011).

Graneau created a strong electric field and sprayed a fine stream of water through it; this dissociated the water into a highly ionized aerosol. Measurements of the electrospray system's energy inputs and outputs indicated that the water again contributed energy to the system.

George Hathaway, a former coworker of Peter Graneau, published a criticism of Neal Graneau's work in 2012. Hathaway argued that it is nonsensical to talk of releasing stored bond energy since the bond energy of liquid water is a negative quantity, and claimed that Graneau's results violated the Second Law of Thermodynamics by converting ambient heat into directed kinetic energy (Hathaway, 2012). Graneau issued a rebuttal later that same year. He contested that chemical bonds must store some non-zero amount of potential energy due to bond vibration and that Hathaway had misquoted the Second Law, citing a corollary that applies only to heat engines. "The type of generator proposed in [the paper] may have two macroscopic state changes but is, however, **not** a heat engine," Graneau said (Graneau et al., 2012, p. 112).

For a water explosion to release potential bond energy, the post-explosion fog must be in a lower-energy state (i.e. contain stronger intermolecular bonds, have more stable electron configurations, etc.) than the pre-explosion water. When the fog reforms into bulk water, it must therefore absorb energy from its surroundings to restore itself to its original higher-energy state. In other words, the fog must absorb heat as it agglomerates back into bulk water.

Tag (1980) presents a mathematical argument for why this might happen. Liquid water has approximately twice the specific heat capacity of water vapor (Stretton, 2004). Essentially, this means that liquid water can hold more heat energy per unit mass than water vapor can. Thus, when water vapor (or fog) condenses into liquid water, the water must absorb some heat to keep the pre- and post-condensation water systems in thermodynamic equilibrium. Tag goes on to say that "in the case of evaporation, this same energy…would be liberated" (Tag, 1980, p. 2349). Of course, condensation is an exothermic process; Tag merely argues that the amount of heat energy released during condensation is slightly less than the latent heat of vaporization since the liquid water must absorb some heat after condensing.

Section IV: Findings (Methods and Results)

Methods

In this project, a high-voltage energy storage capacitor bank was used to supply the pulse current needed to initiate the water explosions. The capacitor bank was charged to up to 15 kV via a voltage step up network, then discharged using a self-triggering spark gap switch. The entire water explosion apparatus was built from scratch and tested thoroughly by the author.

An attenuated voltage probe was used to measure the voltage across the capacitor bank during the charging phase. A Rogowski coil and digital storage oscilloscope were used to measure the pulse current during the discharging phase. These measurements were used to calculate the amount of electrical energy transferred to the water during an explosion event.

The water explosion chamber comprised a cylindrical cup with an open top and two electrodes. One electrode projected through the bottom of the cup and the other formed a ring around the inside of the chamber.

To determine a water explosion's kinetic energy, a porous balsa wood projectile of mass M was placed over the muzzle of the accelerator barrel. A water explosion within the barrel would launch the projectile vertically to a height h, and fog would penetrate into the projectile during the process.

Let m_0 be the total mass of the expelled water, m_1 be the mass of the water that bounces off the projectile, and m2 be the mass of the water absorbed by the projectile. The collision of m_1

with M is elastic, and the collision of m_2 with M is inelastic. Say m_1 has initial average velocity μ_{01} and m_2 has initial average velocity μ_{02}. After the collision of m_1 with M, say m_1 has average velocity μ_{f1} and M has velocity v_{M1}. After the collision of m_2 with M, say the combined mass M+m_2 has velocity v_{M2}.

M, m_0, and m_2 can be determined by before and after measurements of the projectile mass and water mass. h can be measured by taking a video recording of the explosion and analyzing the video frame-by-frame. The other quantities of interest, namely m_1, μ_{01}, and μ_{02}, must be found indirectly.

Energy and momentum conservation in the collision of m_1 with M require that:

$$m_1\mu_{01} = Mv_1 + m_1\mu_{f1}$$
$$\frac{1}{2}m_1{\mu_{01}}^2 = \frac{1}{2}M{v_1}^2 + \frac{1}{2}m_1{\mu_{f1}}^2$$

and momentum conservation in the collision of m_2 with M requires that:

$$m_2\mu_{02} + Mv_1 = (M + m_2)v_2$$

Examining the projectile, it follows from the conservation of mechanical energy that:

$$\frac{1}{2}(M + m_2){v_2}^2 = (M + m_2)gh$$

where g is the acceleration due to gravity. Solving (3) for v_2 yields:

$$v_2 = \sqrt{2gh}$$

By making some assumptions about the fog jet's mass and velocity distributions, we can use (1), (2), and (4) to solve for m_1, μ_{01}, and μ_{02} and then calculate the fog explosion's kinetic energy.

We can obtain a variety of approximations for the explosion's kinetic energy using different models for the explosion's velocity distribution. Each of the below velocity-mass functions (Fig. 3) could plausibly describe a water arc explosion given the behavior of the fog jet in Fig. 2 and the high-speed images presented in Hathaway et al. (1998).

If water explosions release energy because of the difference between the specific heat capacities of water and fog (as discussed towards the end of Section III), the amount of energy released should be directly proportional to the water's temperature. In light of this, experiments were conducted to determine if such a direct relationship existed between a water explosion's kinetic energy and the water's temperature. Distilled water was heated and cooled to a variety of temperatures (using either a hot pad or an ice bath), then placed in the explosion chamber and exploded. The amount of time elapsed between the water's placement in the chamber and the explosion was measured, and a simple exponential cooling model was used to predict the water's temperature at the time of the explosion. The explosion's energies were calculated as before using a balsa wood projectile and video camera.

To determine the amount of heat (if any) absorbed by a quantity of post-explosion fog as it agglomerates back into bulk water, a balsa wood absorber was strapped over the muzzle of the accelerator barrel. The absorber would capture most of the water expelled by an explosion in the barrel. Before an explosion event, the temperatures of the water and balsa wood absorber were both measured, and after an explosion, the final temperature of the water—balsa-wood system was measured by inserting a temperature probe into the absorber. Knowing these temperatures and the heat capacities of the water, balsa wood, and temperature probe, both the initial and final thermal energies of the water—balsa-wood—temperature-probe system can be calculated and compared, revealing whether any heat was absorbed by the water after the explosion. The resistive heating that takes place in the water arc during an explosion is also factored in to these energy calculations; this heat is calculated using the discharge pulse width and the underdamped ringing frequency.

Results:

Figure 4: **Displays the average explosion energy efficiency as a function of the water's temperature T at the time of the explosion. m_0 is approximately 5 g for all data points.**

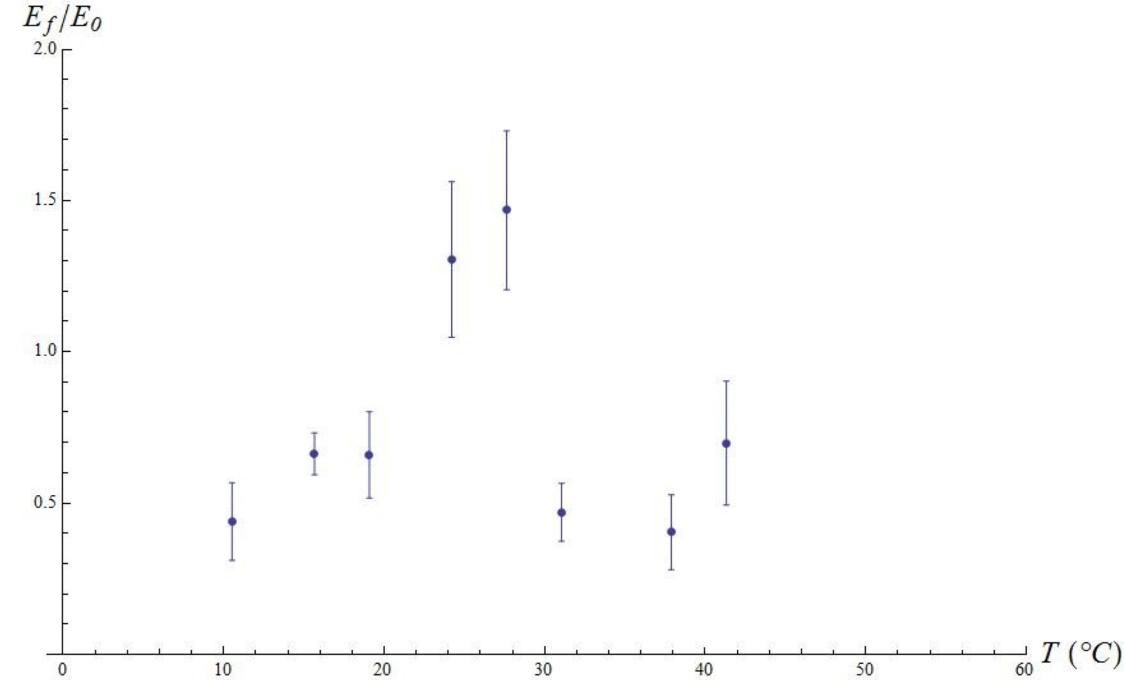
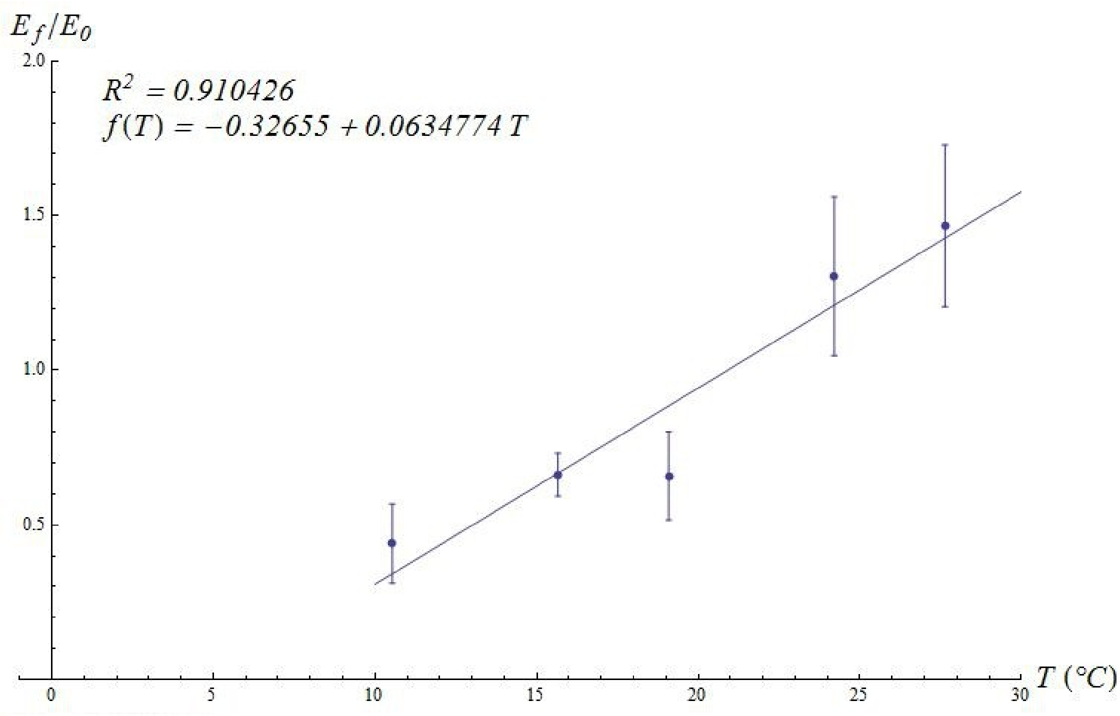


Figure 5: **Uses a least-squares regression to fit a linear trend line to the first five data points in Fig. 3.**



Section V: Conclusion

The first goal of this project was to verify that water arc explosions liberate stored potential energy. The results in Table 1 clearly indicate that they can. Looking at the last 3 columns of Table 1, it can be seen that the water explosion's kinetic energy was even greater than the pulse discharge's electrical energy in three of the eight shots displayed. If electrodynamic forces alone were responsible for the explosions, their kinetic energies should be only a fraction of the total input energy. These results are consistent with the findings reported in Graneau et al. (2000) and require that some sort of internal water energy is released during a water arc explosion.

Note that the accuracy of a kinetic energy measurement depends largely on the explosion's actual velocity-mass distribution. If this actual distribution differs significantly from the model function in eqn. (5), the calculated value for E_f may significantly over- or underestimate the explosion's actual kinetic energy. A more sophisticated measurement system (e.g. a phase Doppler particle analyzer) for determining a fog explosion's velocity and mass distributions would be needed to calculate E_f with greater accuracy.

The second goal of this project was to determine the nature and source of the energy released during a water explosion. One theory, mentioned in Graneau et al. (2011), holds that the energy released during a water arc explosion is due to the difference between the heat capacities of bulk water and fog.

Conceptually, liquid water can hold more heat energy per unit mass than fog or water vapor. The constant-pressure specific heat capacity of liquid water, C_{PL}, is 4.1813 J/(g·K), and the constant-pressure specific heat capacity of water vapor, C_{PV}, is 2.080 J/(g·K). Thus, when an amount of liquid water is dissociated into fog, the fog must release energy previously stored as heat in the liquid water.

The amount of energy released is proportional to the difference in the heat capacities of the water and fog. Procedurally, this energy E can be calculated for a unit mass of water as

$$E = (C_{PL} - C_{PV})T$$

where T is the water's absolute temperature and C_{PL} and C_{PV} are the specific heat capacities of liquid water and fog, respectively. Tag (1980) presents a more thorough discussion of this relationship.

It is likely that only a small part of E contributes to the explosion kinetic energy; the remainder would be dissipated as heat to the environment.

This energy E should also be released when water is vaporized. In this case, the released energy would be undetectable since it is small compared to the latent heat the water absorbs as it evaporates. However, it may also be possible to liberate E without needing to supply the full latent heat using directional (i.e. non-thermal) forces, such as those induced by the high-current arc in a water explosion. Here, the water is not vaporized (it is merely converted to fog), but its specific heat capacity is still reduced (Stretton, 2004). By this reasoning, there should be a fog droplet size that maximizes the released energy by balancing the droplets' decreased heat capacity with their increased surface tension energy related to the breaking of intermolecular bonds (which is equivalent to the latent heat of vaporization). Future efforts to optimize a water explosion's output energy might seek to achieve this optimal droplet size.

If equation (6) is the reason for water arc explosions' high energies, then the energy released during an explosion should be directly proportional to the water's temperature. Figures 4 and 5 exhibit such a direct relationship between explosion energy and temperature, at least until about 30 °C. Above 30 °C, the water evaporated readily while the capacitor bank was charging and condensation could be observed around the sides of the accelerator barrel. If equation (6) governs water explosion behavior, greater evaporation would decrease explosion strength, as the evaporation would dissipate stored energy that could otherwise have contributed to the water explosion. Further experimentation that controls for evaporation is needed to determine the relationship between explosion strength and temperature at higher water temperatures.

On a molecular level, the release of energy during a water explosion can be understood as a reorganization of the water's hydrogen bonding network. Inelastic neutron scattering experiments have revealed the existence of two different kinds of hydrogen bonds in water, each bond with a different strength (Li and Ross, 1993). The "strong" and "weak" bonds have vibrational force constants of 32 meV and 24 meV, respectively, and exist in water in a strong-to-weak ratio of about 2:1 (Graneau, 1998). During an explosion event, forces associated with the high-current arc discharge tear the water into fog droplets. This consumes a certain amount of mechanical energy, which is stored as additional surface tension energy in the fog. However, the molecules in the fog droplets now have significantly fewer neighbors than they did in the bulk water and can more easily reorient themselves into lower energy states. Thus, weak hydrogen bonds can reform into strong hydrogen bonds, and Van der Waals attractions can collapse into weak hydrogen bonds. This bond reformation would, of course, release energy, and could conceivably supply the kinetic energy of a water explosion.

For a water explosion to release potential bond energy, as described above, the post-explosion fog must be in a lower-energy state than the pre-explosion water. The fog should then absorb heat as it agglomerates back into bulk water. Looking at the last three columns of Table 2, one can see that this is the case. For each shot measured, the thermal energy of the water—balsa-wood—temperature-probe system decreased significantly over the course of the explosion event. The difference between the initial and final thermal energies was about 75 J on average, which is sufficiently large to account for the explosion kinetic energies reported in Table 1. Of course, since not all the exploded fog was captured in the balsa wood absorber in any of the shots summarized in Table 2, each reported value for ΔQ underestimates the total heat absorbed by the fog upon reforming into water.

It is possible that evaporative cooling is partially responsible for the low values T_f seen in Table 2. However, the evaporation of water from the balsa wood absorber is thought to have been negligible while data was being collected since the absorber's mass did not decrease significantly while its temperature was being measured.

Since there is energy released during a water arc explosion, it may be practical to harness the explosions to perform useful work. One could conceivably create a "water explosion engine" by replacing the gasoline explosions in an internal combustion engine with water explosions. The engine would not produce carbon dioxide or any complex hydrocarbons, and may be more efficient than its petroleum-burning counterparts.

Water explosions may also be used to drive magnetohydrodynamic (MHD) generators and directly produce electrical power. The generator's electrical output energy could exceed the electrical input energy if high enough efficiencies were achieved.

It may also be possible to create a jet propulsion system using water explosions. By mounting an explosion chamber on the back of a boat, submarine, or similar vessel, so that water from the surroundings can flow freely through the chamber, the vessel could be propelled through the water by the forward thrust from an explosion in the chamber. The device would work much like a jet engine or MHD propulsor, and may prove to be more efficient than either of these since the water itself would contribute energy to the system.

The creation of a device for harnessing the energy of a water explosion is beyond the scope of this project. Designing and testing such a device would be a worthwhile topic for future research.

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