THE ANOMALOUS STRENGTH OF COLD FOG EXPLOSIONS CAUSED BY HIGH CURRENT WATER ARCS

N. Graneau

History of Water Arc Explosions

The unusual strength of explosions caused by a pulsed current flowing through water plasma was first noticed in 1907 by Trowbridge [1] in his early high voltage laboratory at Harvard University. When he passed an arc through a spray of water, the resulting explosion was louder than in ordinary laboratory air. During the Second World War, Früngel measured the strength of water arc explosions and published his results in 1948 [2]. He concluded that they were not caused by heat and steam and freely admitted that he was unable to explain the phenomenon. Soon after Früngel's publications, water arc explosions found applications in electrohydraulic metal forming [3] and underwater pulse echo sounding [4]. In 1969, the US Bureau of Mines issued a long report on their investigation into using water arc explosions for rock fragmentation [5]. In one experiment the investigators at the Twin City Mining Research Center noticed that the energy output was apparently 156% of the input. This result was reported, but treated as an experimental error.

Not until the mid-1980s was the scientific basis of the puzzling explosions more extensively researched. At MIT [6,7]. It was shown that the discharge of 3.6 kJ of stored capacitor energy would create pressures in excess of 20,000 atm. in 7 ml of water. 3.6 gm of water was ejected from an accelerator barrel at a velocity of the order of 1000 m/s, sufficient to penetrate a ¼" thick aluminium plate [8].

At the time it was thought that the water was flying through the air as a coherent liquid. No evidence of boiling and steam formation could be detected and all the water found after the explosion was cool. Accepting the general view that plasmas are quasineutral and therefore do not explode as a result of Coulomb forces, the available evidence seemed to leave little doubt that the explosions had to be driven by electrodynamic forces. This discovery motivated a ten year investigation into the electrodynamics of water arcs. The Lorentz force could only account for a small fraction of the observed force. Ampère's force law [9], a less well known electrodynamic force law still fell short of measured values by more than an order of magnitude. The search for a new electrodynamic explanation was finally abandoned in 1994.

Details of a Water Arc Accelerator

Figure 1 shows a cross-section through a typical accelerator which has been extensively tested since 1984. In the latest experiments, the metal components (black in figure 1) were made of copper and the remainder was nylon. The central electrode was 6mm diameter, and the barrel had an inner diameter of 12 mm. The device is constructed so that all parts create a tight sliding fit. Typically the breach to muzzle length was about 20 mm. The circuit was simply a capacitor connected to the two terminals (the barrel and the baseplate) via a very simple mechanical drop switch. For the experiments presented here, a 0.5μF, 20 kV capacitor was used, and a typical water charge was 2 - 5 ml.

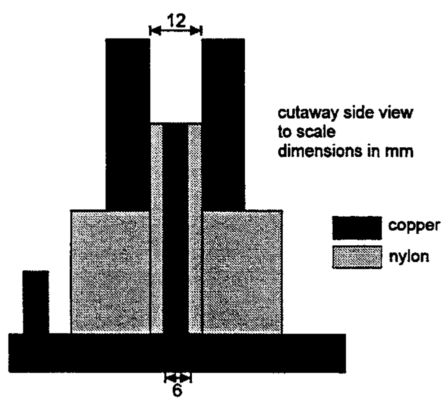

Figure 1 : A typical water-arc accelerator

Evidence of Fog

High speed photography has revealed the emergence of a whitish -grey high velocity discharge from a water arc accelerator barrel. The discharge is interpreted to be fog due to light scattering by the multitude of small droplets. Water vapour would be invisible in air, and large water drops and films of waters are only detectable as thin lines which are reflections from the water surface. Video records taken by Richard Hull in the TCBOR laboratory in

N. Graneau is in the Pulsed Power & Applications Group, Dept. of Engineering Science, University of Oxford

Virginia, have revealed that the fog slows down rapidly as it pierces the atmosphere, and on reaching the ceiling rolls around like a cloud for a number of seconds while it evaporates. Fog droplets that float in air are said to be between 1 - 100 μm in diameter.

In the highest energy shots, the tip of the fog jet is pointed, indicating that it was travelling at supersonic speed, pushing a conical shockwave of air ahead of it. With less energy in the explosion, the head of the fog jet has a mushroom shaped front which shows that it travelled at subsonic speed. Larger drops of water are seen to follow behind the fog, some of which are millimeters in diameter and travelling at velocities of only around 1 m/s.

Balsa-Wood Projectile

When a balsa wood cylinder was stood on the muzzle of the accelerator, the fog penetrated deep into the porous material and transferred momentum to the wood. To limit the throw height of the balsa-wood projectile, it was inserted into a tight fitting brass cap. This also stopped the balsa-wood from being shattered by the explosion. Weighing the projectile before and after a shot made it possible to determine the dry mass M of the projectile and the absorbed fog mass, m. Since the two masses travelled together at the initial projectile velocity, v_0, momentum conservation requires

$$m\,u_{av} = (M+m)\,v_0 \qquad (1)$$

where u_{av} was the average velocity of the absorbed fog. The fog damage to the balsa was so severe and the division between the velocities of the fog and slow water so distinct, that it is considered a safe assumption that all of the high speed fog was absorbed by the wood. From energy conservation it follows that

$$1/2\,(M+m)\,v_0^2 = (M+m)\,g\,h \qquad or \qquad v_0 = \sqrt{2gh} \qquad (2)$$

where g is the acceleration due to gravity and h is the maximum height gained by the projectile measured by video camera. From Eqs.(1) and (2), the average fog velocity could be calculated with

$$u_{av} = \frac{(M+m)}{m}\sqrt{2gh} \qquad (3)$$

and thus the minimum estimate of the kinetic energy of the fog is

$$E_{k,min} = E_{water} = 1/2\,m\,u_{av}^2 = \frac{(M+m)^2 g\,h}{m} \qquad (4)$$

Eq.(4) gives us a method of measuring the fog energy, E_{water}, so that we can compare it to the energy stored in the capacitor before the discharge, E_{stored}. Figure 2 which was a typical experiment shows the ratio of (E_{water}/E_{stored}) as a function of the volume of the initial water volume. This data shows that while this ratio is quite variable from shot to shot, it does sometimes demonstrate an overunity energy gain. This and other sets of data appear to indicate that there is an optimum value of the initial water volume for a given accelerator geometry. It is hypothesized that if there is too much water in the barrel, then it simply provides too much resistance to the high speed fog moving up from the bottom electrode. However a certain amount of water clearly has a beneficial effect, which may be due the fact that it inertially confines the high current arc region so that the fog droplets formed by the fast electrodynamic forces do not spread apart too far before the later acting chemical forces take over.

There is now a large body of evidence confirming this near breakeven behaviour, however all of the existing experiments do suffer from shot to shot variability. This is presumably due to the statistical nature of arc breakdown, thus leading to variable current density and location from one discharge to another.

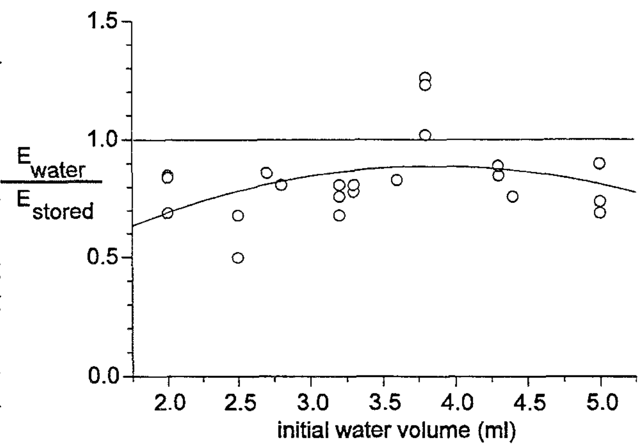

Figure 2 : energy gain vs. water volume

Theoretical Understanding

The most likely explanation of the fog explosions is that they are caused by the liberation of intermolecular bonding energy when the bulk water is transformed into tiny fog droplets. This bonding is caused both by hydrogen bonds and Van der Waals forces, and the energy stored by the bonds is roughly equal to the latent heat of the water, and is found to be 2.3 kJ/gm at room temperature. The creation of a large number of droplets is thought to be caused by the mechanical effects of the electrodynamic forces in the arc discharge. A certain amount of mechanical energy is thus used to create the droplets and is consequently stored as surface tension energy. However the molecules in the small droplets now have significantly fewer neighbours than in the bulk water and can thus reorientate themselves more easily into lower energy states. These lower energies imply that the bonds become stronger. This bond redistribution behaviour is normally observed in thin films of water called vicinal water. Recent results of inelastic incoherent neutron scattering (IINS) experiments in water and ice [10] have revealed the existence of two strengths of hydrogen bond. In water they are found to have bonding vibrational force constants of 24 and 32 meV, and are referred to as the weak and strong bonds respectively. If in the newly formed droplet, some of the weak bonds drop to the strong bond energy in a quantum shift, there will be a consequent release of kinetic energy causing the vicinal droplets to repel each other, resulting in the observed explosion. The same is true if a hydrogen bond is formed between a pair of molecules that were previously held together only by Van der Waals forces.

After the explosion, in order to restore the droplets to their normal bulk state, some energy input must be required, and in our case this must come from atmospheric heat. This process can occur away from the explosion region and over a much longer time. Therefore the explosion is conjectured to be a sudden release of energy from the water that was initially stored by atmospheric heating, and is later restored into the water after the explosion also by atmospheric heat, while in the meantime the net gain in kinetic energy can be harnessed for useful means.

Figure 3 clarifies how atmospheric heat is stored in the bulk water. When molecules condense into a droplet, the system is heated by the kinetic energy produced by the drop in potential energy from (a) the molecule and droplet infinitely far apart and (b) in the bonded position, and represents the quantity of energy normally referred to as latent heat. In figure 3, this is represented by E_2+E_4. This process represents the creation of atmospheric heat as a result of collisions of the incoming molecule (attracted by the droplet) with other vapour and atmospheric molecules. If the molecule arrives at the droplet with a non-zero kinetic energy, this will heat the droplet additionally. Similarly when two molecules inside the droplet form a hydrogen bond or change from a weak to a strong bond, the drop in potential energy must also create an increase in kinetic energy, represented by E_3. This process represents the liberation of thermal energy stored in the water which must have been there to allow weak bonds and unbonded molecules to exist. Figure 3 also shows that the energy cycle must be completed by reabsorption of atmospheric heat E_1+E_4 in order to restore the water back to ambient vapour. This cycle thus makes it possible to effectively tap the solar energy that is stored in normal bulk water.

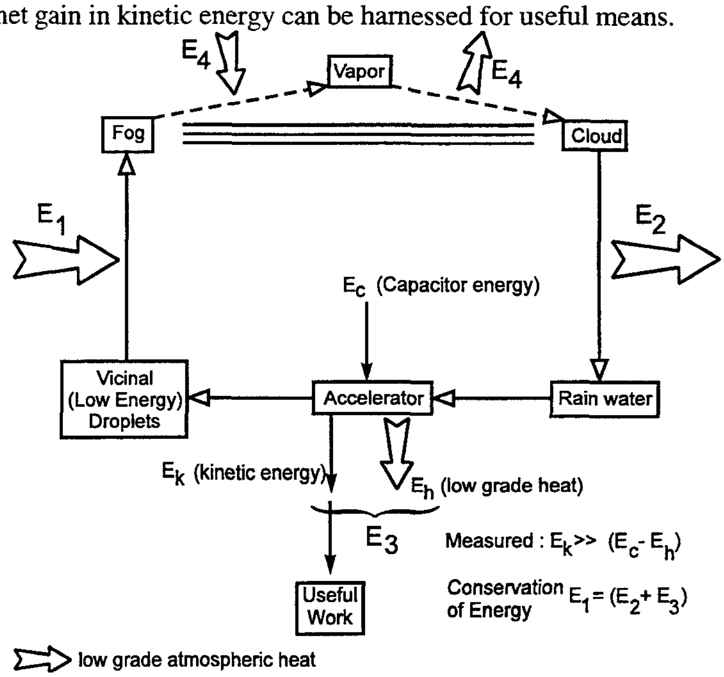

Figure 3 : Renewable Water Energy Cycle

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