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Design of a hypersonic waterjet apparatus driven by high explosives

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The design and construction of a hypersonic waterjet apparatus is described. Jet velocities from 0.5 to 5 km/s have been achieved using a high explosive charge. Images are obtained *in situ* on various target substrates using a high-speed framing camera. Experimental results are shown for the impact of high velocity waterjets on propellants and high explosive samples. By observing the impact of the waterjet at a wide range of velocities a safety threshold can be determined where no reaction takes place. [DOI: 10.1063/1.1388212]

The investigation of supersonic liquids and their interaction with surfaces is needed for the fundamental understanding of many processes. High velocity liquid jets have been utilized for numerous applications including rain erosion studies,[1–4] cavitation,[4,5] jet cutting of materials,[6,7] bonding of metals,[8] and studies of fuel jets for diesel engines.[9] Although a significant amount of research has been undertaken to describe the theory behind these jets, there remains unexplained and poorly understood phenomena.[10]

Jets used for these types of investigations can be of two forms: continuous and impulsive. The field of continuous waterjets is well established commercially for cutting and cleaning applications. Jets formed by continuous methods typically have velocities under 1 km/s and operate at pressures up to 500 MPa. At these extreme pressures the diameter and range of a continuous jet is quite limited. For higher velocities, impulsive jets can be used where velocities in excess of 3 km/s can be achieved. Impulsive jets have the advantage of providing much higher pressures and instantaneous power levels, but suffer from the lag time between experimental shots.

Currently, there are several methods of generating high-speed impulse liquid jets. One approach is by compression of large volumes of water to high pressures and allowed to expand by an adiabatic process through a small aperture.[11] However, the most common method, which was first demonstrated by Bowden *et al.*[12] is to fire a deformable lead slug from an air rifle into a stainless steel injector containing a few microliters of water sealed with a neoprene disk. This method is now well established and has been implemented and modified over time by various groups.[1,13] As the slug comes into contact with the stainless steel nozzle, the projectile and the neoprene move forward as an intermediate free piston and extrude the liquid through a narrow orifice. Liquid velocities can be obtained that are 3–5 times the projectile velocity up to ∼1.5 km/s but with careful design velocities of ∼5 km/s can be achieved which are as high as 12 times the projectile velocity.[14]

Our design is similar to that of Bowden *et al.* However, rather than firing a slug though the air, a high explosive charge is used to accelerate a piston. The advantages of this method are that the apparatus consists of one piece, thus eliminating any alignment issues, and a rather large amount of water can be utilized (up to 5 ml with the current design). Timing for high-speed photography is incorporated by the use of a precision detonator.

Figure 1 shows a schematic for the waterjet apparatus. The lower barrel section is constructed from tempered steel and contains the piston and nozzle assembly. The piston accelerates 5 ml of water rapidly by an explosive charge (up to 6 g) initiated by an exploding bridge-wire detonator (EBW). An EBW detonator is used due to the high precision timing needed for the image capture system. The piston/barrel arrangement was experimentally designed to eliminate contamination of the upper chamber by the gaseous products of

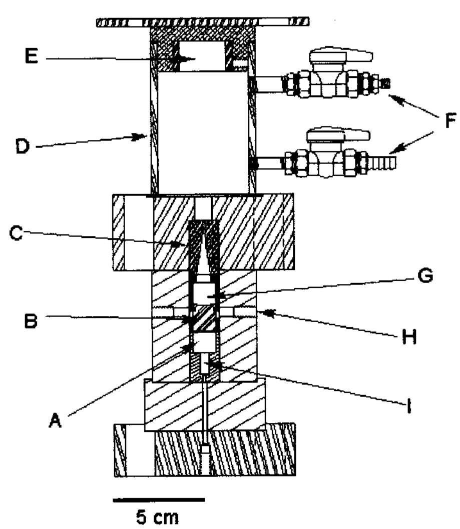

FIG. 1. Schematic of the supersonic waterjet apparatus. (a) High explosive charge, (b) piston, (c) supersonic jet, (d) perspex tube, (e) target, (f) gas feedthroughs, (g) water reservoir, (h) vents, and (i) exploding bridgewire initiator.

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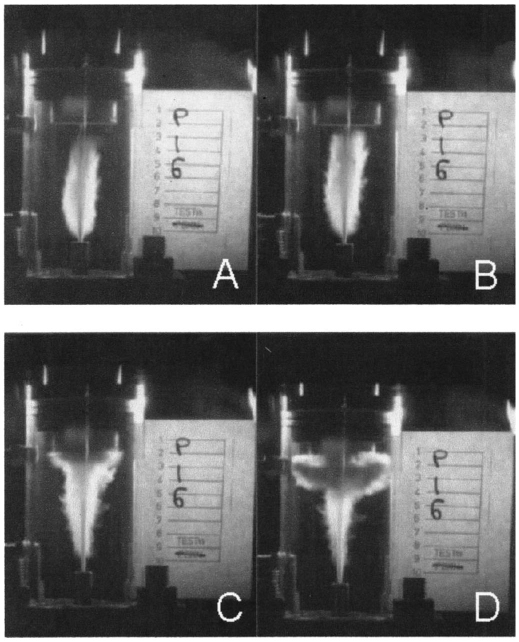

FIG. 2. Series of photographs showing a 2.8 km/s waterjet. The time between each frame is 6.7 μs. The scale bar on the right of each image is in centimeters.

the propulsion charge. This involved incorporating vents into the barrel assembly to allow the propulsion gases to escape. The nozzle design is similar to Laval nozzles used in ultrahigh vacuum studies and are discussed in detail elsewhere.[15,16] The velocity of the jet produced primarily depends on the nozzle construction and diameter and the amount of high explosive used to accelerate the piston. Waterjet velocities were observed ranging from 0.5 to 5 km/s.

The upper chamber is constructed out of a clear Perspex tube that acts as a containment vessel. The target is fixed at the top of the tube with a standoff distance of 100 mm from the nozzle. Two gas-sampling ports allow for a controlled atmosphere within the containment vessel and a method of collecting gaseous products produced by the jet and target interaction. The main species of interest are the nitrite and nitrate ions, which are indicative of and specific for reactions of explosives and propellants. The transparency of the Perspex tube also provides an optical path to obtain high-speed images of the waterjet event. This design has good survivability and can last up to 50 shots before a major overhaul of the apparatus is necessary.

Due to the potential violent nature of the waterjet apparatus and target material, all tests were performed within an explosive chamber. The chamber has an internal capacity of 25 m^3 and is rated for 1 kg of TNT. It has a 1.4 m internal diameter with four ports allowing for gas sampling tubes, high voltage firing and flash synchronization. Each test is observed with a high speed-framing camera[17] capable of recording up to 1 250 000 frames/s. Standard camera flashes are used as illumination sources.

Figure 2 shows a series of images of a typical test. The velocity is determined by comparing the imaging rate of the camera to the distance the jet from travels between frames. For this series of images the jet was traveling 2.8 km/s. As can be clearly seen, the central section of the jet is the best formed and is the section primarily responsible for the damage to a given surface. Due to the hypersonic nature of this jet, decompression occurs after leaving the nozzle. This effect along with drag and Taylor instabilities causes the disruptions observed.[18]

The instrument was primarily designed to investigate the effects of high velocity water impacts on explosive and propellant charges due to the extensive use of waterjets in demilitarization of ordinance. For this set of tests a high explosive was used as the target. Figure 3 shows a series of images of an impact with a pentaerythritol tetranitrate (PETN) high explosive where a visible reaction (detonation) has taken place. A divergent nozzle is used to create a larger contact area on the explosive. In Fig. 3(a) the jet is about half way to the target and is clearly visible in the center of the image. By Fig. 3(d) the waterjet has impacted the target and a reaction can be observed. In Fig. 3(e) a total detonation occurs as the target is consumed by the reaction. Violent reactions of this nature often cause destruction of the Perspex tube. Figure 4 shows a histogram of jet velocities versus frequency for observable and nonobservable reaction for a class 1.1 propellant. The histogram shows that the point at which a reaction occurs is not well defined, rather there is a range of velocities where reactions may, or may not, be observed. This transition region also includes experimental results where a brief onset of a visible reaction occurs but does not lead to a total detonation. The results show that there is an obvious safety threshold where a reaction will not take place. In this case, waterjets with velocities less then 2 km/s do not initiate reactions. Currently 34 different explosives and propellants have been investigated. These results are invaluable for

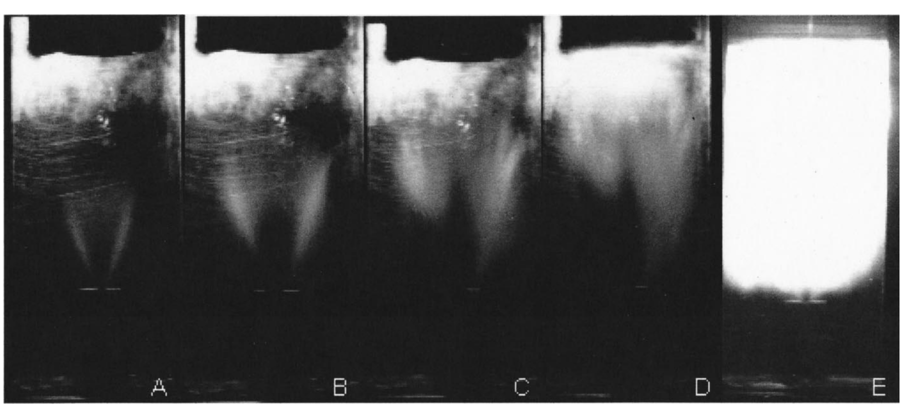

FIG. 3. Shows the effect of a 1.7 km/s jets impact on PETN, a high explosive. The jet can be seen in the middle of the frame in (a). The jet impacts the target at (d) where a reaction of the substrate is observed which leads to the complete detonation of the target (e).

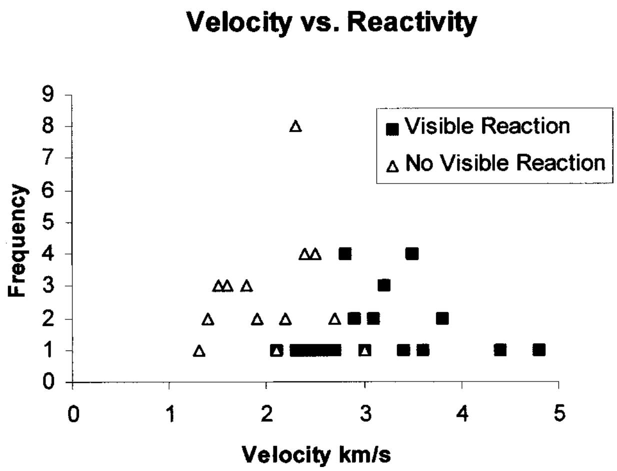

FIG. 4. Graph showing the number of observable/nonobservable reactions on a class 1.1 propellant vs the waterjet velocity. An observable reaction is any combustion of the target material; from a brief reaction to a sustained reaction. It can clearly be seen that there is a region between 2 and 3 km/s where both observable and nonobservable reactions occur and the lower value is considered the threshold for safety considerations.

safety considerations in the waterjet washout, machining of high explosives and propellants, and sensitivity tests.[19,20]

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