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SIMULATION AND EXPERIMENTS REGARDING THE FORMATION OF WATER JETS USING EXPLOSIVE CHARGES

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Explosively formed water jets are used in counter-terrorism operations for the neutralization of improvised explosive devices. As opposed to classic shaped charged, a high velocity water jet has the ability to impact a package and disrupt the explosive train inside, without causing the detonation of the explosive charge. This paper compares to methods for calculation of tip velocity, one based on the Gurney equations and the other one based on Euler multi material – FEM computer simulation. Several types of explosive configurations are considered, with different geometrical shapes of the water lens and the quantity of explosive. The Gurney velocity and the numerical results are compared with experiments conducted using plastic explosive and water, contained in a 3D printed shaped container. Experimental results validated the Gurney open sandwich analytical method, with an average error of 10%.

Keywords: water disruptor, explosives, Gurney equations,

1. Introduction

Improvised explosive devices (IEDs) are one of the principle means of action of terrorist attacks, both in civilian, military and governmental scenarios. IED's can pose a great threat both to people and infrastructures. IEDs are concealed in different common packages or cases like boxes, bags, backpacks and others. The neutralization of an IED is a difficult task, because in the construction of the IED there can be different types of sensors (photodiodes, accelerometers, pressure sensors, contact sensors etc.) designed to trigger the explosive train of the IED in case of any intervention to it. Disruptors are counter terrorist equipment designed to propel an inert mass trough the casing of an IED, causing the

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disruption of the continuity of the explosive train (battery, cables, triggers, detonating cap, explosive charge), before any of the triggering sensors could react and cause the initiation of the IED. To meet this objective, the propelled mass has to be accelerated high enough to be able to disintegrate the package before triggering the electronic circuits of the IED. In the same time, a high energy delivered to the IED trough the propelled mass by a disruptor system could cause shock initiation of the detonating cap or the explosive charge, rendering the neutralization procedure dangerous. The design of a disruptor system will have to take into account the two mentioned issues regarding the neutralization of an IED.

The propelled inert mass consists of particle or pellet shaped materials like sand, aluminum, ceramic or steel [1]. Because of its advantageous mechanical properties when subjected to shock and its availability, water is a good choice to be used as inert mass with an explosive based disruptor. The other advantage related to using water as an impacting inert mass, is that it cannot cause the detonation of conventional explosive materials [1,2,3]. Water disruptors can have a planar symmetry configuration or can be axial symmetric, having the explosive charge placed behind a water liner (lens in axial symmetry). By the detonation of the charge, energy is transferred to water, being propelled and focused intro a jet directed to the target (IED). The most important parameter of the obtained water jet is the velocity of the tip, giving the device its disruption capability.

In the past decade, explosive-driven water jet technologies have seen increased usage in various real-world applications, particularly in counterterrorism and EOD. Systems like the Hydra-Jet, the MiniMod Mk2 and other commercial water disruptors have become critical tools for neutralizing improvised explosive devices (IEDs) without triggering detonation, thanks to their ability to focus water jets at high velocities to break explosive circuits safely. In military operations, these water disruptors are also employed for tasks like breaching operations and mine clearance, where their ability to precisely disrupt or destroy targets with minimal collateral damage has proven essential. The physics behind these technologies closely aligns with the experimental and computational results discussed in this paper, further validating the relevance of high-velocity water jets generated by explosives for modern operational requirements. As these technologies advance, understanding the behavior and optimization of water jets will play a crucial role in improving the safety and effectiveness of explosive-based tools in high-stakes scenarios.

Lupoae et al. [2] considers that the energy liberated by the explosion of the energetic material is retained in part as internal energy of the detonation product and as kinetic energy retained of the detonation gases or transferred to the propelled material. They studied Gurney equations [4] for closed symmetrical systems and for asymmetrical open systems, and compared the results with experimental tests. When using Gurney energy to calculate the velocity of the propelled fragments they observed big differences between calculations and experiments (>30%). If they introduced the efficiency factor [5] and characteristic quantity [6], they succeeded to reduce the error in calculations to 15%. They concluded that the loading density of the material and the heat of detonation can be used in calculation, instead of Gurney energy, leading to an acceptable difference of 5% between calculations and experiments.

Enache et al [1] investigated the use of Gurney equation for estimation of water jet velocity, in an annular concentric configuration. They compared this analytical method with a numerical computer simulation made using the Solid Particle Hydrodynamic (SPH) method. Authors observed that the Gurney method tends to overestimate the jet velocity, because it does not consider the vaporization of water droplets and the turbulent mixing between the gaseous detonation products and the water droplets in the energy balance. Using SPH numerical simulations, the authors conclude that if the particle dimension is well chosen, a maximum 10% difference between experiments and numerical simulation can be achieved, in terms of water jet velocity.

In this paper we present the calculations made with Explo5 V6.06.02 thermochemical code to calculate the detonation parameters of a plastic explosive (90% RDX, 10% polymeric binder) at a loading density of 1,6g/cm^3. The obtained detonation parameters and the John-Wilkins-Lee (JWL) coefficients are further used in order to estimate by an analytical model (Gurney model for open face sandwich) and by numerical simulation (Euler multi material) the water jet velocity. The calculated values are compared to field experiments, conducted with open sandwich structures of water and plastic explosive.

2. Calculation of the detonation parameters

For the calculation of detonation parameters of the plastic explosive used in the experiments, the Explo5 V6.06.02 thermochemical code was used. The calculations are made by the following procedure [7]:

- The state of gaseous detonation products is described by Becker-Kistiakowsky-Wilson equation of state (BKW EOS);
- The state of solid products of detonation (carbon) is calculated by using Murnanghan equation of state;
- The thermodynamic functions of gaseous products (as real gases) are derived using BKW EOS;
- The thermodynamic functions of condensed products (as compressible) are derived using the Murnanghan equation of state;
- The thermodynamic functions of detonations products in standard state are calculated from the enthalpy (which is expressed in a forth degree polynomial form as a function of temperature);
- The chemical equilibrium of detonation products is calculated by using the free-energy minimization method, like described by White-Johnson-Dantzing
- The system of equations describing chemical equilibrium in detonation products is solved by a modified Newton-Raphson method;
- The Chapman Jouguet point (C-J point) is determined as the point on the shock adiabat of detonation products at which the detonation velocity (D) has its minimum value.

The detonation parameters of the plastic explosive used in the experiments were computed, based on the input data presented in table 1.

Table 1

Input data for the calculation of detonation parameters of the plastic explosive

Parameter	Value
Component 1: Hexogen (RDX)	90% by mass
Component 2: Binder (Rubber, plasticizer, taggant)	10% by mass
Brutto formula of the mixture	$C_{3.853}H_{6.952}N_{4.812}O_{4.828}$
Oxygen balance	-51.37%
Loading density	1.6 g/cm^3
Enthalpy of formation (at 298.15 K)	254.09 kJ/kg
Relative molar mass	197.93 g/mol explosive mixture

The initial pressure of the system was set to 0.1 MPa, the shock adiabatic calculation was limited to a maximum pressure of 38 GPa and the density increase ration was set to 1.025. For the isentropic expansion of the products a density decrease ration of 1.1 was set, while the freeze out temperature of the detonation products equilibrium was set to 2250 K. The cut-off pressure for the calculation of the detonation energy was set to 100 MPa. The BKW set of constants used in the calculation were: Alpha =0.5, Beta =0.38, Kappa =9.41, Theta = 4250.

The detonation parameters and the JWL coefficients obtained in the calculations are presented in table 2. The adiabatic shock of the explosive is presented in Fig. 1 while the isentropic expansion of the detonation products is presented in Fig. 2.

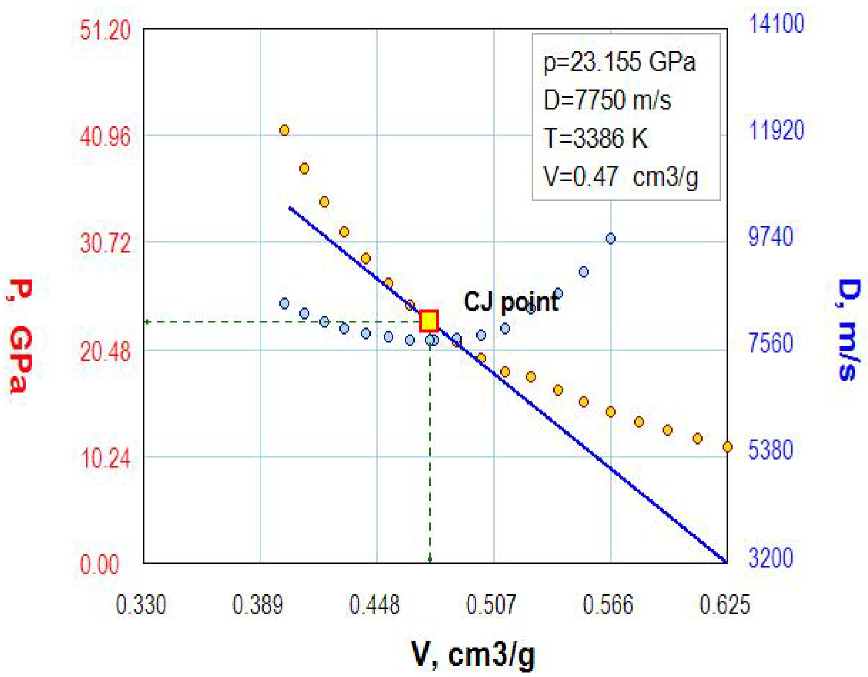


Fig. 1. The adiabatic shock line of the detonation of the plastic explosive

Table 2

Detonation parameters at C-J point and JWL coefficients for the plastic explosive used in experiments

Parameter	Value
Heat of detonation	-5129.86 kJ/kg explosive
Detonation temperature	3385.65K
Detonation pressure	23.15 GPa
Detonation velocity	7750.19 m/s
Density of products	2.11 g/cm^3
Internal energy of products	6873.31 kJ/kg explosive
Compression energy	1743.44 kJ/kg explosive
JWL coefficients	**Value**
Total energy of detonation	8.028 kJ/cm^3
Coefficient A	469.3694 GPa
Coefficient B	11.2673 GPa
Coefficient C	1.19132 GPa
Coefficient R1	4.4040008
Coefficient R2	1.181704
Omega	0.362682

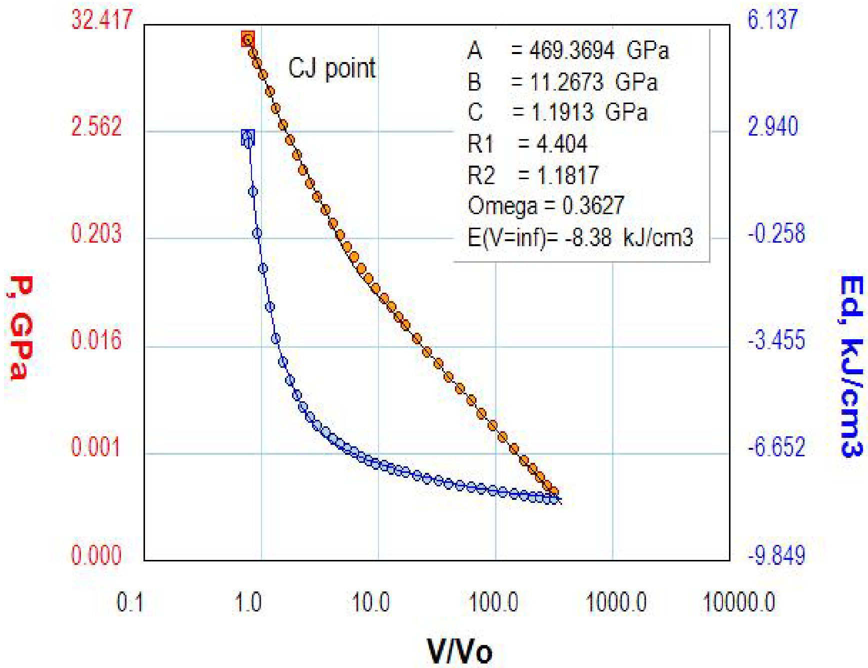


Fig. 2. The expansion isentrope of the products of detonation

3. Calculation of water jet velocity by Gurney analytical method

For the calculation of water jet velocity the open face sandwich configuration Gurney equation was implemented, as described by Cooper [8], and presented in eq. 1.

$$\upsilon_W = 10^3\sqrt{2E}\left[\frac{(1+2\frac{M}{C})^3+1}{6(1+\frac{M}{C})}+\frac{M}{C}\right]^{-1/2} \quad (1)$$

Where υ_w is the water jet velocity, in m/s, M is the mass of water in kg and C is the mass of explosive in kg. The term $\sqrt{2E}$ is the Gurney velocity and is calculated by the formula described in eq. 2.

$$\sqrt{2E} = 10^3(2\frac{E_d(V/V_0=2.9)}{\rho_0})^{1/2} \quad (2)$$

Where $\sqrt{2E}$ is the Gurney velocity in m/s, E_d is the energy of detonation, extracted from the expansion isentrope of detonation products, at a relative volume V/V0=2.9, like demonstrated by Stimac et al [9], and ρ_0 is the loading density of explosive.

For an open sandwich structure, like illustrated in figure 3, the actual quantity of explosive (C) or the quantity of water (M) can be expressed as the ratio M/C, which is direct proportional to the thickness of the two materials in the structure and their relative density. The ratio M/C is calculated by the use of eq. 3:

$$\frac{M}{C} = \frac{h_w\rho_w}{h_c\rho_0} \quad (3)$$

Where h_w is the thickness of the water layer in m, ρ_w is the density of water (1000 kg/m^3), h_c is the thickness of the explosive layer and ρ_0 is the density of the plastic explosive (1600 kg/m^3).

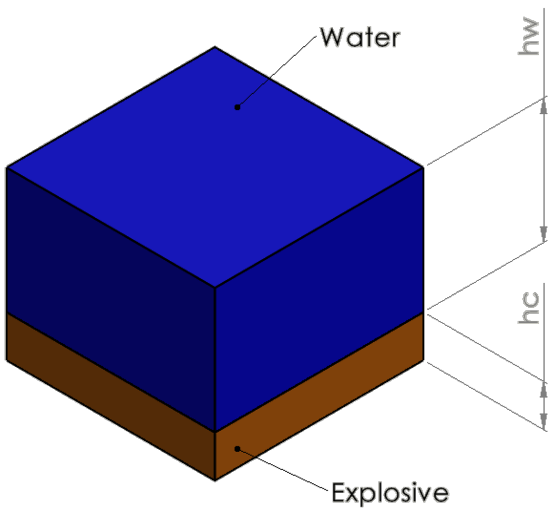


Fig. 3. The open sandwich structure

4. The numerical simulation

An Euler multi material 2D simulation with planar symmetry has been implemented in order to study the propulsion of a water jet by a detonating explosive. An Euler part has been created with the dimension of 70mm on X axis and 300mm on Y axis. Rectangular mesh has been used, with constant size of 0.25 by 0.25 mm, resulting in a computational domain of 384000 cells. A boundary has been implemented on all computational domain limits, consisting in a flow out condition for all materials. The Euler part is represented in Fig. 4.

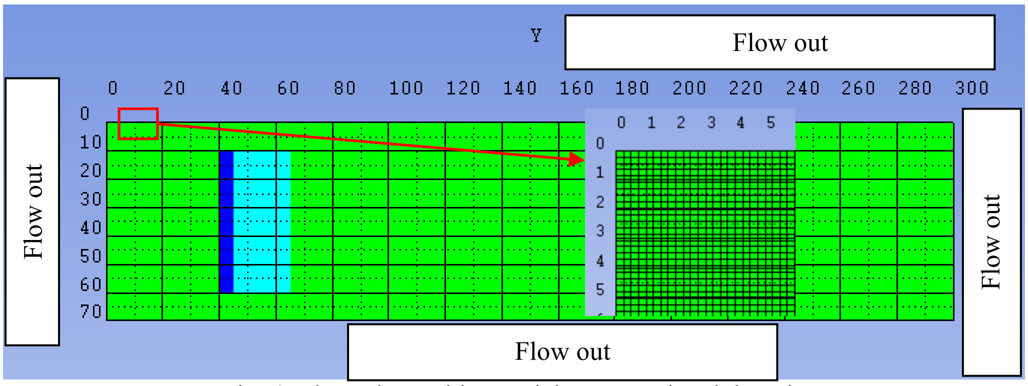


Fig. 4. The Euler multi material computational domain

The materials used in the simulation consisted in plastic explosive, with JWL EOS, calculated previously with Explo5 Software, Air with Ideal gas EOS, like described in [10] and Water, with Shock EOS, like described in [11]. The explosive material was placed 40 mm away from the Y axis origin and 10 mm away from X axis origin. The water material was placed in front of the explosive, in regard to Y axis, having different layer thickness, thus giving different M/C ratios. A detonation line has been placed on the Y=40mm line, all along the explosive, in order to simulate the detonation wave in the material. Three arrays of gauges have been placed in the water, in order to record the Y velocity versus time history, in different points in the material. The gauges move along with the water, being placed in three arrays, placed 1, 10 and 19 mm away from the explosive and 10 mm away of each other, like represented in Fig. 5.

A total limit of 10^6 cycles and 10ms limit was implemented, with a maximum energy fraction error of 5%. The damping options were set to quadratic viscosity of 1 and linear viscosity of 0.2. The Euler solver was set to a weighted method for strain rate calculation and an equilibrium method for pressure calculation. The history profile was saved for each 10^{-7} seconds in simulation.

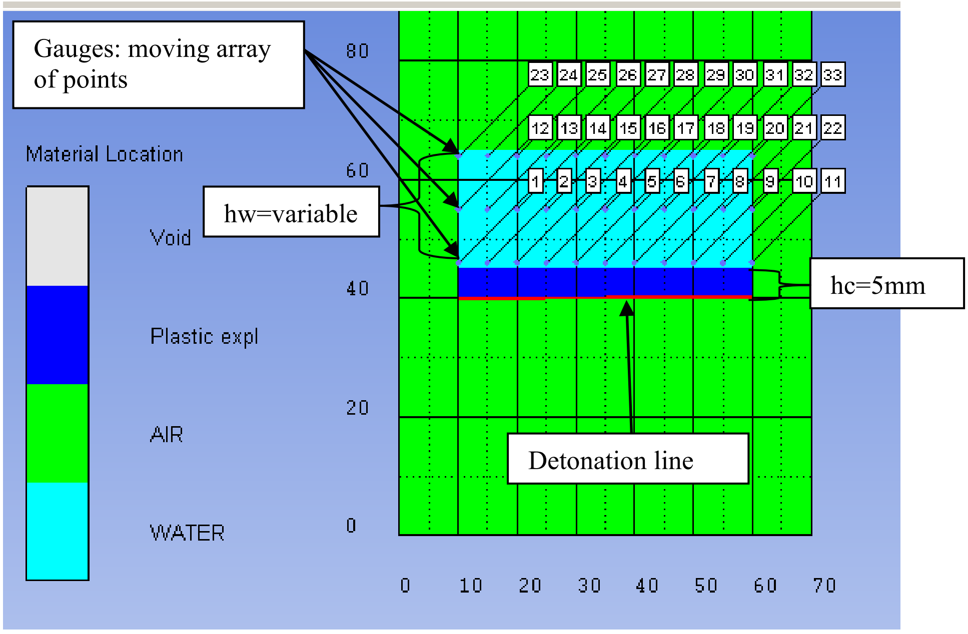


Fig. 5. The material, detonation line and gauge placement in Euler computational domain

In figure 6 the absolute velocity versus time is presented for the configuration with h_w=10mm (M/C = 1,25), while in figure 7 the Y velocity is represented in a time plot, for each gauge and the average Y velocity for all Euler cells filled with water.

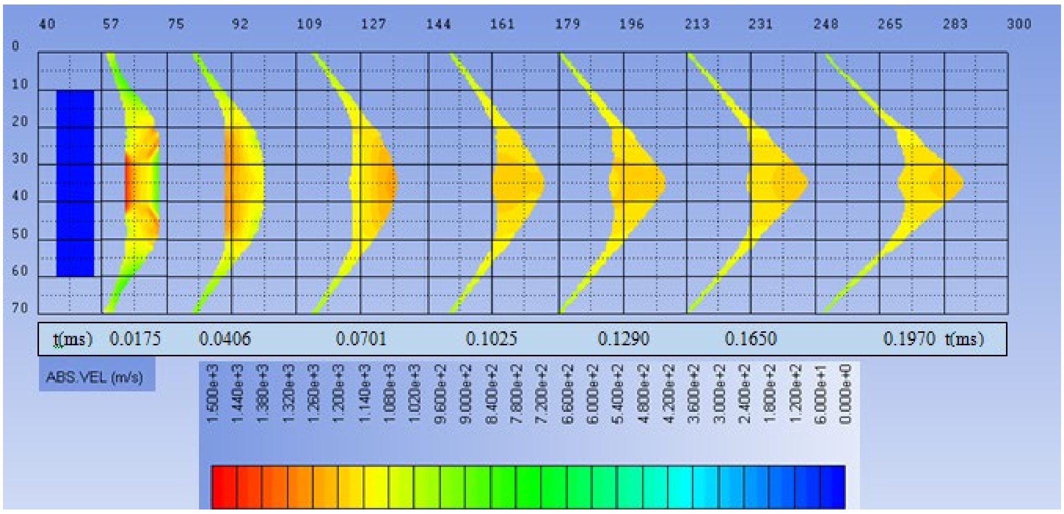


Fig. 6. Velocity and shape of the water jet at 200mm away from the detonation point for configuration with h_w=10mm (M/C=1.25)

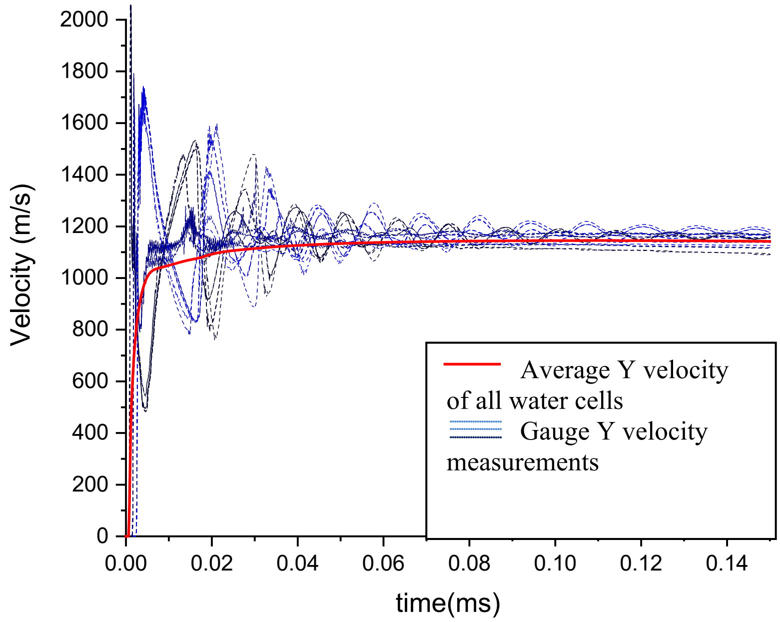


Fig. 7. Gauge point and average material velocity for configuration with h_w=10mm (M/C=1,25)

For h_w of 5 to 30mm (M/C in the interval 0.625 to 3.75) the water jet velocity is represented in figure 8, when the water jet reaches 200mm away from the detonation point. The average Y velocity for all water cells is plotted against time in figure 9, for different MC.

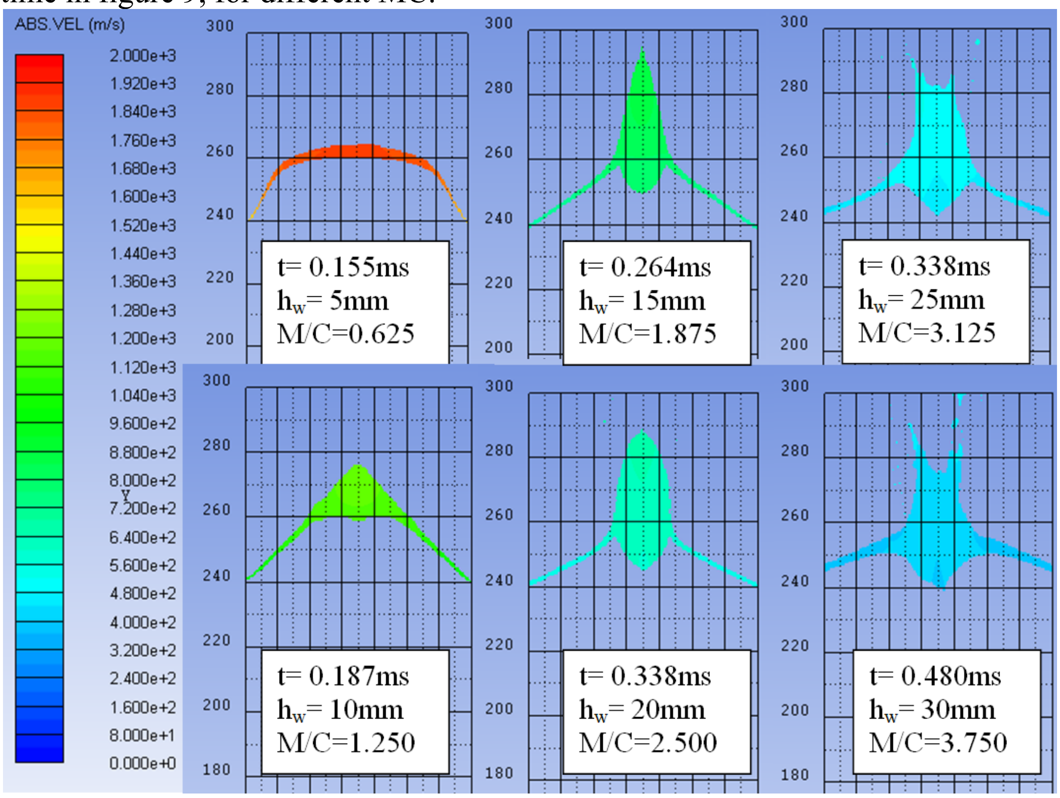


Fig. 8. Velocity and shape or the water jet at 200mm away from the detonation point

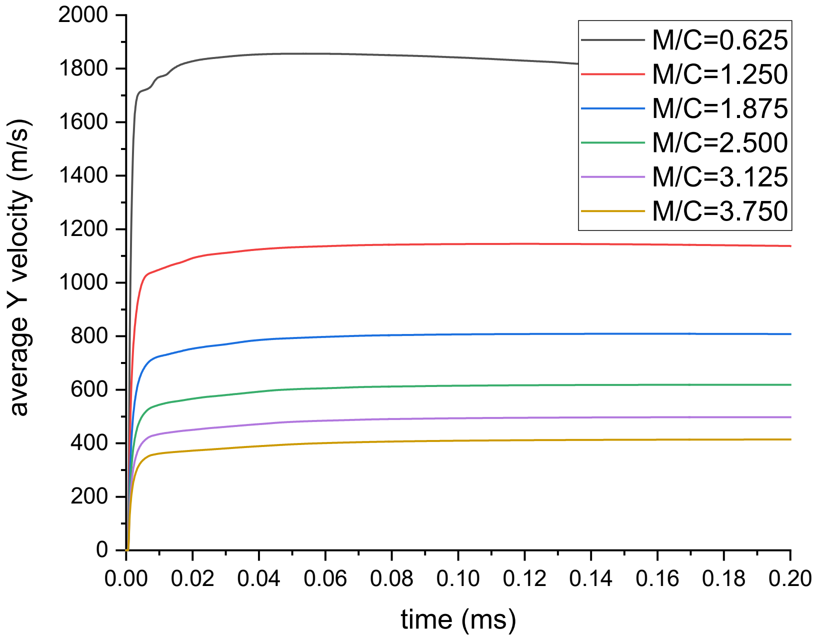


Fig. 9. Average Y velocity for different configurations (MC= 0.625-3.750)

3. Experimental determinations

The experimental determinations have been performed on planar open sandwich configurations consisting of a layer of plastic explosive with a constant thickness of 5mm and a layer of water with a variable thickness (5-30mm) in order to reproduce the M/C ratio of 0.625, 1.250, 1.875, 2.500, 3.125 and 3.750. Both the explosive and the water were loaded in a plastic case made of PLA (polylactic acid) fabricated by 3D printing. The wall thickness of the case was 1mm, and the interior dimensions were 50mm by 150mm. In order to avoid reflections from the ground, the device was suspended on 4 PVC tubes with the length of 1m. The explosive charge was initiated with an electric detonator (number 8 type) from one side (5mm away from the margin) in order to develop full detonation until reaching the opposite side of the case. The device construction is represented in figure 10. For each M/C the tests were repeated at least two times, in order to obtain an average value for the water jet velocity.

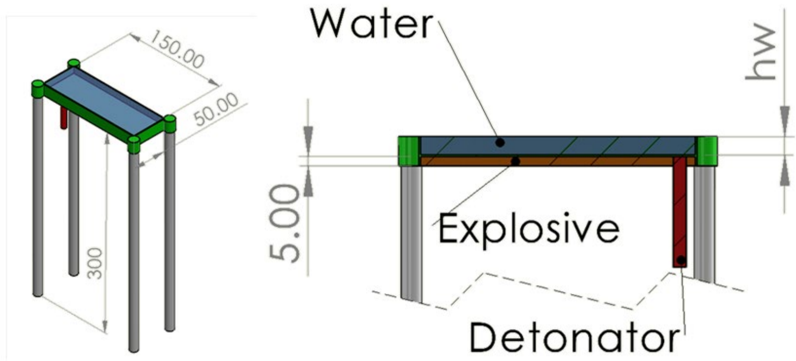


Fig. 10. The explosive device configuration.

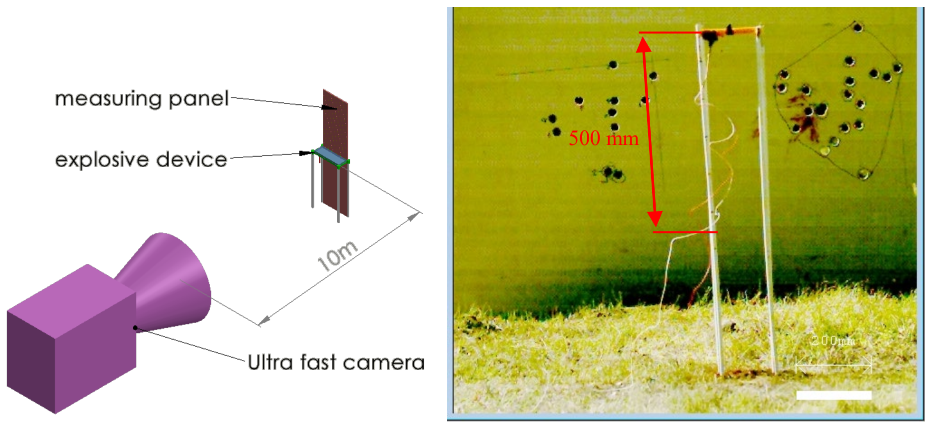
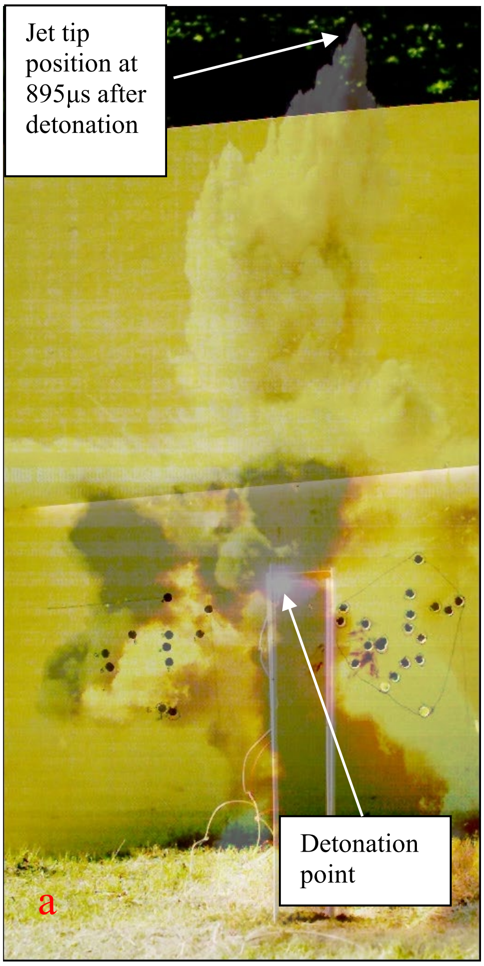


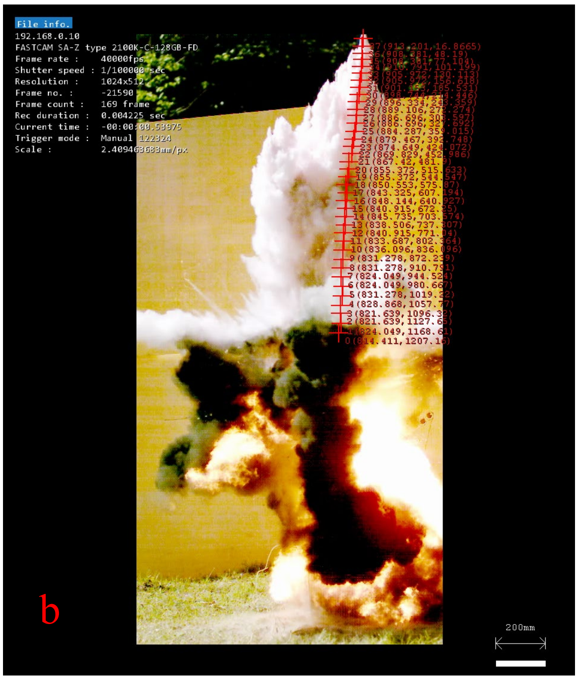
Fig. 11. The experimental setup

The water jet velocity was recorded using an ultra-fast video camera Photron Fastcam SA-Z. The camera was set to an acquisition rate of 40.000 fps (frames per second), using a shutter speed of 1/100.000s. The spatial calibration was performed on one of the PVC tube standers by marking each 100mm distance. The jet tip velocity was calculated by interpolation of time-distance measurements on the camera. The experimental setup is represented in Fig. 11. In order to better observe the jet trajectory, the water used in experiments was colored using a red pigment.

4. Results

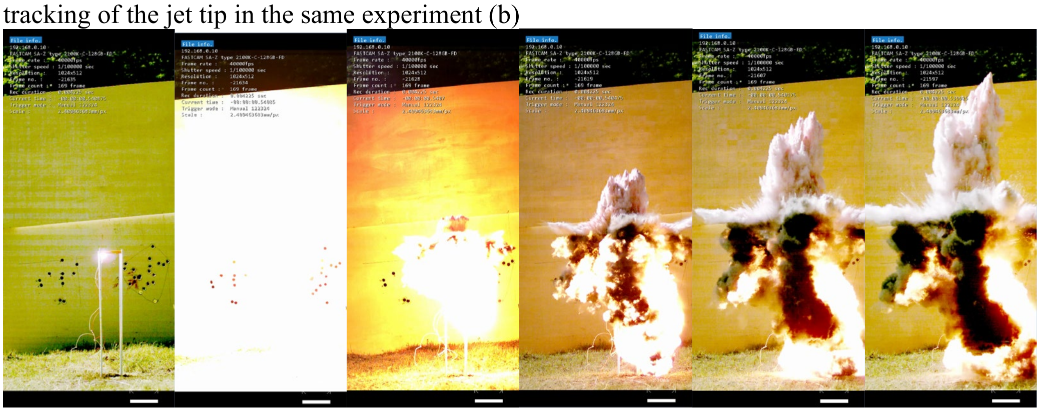
The experiments revealed that the highest velocity of the jet tip was achieved in the opposite part of the electrical detonator position, and validated the numerical approach, to consider a line detonation in a 2D planar symmetry pane, like shown in figure 12. The experiment could not be observed in the first ≈100μs after detonation because of the overexposure of the camera sensor, shown in Fig. 13.





Frame by frame tracking in x,y coordinates of the jet tip. The first 250mm trajectory could not be tracked because of sensor overexposure. The frame-to-frame time step is 25µs.

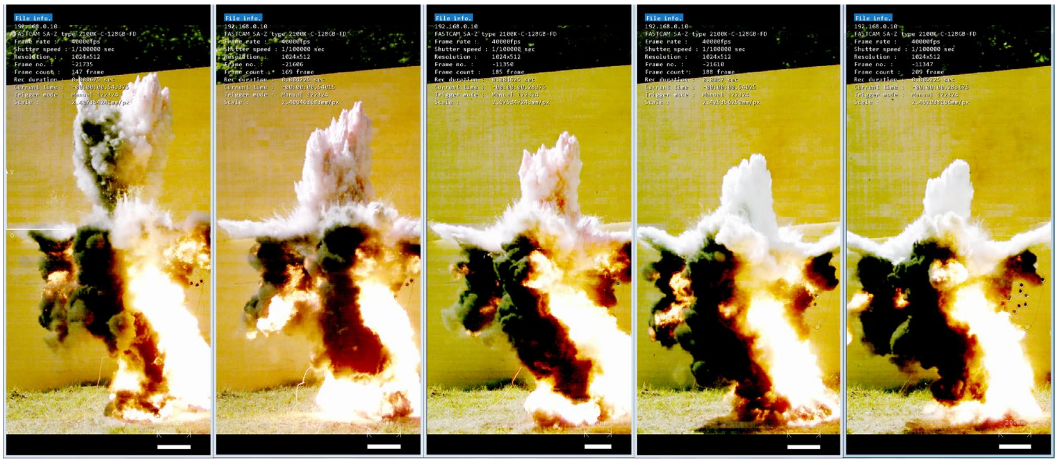
Fig.12. Overlayed images of the experiment with a 1.875 M/C ratio (a) and frame by frame tracking of the jet tip in the same experiment (b)



0 µs 25 µs 175 µs 400 µs 700 µs 950 µs

Fig 13. Water jet propagation in the first millisecond after detonation, in the 1.875 M/C ratio experiment

As expected, the ultra-fast recordings revealed a proportional velocity of the water jet with the M/C ratio. High M/C ratio experiments developed a more homogenous propulsion with a single broad tip while low M/C experiments developed turbulent propulsion with several tips. In case of M/C = 1.250 the detonation gaseous products overpassed the water jet tip, showing a gray trail of smoke and debris, as it can be seen in Fig. 14.



1.250 M/C 1.875 M/C 2.500 M/C 3.125 M/C 3.750 M/C

Fig. 14. Water jet development after 700µs after initial detonation of the electric detonator

The experiments revealed that the water jet is decelerated along the trajectory in contradiction with the FEM numerical simulation (fig. 9) where the velocity is relatively constant. The analytical method does not consider any deceleration of the projected mass. The higher velocity jet tip is more decelerated on the trajectory while the higher M/C ration experiments develop a water jet tip that is relatively constant in velocity. This is consistent with the interaction of water particles with the surrounding air. The frame-by-frame measurements of the jet tip velocity is represented in Fig. 15.

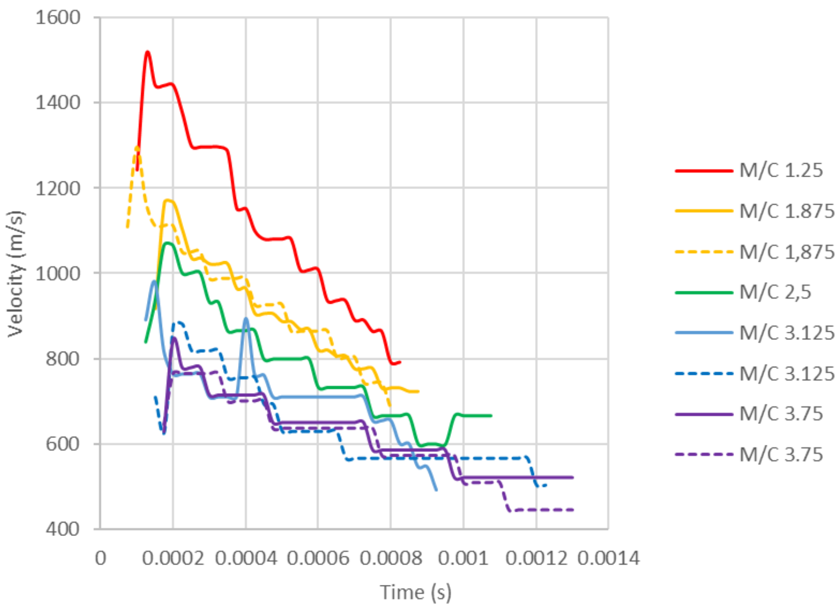


Fig. 14. Water jet velocity time dependent plots extracted from ultra-fast video recordings

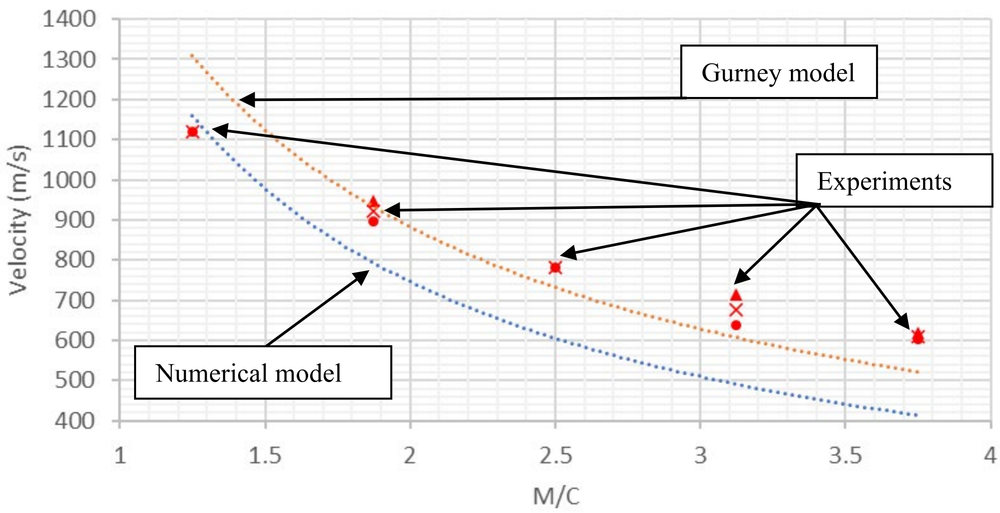


Fig. 15. Water jet velocity time dependent plots extracted from ultra-fast video recordings

The tip velocity considered for validating the analytical and the numerical model was the averaged velocity from each measurement made along the trajectory, of a given experiment. The triplicate results for each M/C could not be retrieved for each experiment because of camera trigger was set to sound, and in some cases started before of the experiment, from sourounding enviroment sounds. The experimental results are presented in figure 15, as points while the analytical model and numerical model is presented as curves in the M/C-velocity plot.

The comparative results show that the numerical model is more appropriate to simulate water jet propulsion in open sandwich configuration only for low M/C ratio (<1.5), where a more turbulent mixing with air is taking place. For a M/C > 1.5, the analytical model is more accurate, considering the average velocity values extracted from the time-velocity plots of the experiments.

An error was calculated for each theoretical model, considering as reference for each M/C the value obtianed by averaging the velocity obtained in each duplicate of triplicate experiment. A global error of 19% was calculated for the numerical method while the Gurney analytical model in open sandwich configuration had a acceptable accuracy, with a global error of 10%. The error computed for each M/C calculations is presented in Fig. 16.

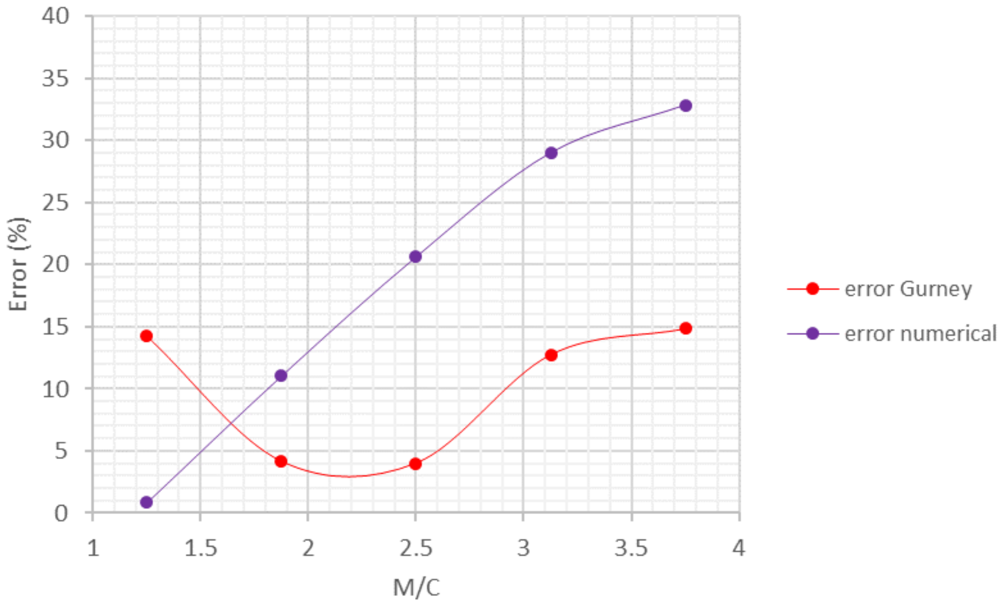


Fig. 16. The error computed for the numerical and analytical model with reference to the measured velocity in each M/C field determinations

4. Conclusions

The Gurney open sandwich model and Euler 2D FEM model was evaluated in terms of accuracy regarding the velocity calculation of water jet propulsion by detonation of explosion. Experiments were conducted where the M/C ratio varied in 1.25-3.75 interval. The following conclusions can be drawn:

The analytical model is not a time dependent model, and the calculated velocity is constant with time. For this reason, the model did not accurately calculate the velocity of water jet tip in low M/C ratios, where the tip velocity has a steep descend with time evolution, as the interaction with surrounding air is more turbulent at higher velocities. At higher M/C where the velocity of the water jet tip is relatively constant and has averaged values under 1000m/s, the analytical model has acceptable accuracy.

The numerical model does not have acceptable accuracy, having the tendency to underestimate the velocity of the developed water jet. More material models and numerical approaches, like SPH (solid particle hydrodynamics) could be evaluated in order to further investigate the model.

The numerical model accuracy, validated with varied M/C open sandwich water-explosive experiments, proved to have a 10% average error, comparable to other models presented by Lupoe et al., with a 5% error and Enache et al., with a 15% error.

The Gurney model proves to be a useful tool in the approximation of water jet velocity generated by explosive propulsion and can be implemented in the design and development of water jet disruptors for countering IEDs.

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