PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

ISSN 2081-5891 **10, 2 (36), 2019, 23-41**

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

Experimental and Theoretical Determination of Water-Jet Velocity for Disruptor Application Using High Speed Videography

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Received by the editorial staff on 2 July 2018
The reviewed and verified version was received on 11 May 2019

DOI 10.5604/01.3001.0013.2114

Abstract. Experimental and theoretical determination of water-jet velocity using high speed videography for disruptor application is reported in this paper. Water-jet disruptor extensively uses the water as a liquid projectile. It helps to destroy improvised explosive devices (IEDs) or explosive devices (EDs) by breaking detonating cord in the system, making it non-operational. The use of such system against suspected objects is a fashion that continues to be met tremendous achievement. Such a device is also known as explosive ordnance disposal (EOD) disruptor. It is used by bomb technicians or squad to make disable and/or neutralize at a safe distance. The primary purpose of an EOD disruptor is to remotely open or provide destruction to suspected objects. To "remotely open" is to open the suspect objects, exposing their contents. "Provide destruction" means penetrating, cutting, or removing the components of the fusing system in order to make them disable.

A secondary purpose of a disruptor is to create a means of access (for example, through a window or door of vehicle or into a trunk). Double and single base propellants are used in the experimental trials for assessing water-jet velocities. An attempt has been made to validate the water-jet velocity using experimentally high-speed videography for the first time and making its theoretical analysis by conducting the various trials at a laboratory with different propellants. The stand-off distance between disruptor and target is 0.5 m. This kind of research work is not reported in open access till the date. This is the newness of this research work. The experimental water-jet velocity for single base propellant varies from 349.63 to 503.56 m/s and for double base propellant it varies from 515.07 to 890 m/s. The theoretical water-jet velocity for single base and double base propellant works out to be as 616.44 m/s and 692.62 m/s respectively. From this research study, it is concluded that there is good agreement between theoretical and experimental results.
Keywords: disruptors, high speed videography, improvised explosive devices, propellant, water-jet velocity, water-jet disruptor

1. INTRODUCTION

Experimental determination of water-jet velocity using high speed videography is motivated by practical questions and applications. A theoretical and experimental research work has been done on water-jet technology in different fields. It is felt necessary to carry out the theoretical study and experimental validation of a liquid projectile on a stationary target by creating pure water-jet using explosives. Water-jet disruptors are mainly used for disintegration of explosive or unknown packaging using water as a medium. They are preferred in destroying IEDs, ignition mechanism and electric detonating cap to disable them without causing a spark that may set off explosive components [1]. Using a projected water-jet disruptor, technicians have better forensic analysis and intelligence gathering capabilities for IED source identification. Handling IEDs with disruptors eliminates the risk in a situation where there is unknown explosive. If X-ray device is not portable to identify the contents of the suspect objects, handling may put the life of the specialist in danger [2].

The pure water-jet terminology refers to water-jet cutting without any abrasives. It is always used against for soft materials such paper, wood, rubber etc. Hashish & *et al*. [3-5] explained that the plane water-jet cutting is useful for soft materials like “paper, food, textiles, and wood”. It is used in manufacturing of machine parts. The recommended methods as the materials are sensitive and cut by other methods at elevated temperatures. Presently, such devices use different disrupting agent such as water, aluminium, sand, ceramic and steel projectile. Above them materials, due to its physical properties, water is an appropriate choice.

Numerical simulation of high-speed turbulent water-jets in air and its validation with experimental data has been reported by Guha [6]. Huang & *et al*. presents the numerical simulation of underwater explosions using a one-dimensional "wedge" model of ANSYS-AUTODYN explicit software for nonlinear dynamics [7]. Radomski [8] has carried out the analysis pertaining to the recoil effect and its mathematical model describing the internal ballistics of a two-chambered projected water disruptor. Kirkpatrik & *et al.* [9] describes the experimental technique and present the results from the range of disruptor that compare favourably with respect to generic target tests. It is suggested that radial impulse provide the quantitative measures of disruption. It should be considered as a potential future standard test for evaluating disruptor performance. Constantin & *et al.* [10] aim to investigate whether the Gurney theory is an appropriate alternative for explosively driven water-jet.

Experimental lab tests and smooth particle hydrodynamic (SPH) numerical simulations were performed to evolve a correlation between theoretical and experimental results. Experimental and numerical findings with respect to water tip velocity, are similar (differences are below 10%), one could say that this method is a good tool for pre-design evaluation of water-jet generating devices performances. Carrying out experimental tests and numerical simulations, water was investigated in terms of tip velocity and total mass average velocity. Based on these data, the findings indicate that Gurney equations misjudge the water mass average velocity. Jain & *et al.* [11] carried out the study to understand the effect of high velocity water-jet on flat surface. Pressure, velocity and stream line have been obtained by simulating a problem in commercial CFD tool ANSYS-Fluent. Bankar *et al.* illustrated design and analysis of small calibre disruptor used in bomb disarmament and explosives finding without human contact. Robots are replacing with the human for bomb detection, transportation, and removal where every time human approach is not accessible [12, 13].

In the present paper, the research effort is focused on to determine the water-jet velocity using high speed photography with different chemical compositions at a stand-off distance of 0.5 meter from the barrel.

1.1. Aim of the research

The aim of this present research study is to estimate water-jet velocity of disruptor using high-speed videography by conducting the experiments and to validate the same with theory. This is the newness of the research work carried out by the authors which is presented in this paper. This kind of work is not reported and not available in open access literature till the date.

1.2. Approach to the problem

The instantaneous energy released by the propellant burning inside the chamber of water-jet is the driving force to create the high velocity which causes the destruction to the suspected IEDs. As the water comes out from the barrel, it gets atomised in the air. This mille second event can't be seen by the naked eyes. Therefore, to capture such an event, high speed videography is utilised. High speed camera is positioned in perpendicular direction to water-jet motion so as to record the water-jet travel towards the target. The stand-off distance between the muzzle end of the barrel of water-jet disruptor and target is 0.5 m. High speed camera is placed approximately 7 m apart from the disruptor to capture the water-jet event. The close vicinity of water-jet disruptor at the target is not carried out due to overturn caused by reflected pressure waves from the target. The block diagram for experimental set up illustrating high speed camera, target and water-jet disruptor (weapon) before the firing is shown in Figure 1. High speed camera is used to trace the path of water droplets and its velocity during flight trajectory. This velocity as an input parameter plays the vital role about the effect of damage on the target. Since the aim of this research study is to understand the effects of water- jet velocity through barrel and to measure the water-jet velocities using high speed camera. Formulation of the problem has been done such that it involves internal flow within barrel and outer flow near to the target surface.

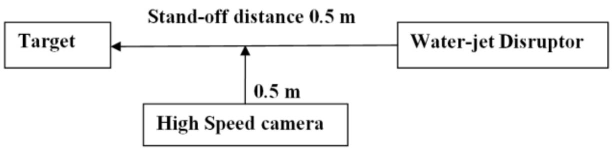


Fig. 1. Block diagram showing high speed camera, target and water-jet disruptor (Distances are not to scale)

1.3. Water-jet applications

There are many applications of water-jet [14]. The general applications of water-jet are given below:

- Removal of degraded concrete layers.
- Used in cutting variety of materials and thicknesses, ranging from hard materials such as ceramic, composite and ceramics materials, rock and steel alloys as in Abrasive Water-Jet (AWJ).
- For cutting soft material such as wood, laminated paper tubes, glasses using pure water jet.
- Used in mining and excavation.

- Medical, aerospace, agriculture and industrial domain.
- For use in cleaning of super conducting cavities.
- Chemical and food industries (as this process is a hygienic method).
- To remove coatings, paint, deposits and even rust from surfaces.
- Cutting mechanism or techniques such as de-burring, turning, milling, drilling, shaping, and reaming, polishing, water-jet peening, water-jet forming and surface treatment.
- To remove the propellant from shell.
- For disrupting suspected IEDs, rocket wrench and De-armour system.

There are certain advantages of water-jet technology:

- A variety of materials and material thicknesses can be cut.
- Variable cutting speed during the process.
- No heat affected zone or thermal cracking.
- Minimal to no burrs produced from cutting.
- No dust or sparks generation.
- The inherent characteristic of this technology is that it is dynamic process.

2. DESCRIPTION AND FUNCTION OF WATER-JET DISRUPTOR

Water-jet disrupter is a modular, recoilless and versatile weapon. In the same context, the target stand endures stress on firing and can be therefore a light weight. It is mounted on remotely operated vehicle (ROV) and utilized for multi-purpose applications. It meets the safety needs when special police counter terrorism attack. It is portable and quickly deployed to the site on tripod (stand) manually for destruction purpose. It aids to locate, handle and destroy the hazardous objects safely. The water-jet disruptor can be used with a water charge, frangible or solid projectile. It has inert tool specifically designed to disrupt ED and IEDs. Because of this feature, weapon itself does not require a heavy mass in itself for recoil. This helps to reduce the recoil. The disruptor can be used either close up or with a stand-off distance from the target. The disruptor comprises a recoilless barrel, light weight multi-position stands, sights, tools and inert consumables. The barrel is designed using alloy steel specification. Disruptor features a capture gate which fits onto a breech plug. This has the effect of allowing the thin closure cap (Top) and water to exit from the compensator. This feature significantly reduces the rear signature of weapon and the means of potential for collateral damage from the compensator blast is minimized.

Figure 2 depicts the various components of water-jet system. The description and function of various parts of water-jet disruptor are explained below.

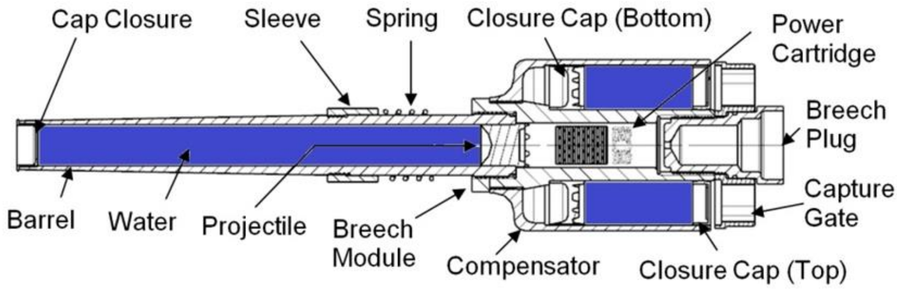


Fig. 2. Water-jet disruptor

Barrel

Barrel is the main part through which a high velocity water-jet is created. Water is filled inside the barrel as indicated in blue colour. It is closed by a cap closure from one side and by a projectile on the other side. It is made up of an alloy steel.

Breech module

It is assembled with a barrel and has six annular holes. Its purpose is to hold the cartridge inside the hole of breech module. The part of gas energy is generated by firing the cartridge providing the recoil action through the annular holes and the cap closure top. It is made up of an alloy steel.

Compensator

Compensator is screwed onto breech module. Further it holds the closure cap (Bottom) around the breech module and closure cap (Top) at the open end. Before placing closure cap (Top) resulting cavity is filled with water as indicated in blue colour. It is made up of aluminium.

Breech plug

It is fitted on a breech module along with a capture gate so as to position the cartridge. It has a central hole through which lead wires of the cartridges are drawn for making electrical connections.

Capture gate

It is screwed on a breech plug with the screw using hexagonal alien key, so that rear signature and the potential for collateral damage are absolutely minimized. It is made up of alloy steel.

Breech plug

It is positioned over the capture gate with the small retainer nut made up of steel.

Spring & sleeve assembly

Spring & sleeve assembled on the barrel. The purpose of this assembly is to retain the whole weapon, in stand, by preventing the barrel from leaving the mounting block.

Projectile

It is fitted inside the barrel to seal the water column before the assembly of breech module. It is designed in such a way so that it gets shear off from barrel when the gas pressure acts on it. It is made up of nylon material.

Closure Cap (Bottom)

It is pressed inside a compensator over the breech module and covers the annular holes of the breech module. This ensures the perfect sealing of annular water column inside the compensator. It is made up of nylon material.

Closure cap (Top)

This is press fit inside the compensator at its brim after pouring the water inside the compensator to seal the annular water column. It features a 0.6-mm bleed hole to vent out entrapped air when it is assembled with the compensator. It is made up of nylon material.

Cap closure

This is press fit inside the barrel at the muzzle end so as to seal water column.

Power cartridge

It is the gas generator utilised to drive a liquid projectile for disruption of suspected improvised explosive devices (IED's). The gases are generated by burning the propellant content in it. It is electrically initiated. The cartridge is assembled inside the breech module and lead wires come out through the breech plug for making the electrical connections.

3. MATERIALS AND METHODS

3.1. Propellant composition

The method for water-jet velocity validation using high speed videography comprises of disruptor and gas generation by burning double base and single base propellant inside the cartridge. The chemical composition and physical properties of double and single base propellant are given in Table 1 and 2 respectively.

Table 1. Chemical composition & physical properties of double base propellant (NGB 051) [15]

Chemical composition		**Physical properties**	
Component	Composition (wt.%)	Propellant shape	Square Flakes
NC	57.50% Nitration (12.75%N)	Density	1.55 g/cc
NG	40.50%	Force constant	1200 cal/g
Carbamite	1.7%	Average web	0.15 mm
Graphite	0.3%		

Table 2. Chemical composition and physical properties of single base propellant (NCC 018) [16]

Chemical composition		**Physical properties**	
Component	Composition (wt.%)	Propellant shape	Circular flake
NC	97.2% Nitration (13.25% N)	Density	0.9 g/cc
DPA	1%	Force constant	950 cal/g
DBP	1.8%	Diameter	0.70 mm
		Web	0.18 mm

The photographs of double and single base propellants used for testing in the power cartridge are illustrated in Figure 3 (a) and (b) respectively.

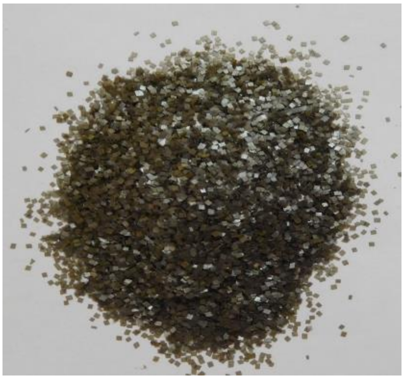


Fig. 3 (a). Double base propellant

Fig. 3 (b). Single base propellant

3.2. Method

An experimental method consists of water-jet disruptor, power cartridge, and a high-speed camera. The camera is placed in a perpendicular direction to motion of water-jet so as to trace the trajectory. The frame per second and visibility is adjusted for the camera to record every event passing through it.

4. EXPERIMENTAL SECTION

4.1. Test set-up for measurement of velocity using high speed videography

Measurement of water-jet velocity wherein water used as liquid projectile is one of the important factors related to the armament research studies.

Water-jet velocity measurement after expelling from the barrel is essential pre-requisite requirement. Water-jet velocity gives indication for damage criterion against the target. A high-speed camera is able to capture exposure of event images more than 5000 frames/second. This is used for recording fast-moving objects as a photographic image(s) onto a storage medium.

An experimental set-up for measurement of velocity of water-jet using high speed camera, disruptor and target is depicted in Figure 4. High-speed video cameras are widely used for scientific study, military test and performance evaluation and industrial domain. Various methods such as Doppler RADAR, photocell, flash radiograph and high-speed camera are available. The water-jet velocity as a liquid projectile can be calculated if the interval of a projectile is measured over a known distance. A time interval counter with a suitable start / stop arrangement gives a time measurement very precisely. Kankane and Ranade describe measurement of breech pressure, the computation of velocity-time and travel-time profiles in the barrel from the instantaneous breech pressure values [17]. Bauer, *et al.* [18] describe a simple experiment technique to provide a simple continuous velocity-time history of a projectile using rail gun acceleration. STANAG 4114 defines the measurement of the velocity and pressure related to a projectile of a gun [19]. A passive non-intrusive diagnostic for determination of rail gun projectile position and velocity was measured by Sloan [20]. The author reported for the shorted transmission line characteristics of the gun rail-armature system. Kirkpatrik, *et al.* have carried out the development of novel light weight recoilless EOD Disruptor based on the Davis gun principle, for neutralizing IED [21].

Fig. 4. An experimental set-up for measurement of velocity of water-jet using a high-speed camera. It consists of camera, water-jet disruptor and target for arresting the projectile using the firing stand

4.2. Methodology adapted to measure velocity of water-jet

Full frame of high speed recorded data is calibrated against the distance between two points of the disruptor by finding the pixel co-ordinates of two points. For measurement of water-jet velocity, it is necessary to find out the calibration factor of the disruptor as shown in Figure 5. On firing of water-jet disruptor, the water gets atomised in the air and forms a mist of clouds during its travel. The chronological events for both the propellants are shown in Figures 6(a) and 6(b) respectively.

Calibration Factor Calculation:

Co-ordinate of the point A is (X_1, Y_1). Co-ordinate of the point B is (X_2, Y_2).

Number of pixels between the point A and B

$$= \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2} \quad (1)$$

= W Pixels calibration Factor = 224/ (W Pixels)

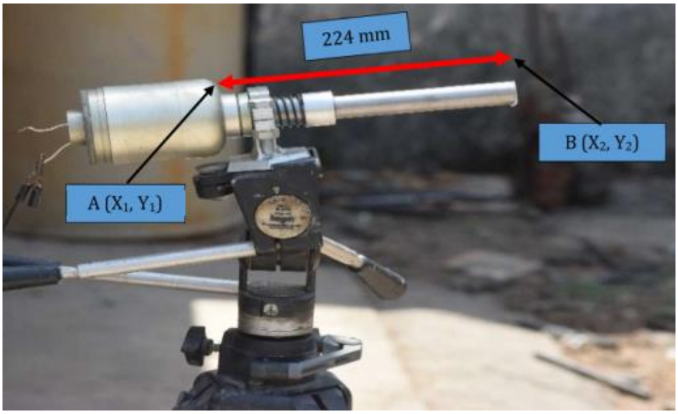
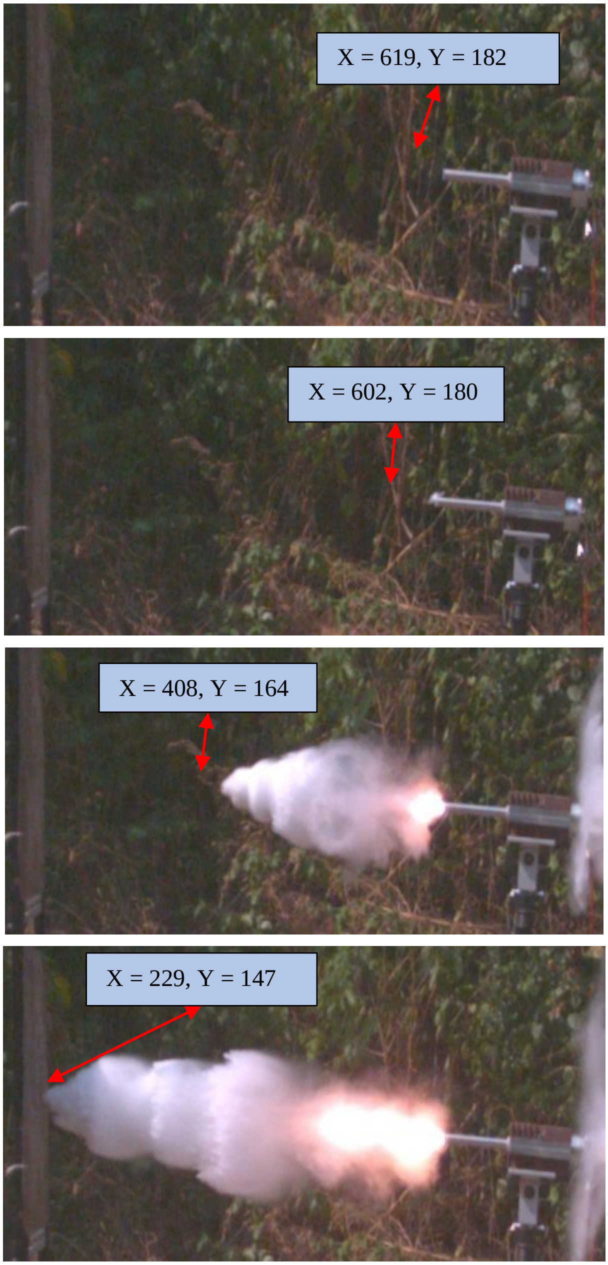


Fig. 5. Calculation of calibration factor from recorded image

Using the above calibration factor and tracking the high speed recorded data frame by frame w.r.t. time, distance covered in every frame is calculated. After calculation of distance in every subsequent frame and time interval of every successive frame, first derivative w.r.t. time implies the velocity of water-jet in every successive frame. Some of the tracked frame and calculation methodology is illustrated in Table 3, while some of high speed recorded image sequence for tracking of water-jet tip w.r.t. time showing co-ordinates for different propellants composition are depicted in Figure 6 (a, b).



T = 0.00 ms

T = 0.16 ms

T = 2.67 ms

T = 4.33 ms

Fig. 6(a). Various events of water-jet w.r.t. time showing co-ordinates for different propellants composition. High Speed recorded Image sequence for tracking of Water-Jet Tip for NGB051 (DB propellant). Frame with tracked Pixel Co-Ordinate

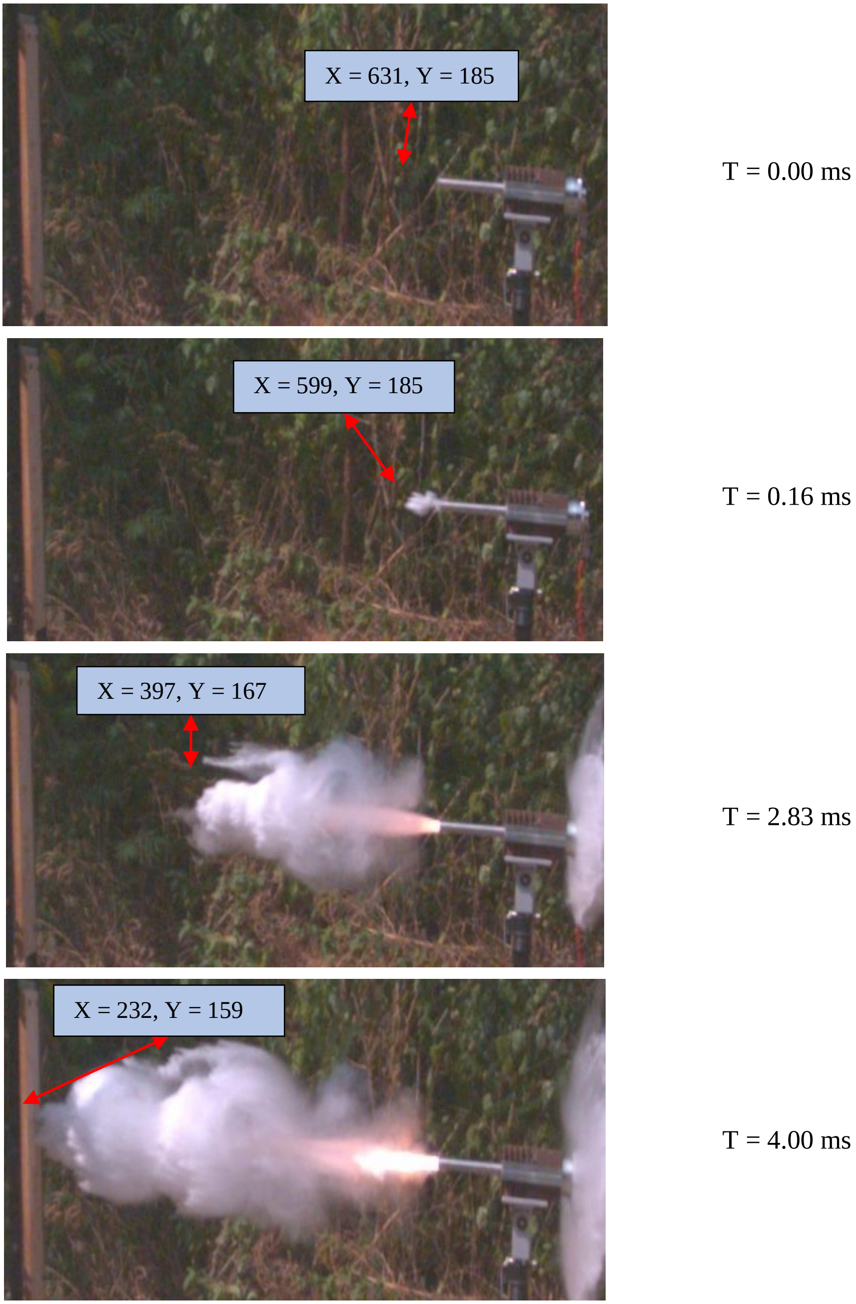


Fig. 6(b). Various events of water-jet w.r.t. time showing co-ordinates for different propellants composition. High Speed recorded Image sequence for tracking of Water-Jet Tip for NCC 018 (SB propellant). Frame with tracked Pixel Co-Ordinate

Table 3. The tracked frame and calculation methodology for velocity of water-jet

Tracked frames					**Distance / frame**	**Cumulative time**	**Cumulative distance**	**Velocity**
Frames	X1	Y1	X2	Y2	meter	sec	meter	m/s
1076	102	303	102	303	0.0000	0.0000	0.0000	0.0000
1077	105	305	102	303	0.0113	0.0002	0.0113	55.60
1078	114	302	105	305	0.0412	0.0004	0.0412	146.30
1079	125	303	114	302	0.0760	0.0006	0.0760	170.33
1080	139	304	125	303	0.1201	0.0008	0.1201	216.44
1081	157	303	139	304	0.1769	0.0010	0.1769	278.01
1082	176	297	157	303	0.2396	0.0012	0.2396	307.26
1083	202	291	176	297	0.3236	0.0014	0.3236	411.48
1084	235	292	202	291	0.4275	0.0016	0.4275	509.13
1085	263	290	235	292	0.5158	0.0018	0.5158	432.89

By analysing the various frames by frame velocities it has been observed that the water-jet attains its maximum velocity at the distance of 0.4 to 0.5 m from the muzzle so that we have restricted our analysis for the stand-off distance of 0.5 meter and average velocity for 0.5 meter has been calculated.

5. DISCUSSIONS OF RESULTS

5.1. Estimation of internal pressure (P_i)

Internal pressure generated by burning of propellant inside a closed vessel having volume 100cc and loading density of 0.2 g/cc is obtained by using the following relation [21]

$$P_i = \frac{FC}{\mathrm{V}} \tag{2}$$

where F and C are the force constant and charge mass of propellant, and V is the vessel volume available (100 cc) for expansion of gases

Substituting the force constant F = 1200 J/g and charge mass C = 20 g in equation (2) gives internal pressure = 240 MPa for double base propellant. This is the theoretical pressure.

Similarly using equation (2) putting F = 950 J/g and C = 20 g gives internal pressure = 190 MPa for single base propellant. This is the theoretical pressure.

5.2. Water-jet velocity measurement as a liquid projectile

The relation between velocity and internal pressure acting on the projectile is given by following equation. The subscripts *i* and *o* represents the inlet and outlet conditions. This velocity is obtained using Bernoulli's equation with assumption as given below [22]:

- For steady i.e. mass flow rate at entry is equal to that at exit ($m_i = m_o$).
- Incompressible flow (density remains constant).
- Frictionless flow.
- No mechanical work is done on or by the fluid ($Ws = 0$).
- Adiabatic i.e. there is no heat transfer across the system boundaries, ($Q = 0$).
- Fluid internal energy remains constant ($e_i = e_o$) if work and heat exchange are zero.
- Datum $y_i = y_o$.

$$m_i \left[e_i + \frac{P_i}{\rho_i} + \frac{V_i^2}{2} + gy_i + Q \right] = m_o \left[e_o + \frac{P_o}{\rho_o} + \frac{V_o^2}{2} + gy_o + Ws \right] \qquad (3)$$

$$V_o \; or \; V_{th} = \sqrt{\frac{2P_i}{\rho}} \qquad (4)$$

It is assumed that the internal pressure P_i generated by the propellant using 0.2 g/cc loading density is considered for theoretical determination of water-jet velocity as an input parameter. However, in actual scenario, the mass of propellant in the cartridge case is 3 g for this research work. All the experimental trials were carried out with this charge mass.

Where P_i is the internal pressure generated by propellant burning and acting on the water column inside the barrel and can be determined as explained in above paragraph.

ρ = density of water = 1000 kg/m^3

Substituting internal pressure as 240 MPa and density, the water-jet velocity works out to be as 692.62 m/s for double base propellant (DB) NGB 051.

The same exercise is repeated for single base (SB) propellant NCC 018 as explained above to determine the water-jet velocity. It is estimated as 616.44 m/s. The experimentally measured water-jet velocities for each round for different propellants composition are given in Table 4 and 5 respectively. Total 15 Nos. of rounds were fired for each type of propellants at ambient conditions.

Table 4. SB Propellant (NCC 018) Table 5. DB Propellant (NGB 051)

Sl. No.	Water- jet velocity (m/s)			Sl. No.	Water- jet velocity (m/s)		
	Max.	Min.	Average		Max.	Min.	Average
1	446.47	63.91	337.76	1	890.00	410.00	690.00
2	503.56	175.23	348.24	2	761.38	313.67	588.66
3	484.00	50.99	324.54	3	772.40	656.78	721.31
4	462.64	222.14	341.96	4	661.97	521.47	597.83
5	420.70	285.9	356.77	5	768.80	631.72	696.37
6	450.35	65.08	330.54	6	667.45	18.89	383.73
7	444.24	138.76	296.34	7	515.07	145.13	351.95
8	349.63	182.15	229.89	8	626.10	136.10	294.58
9	370.64	69.03	252.04	9	658.40	368.70	530.17
10	394.20	211.10	151.30	10	718.80	414.50	518.93
11	406.50	337.82	372.15	11	658.40	368.70	530.17
12	409.10	200.5	234.90	12	528.90	55.09	177.65
13	425.60	282.00	355.22	13	594.70	519.70	546.34
14	408.80	138.90	208.30	14	570.23	320.38	445.03
15	438.90	230.30	281.30	15	621.13	180.94	401.03
Mean	427.68	176.92	294.75	Mean	667.58	337.45	498.25
*SD	40.61	89.09	65.71	SD	101.23	198.72	155.77
Min.	349.63	50.99	151.31	Min.	515.07	18.89	177.65
Max.	503.56	337.82	372.15	Max.	890.00	656.78	721.31

*SD – Standard deviation

From Table 4, it is observed that the water-jet velocity varies from 349.63 to 503.56 m/s for single base propellant NCC 018. The mean velocity is 427.68 m/s. The theoretical estimated water-jet velocity is 616.44 m/s. The standard deviation for maximum theoretical water-jet velocity is 40.61.

From the Table 5, it is observed that the water-jet velocity varies from 515.07 to 890 m/s for double propellant. The mean velocity is 667.58 m/s. The theoretical estimated water-jet velocity is 692.62 m/s. The standard deviation for maximum theoretical water-jet velocity is 101.23. The water-jet velocity spread is more for double base propellant NGB 051. The variations of water-jet velocities are due to droplet formation in the air and the wind velocities prevailing during conduct of trials on different occasions. The standard deviation values for both the propellants are as it is difficult to control the motion of water droplet in the open atmosphere.

From the Tables 4 and 5, it is observed that the range of water-jet velocities for DB NGB 051 propellant is more. This is due to more force constant, as it imparts more energy to water column.

As the combustion of propellant takes place inside the cartridge, the pressure acts on water column inside the barrel. The pressure rises and water starts its motion through the barrel.

The pressure reaches to its maximum pressure. The water column is moving in the forward direction through the barrel. The final pressure after leaving near the muzzle end of barrel is above the atmospheric pressure. At the exit of muzzle end, the liquid projectile has maximum velocity. From this research work it is concluded that maximum velocity lies at a stand-off distance of 0.4 to 0.5 meter from the barrel end.

The high-speed videography is recorded at stand-off distance of 0.5 meter. These variations are due to frictional losses, wind velocity, accuracy in the measurement which varies from person to person. The effect of water-jet velocity on wood with 15 mm thickness and combination of wood – aluminium plate (2 mm) at a stand-off distance of 0.5 meter are depicted in Figure 7(a) and (b) respectively. The wooden target breaks into pieces as shown in Figure 7(a). The aluminium plate gets deformed and projectile penetrates through wood in Figure 7(b). This ensures the penetration capability of water-jet disruptor where suspected objects can break open using high velocity. Both the propellants give the same performance.

Fig. 7 (a). Wood target

Fig. 7 (b). Combination of wood & aluminium

6. SUMMARY AND CONCLUSIONS

In this paper, an attempt has been made to measure the water-jet velocity using high speed videography and validate the same with theory. An experimental study is helpful for predicting the water-jet velocity used in disruptor application. This research article describes experimental and theoretical validation for water-jet velocity measurement to evaluate the performance of water-jet disruptor using different propellant compositions.

Water-jet velocity measurement is one of the most demanding requirements for selection of suitable propellant for particular weapon. Therefore, performance of water-jet disruptor depends upon on water-jet velocity.

Thus, the water-jet velocity measurement using high speed videography related to water-jet disruptor is successfully established at a laboratory. From this research study, it is concluded that there is a good agreement between experimental and theoretical results of maximum water-jet velocities for water-jet disruptor. The studies conducted in this paper identified very interesting and promising results.

ACKNOWLEDGEMENTS

The authors thanks to Dr. K M Rajan, Distinguished Scientist and Director, Armament Research and Development Establishment (ARDE), Pashan, Pune – 411 021 for generous support and consent to publish this work. The authors also broaden their sincere thanks to Shri. V K Dixit, Sc. 'H', Outstanding Scientist and Associate Director for precious guidance and continuous support and Mrs. Devyani Jadhav, Sc 'F' Division Head of Range Group for their instrument support.

FUNDING

The authors received no financial support for the research, authorship, and/or publication of this article.

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