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Research paper

A Novel Method for Dynamic Pressure and Velocity Measurement Related to a Power Cartridge Using a Velocity Test Rig for Water-Jet Disruptor Applications

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Abstract: Power cartridges are gas generators utilised to drive a liquid projectile for disruption of suspect improvised explosive devices (IED's). The purpose of a water-jet disruptor is to destroy the suspected IED. A novel method was devised for pressure measurement at the exit of the cartridge for launching liquid projectile. An experimental test set-up was designed and fabricated for measurement of projectile velocity and the propellant gas pressure in a velocity test rig (VTR). In these experiments, double base propellants having different physical and chemical properties were utilised to drive the solid projectile. This projectile was made of nylon material. This projectile velocity measurement is an important parameter in the armament field.

An experimental study is the unique design feature. It is responsible for the measurement of pressure at the exit of the cartridge and the projectile velocity at the muzzle end of the barrel. The projectile velocity was measured using high speed photography. The pressure was measured using a pressure sensor. The maximum projectile velocities for spherical ball powder and NGB 051

propellants have been experimentally measured as 384.23 m/s and 418.32 m/s, respectively. Experimentally the maximum pressures for spherical ball powder and NGB 051 propellants have been evaluated as 50.12 MPa and 63 MPa respectively from data gathered by the acquisition system. The standard deviation between the experimental and theoretical values for the projectile velocity varied from 12.57 to 13.88 for spherical ball powder whereas it was 5.33 to 7.09 for NGB 051 propellant. The percentage error between the experimental and the theoretical values of the projectile velocity was less than 10 for both propellants.

Keywords: power cartridge, data acquisition, double base propellant, high speed photography, projectile velocity, pressure, propellant, projectile, standard deviation, water-jet disruptor, velocity test rig

Nomenclature:

- C* Mass of propellant [g]
d Internal diameter of VTR chamber where propellant pressure is acting on projectile or inside cartridge diameter for loading propellant mass [m]
e Fluid internal energy [J]
F Force constant of propellant [J/g]
g Acceleration due to gravity (9.81 m/s²)
l Length of VTR chamber where propellant pressure is acting on projectile or inside cartridge length for loading propellant mass [mm]
m Mass flow rate [kg/s]
P_i Internal pressure of propellant [MPa]
Q Heat transfer across the system boundaries [J]
V Volume of VTR chamber or volume of cartridge [cm³]
V₀ or *V_{th}* Theoretical projectile velocity [m/s]
W_s Mechanical work [J]
y Datum head [m]

Subscripts:

- i Inlet
o Outlet

Greek Symbols:

- π Constant (3.14)
 ρ Density [kg/m³]

1 Introduction

A power cartridge is a gas generator in which the propellant combustion generating gases occurs for a short duration. These gases help to perform various mechanical tasks [1]. The cartridge is the assembly that contains the case, propellant, and initiation mechanism. The purpose of the cartridge case is to hold the propellant, helps to obturate the breech and keep the propellant protected against the environment. The cartridge under study was filled with double base propellants with different physical and chemical properties. The propellant burns layer by layer and releases the energy, through a process of rapid chemical burning. On burning, the propellant produces high temperature and high pressure gaseous products. The flame temperature of a double base propellant is between 2600 and 3600 K [2]. The propellants in power cartridges are burned in a controlled way (deflagration) to produce the desired thrust [3]. A solid propellant consists of several chemical ingredients such as fuel, oxidiser, plasticizer, burn rate modifier, stabilizer, curing agent and cross linking agent. The specific chemical composition of a propellant depends on the desired combustion characteristics for a particular mission. Solid propellants are often tailored and classified by specific applications such as space launches, missiles and guns. Different chemical ingredients and their properties result in different chemical properties, combustion characteristics and performance [4]. An experimental work reported in this paper is limited to double base propellants.

1.1 Types of propellants

A propellant is a chemical substance which undergoes rapid and predictable combustion, resulting in a large volume of hot gas. This gas can be used to accelerate projectiles from guns of all sizes including rockets and missiles. Propellants contain both oxidizer and fuel in their compositions and are classed as combustible materials. Propellant substances will liberate a large amount of gas at high temperatures during combustion. This will self-sustain the combustion process without the presence of oxygen in the surrounding atmosphere. In general, propellants generate combustion gases by the deflagration process and this process is usually subsonic. Propellants used in power cartridges are gun propellants and are mainly classified as single base propellants, double base propellants and triple base propellants:

- (a) **A single base propellant** is primarily composed of nitrocellulose (NC), an energetic polymeric binder. The composition consists of 85 to 96% of NC which has a nitrogen content of 12.5-13.2% [5]. It is gelled by adding a plasticizer such as dibutyl phthalate (DBP) or carbamate, and then extruded

and chopped into the required grain shape. It has a horny structure and poor mechanical properties [6]. These propellants are manufactured using an ether-alcohol mixture in a 60:40 ratio by a solvent process. These propellants are used in hand guns, rifles, machine guns, aircraft and anti-aircraft guns, cannons, power cartridges and howitzers.

- (b) **A double base propellant** consists of NC with nitroglycerin (NG). Use of this propellant causes gun barrel erosion and higher flame temperatures which will be easily noticed by enemy troops. This is the disadvantage of this propellant. Due to the solventless production technology for double base propellants, larger sized propellant grains with large web and large blocks of propellant with different and complicated geometries became possible. These propellants are used in pistols, grenade launchers, power cartridges and mortars.
- (c) **A triple base propellant** is made up of NC, NG and nitroguanidine (NQ). The introduction of about 50% NQ to the propellant composition results in a reduction in the flame temperature and an increase in the gas volume. They are safe to use and ballistically more stable. These propellants are smokeless in nature because of their low flame temperature. Furthermore, gun barrel erosion and muzzle flash are reduced. There is also a slight reduction in the performance of the propellant. The incorporation of ultra fine grade NQ yields grains with reasonably good mechanical properties [6]. These propellants are processed by a solvent extrusion process. They are used in tank guns, large calibre guns and UK naval guns.

Various ingredients are added to propellants to impart certain required properties. The roles of these additives are as follows:

- **NC:** The role of NC is as a fuel and an oxidizer. It is one of the major ingredients used in single and double base propellants along with other additives so as to enhance the performance of the propellant.
- **Diphenylamine (DPA):** It is used as a stabilizer which further reduces the degradation of a propellant over a period of time [7].
- **Carbamite:** It is used in double base propellants as a stabilizer. Its role is to increase the shelf life of a propellant.
- **NG:** It is used to plasticize the high molecular weight NC to yield thermoplastic materials [7]. NG reduces smoke and increases the energy output.
- **DBP:** It improves the processability of a propellant remarkably and contributes to the thermal energy on oxidation. It is used to improve the mechanical and extrusion properties. The action of DBP is gelation of NC, to reduce the burning rate of the grain surface and flame temperature [8].

- **Mineral jelly:** Mineral jelly acts as a lubricant during manufacturing of the propellant.
- **Graphite:** It is added to propellants to prevent the accumulation of static electricity, modify its burning characteristics or is applied as a glaze which acts as a lubricant [9]. It improves the flow characteristics during manufacturing.
- **Calcium carbonate:** It acts as a cooling agent and increases the combustion stability during the combustion process [10].

1.2 Types of power cartridges

Power cartridges are called cartridge actuated devices (CAD), which gives specified performance to operate various systems in aircraft or helicopters. Based on the functional use, they are classified as:

- Main seat ejection type: To jettison the seat with the pilot from an endangered aircraft in case of emergency. These are sub classified as:
 - (i) Canopy jettisoning cartridges,
 - (ii) Seat ejection cartridges,
 - (iii) Shoulder harness cartridges,
 - (iv) Leg restrain cartridges,
 - (v) Drogue cartridges.
- Ejection release unit (ERU) cartridges: These are used for dropping bombs and empty fuel tanks to ensure positive separation from the parent aircraft in an emergency.
- Fire extinguisher cartridges: To extinguish the fire in an engine/aircraft in case of an accident.
- Miscellaneous cartridges such as cable cutting, disruptor cartridges for IEDs and de-armour, distress signals, and re-cocking for cleaning the gun in case of misfiring of ammunition.

1.3 Aim of this experimental study

The aim of this present research was to devise a novel method for the velocity measurement of projectiles and pressure at the exit of the cartridge for disruptor applications. A velocity test rig (VTR) was fabricated as part of the experimental set-up to measure these parameters. The experiments were performed in the laboratory using the VTR. Experiments were conducted using double base propellants with different physical and chemical properties.

Pressure sensor with a closed vessel (CV) were used to determine the gas pressure during burning of the different propellant types under constant volume. CV is a test method having constant volume. However, pressure measurements for propellants using a CV for the cartridge does not give

the correct pressure realized in an actual situation. This is because of the constant volume and there is no moving projectile in a CV. Therefore, the aim of this investigation was to fill the gap by establishing a method for pressure measurement of the propellants by a VTR, which has a moving projectile as shown in Figure 1 (see Paragraph 2.1). Assessing the pressure measurement of double base propellants at the exit of a cartridge by VTR and projectile velocity is an added value.

2 Background Studies

During the 1960s, the copper crusher gauge was extensively used for the measurement of internal pressure for different ammunitions. This gauge was placed inside the shell. As the pressure is generated inside the shell, the copper ball gets deformed. This deformation is related to the internal pressure. More recently, with the advancement in the science and technology, pressure sensors with quartz crystals are being widely used for the measurement of gas pressure generated by ammunition [11]. In present study experimental arrangement, a pressure sensor is used to record the gas pressure generated by the cartridge which acts on the projectile. Frank *et al.* [12] experimented with the dynamic pressure measurement of cartridge-operated captive bolt devices. This is a powder actuated stationary spring gun that is widely used in pest control. Pressure measurement of propellants in CV is carried out to understand the burning characteristics at different temperatures. The data generated during trials with CV helps to obtain important information (force, quickness, *etc.*) for the propellant under test, with the help of data acquisition software. Data thus obtained from CV can be used in the development and manufacturing of new propellants [13]. Divekar *et al.* [14] has studied the effect of the web size of double base propellant grains. The interior ballistics of guns comprises a study of a chemical energy source, a working substance and ancillary apparatus for controlling the release of energy [15-18]. The measurement of projectile velocities inside the bore using a LASER Doppler interferometer was carried out by Cattin [19]. Bauer [20] described a simple experimental technique to provide a continuous velocity-time history of a projectile using rail gun acceleration. STANAG 4114 defines the measurement of the velocity and pressure related to the projectile of a gun [21]. A passive non-intrusive diagnostic for the determination of a rail gun projectile position and velocity during acceleration was measured by Sloan [22] for the shorten transmission line characteristics of the gun rail-armature system. Boulkadid [23, 24] investigated

the effect of the initial temperature on the mechanical properties of spherical single base gun propellant by means of a compression test, which consisted of the compression of a propellant bed conditioned at various initial temperatures. The author further performed closed vessel experiments at different temperatures to determine the burning rates of deterred spherical single base propellants.

2.1 Problem description

A water-jet disruptor is utilised to safely disrupt suspect objects. A 3D view of a water-jet disruptor is illustrated in Figure 1. It consists of a breech plug, cap closure (top), breech module, spring, closure cap, barrel, sleeve, projectile, compensator, cap closure (bottom) and capture gate. The barrel and compensator are filled with water as indicated in blue. The cartridge is loaded inside the breech module. The cartridge dimensions are:

- outer diameter 20 mm,
- thickness 1.5 mm,

and the barrel dimensions are:

- outer diameter 26 mm,
- variable thickness from 3.75 to 1.75 mm.

As the thicknesses of these components are small, pressure sensor cannot be directly mounted onto them. The thread length of the pressure sensor is 12.1 mm. In order to mount the pressure sensor more thread length is required, which is not possible considering the thickness of the cartridge and barrel. The thickness of the barrel reduces from projectile to closure cap. A detailed view of a pressure sensor is illustrated in Figure 2. For the same purpose, a VTR was designed and manufactured. A 15 mm gap was maintained between projectile and barrel. The cartridge is loaded inside the cartridge holder. The VTR chamber is the place where the propellant gases act against the projectile. A gauge adaptor with pressure sensor assembly is screwed to the VTR body. The assembly of barrel and projectile is screwed to the body.

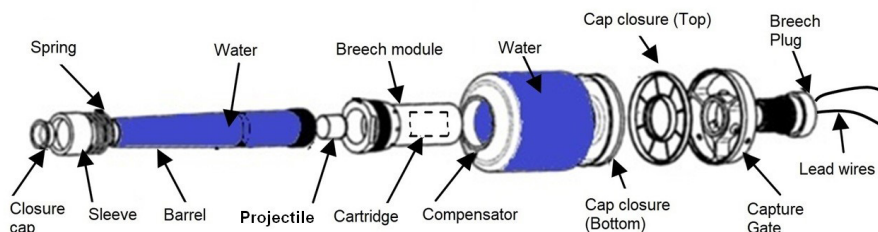


Figure 1. Components of a water-jet disruptor

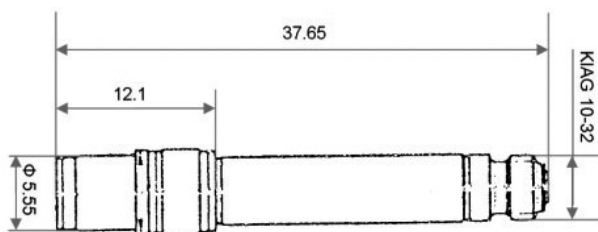


Figure 2. Pressure sensor (all dimensions are in mm)

Figure 3 illustrates the assembly sequence of projectile and barrel. A 3D view of the VTR is shown in Figure 4. It comprises of mounting plate, cartridge holder, sealing ring, gauge adaptor, projectile, closure cap, barrel and washer. Figure 5 shows an engineering drawing of the VTR with other important accessories. This situation is exactly similar to the actual weapon except for the water inside the barrel. The length and internal diameter of the barrel of the disruptor through which the projectile moves are 225 and 18.5 mm, respectively. On burning the propellant the gas pressure acts against the water column with a projectile inside the barrel. Water, on disintegration, creates a mist cloud which makes it difficult to trace the projectile path during motion. The projectile is made of nylon material and is white in colour. The water mist and projectile both become camouflaged during the trajectory. In order to track the projectile and measure its velocity, water is not used inside the VTR barrel. High speed photography was used to trace the path of the projectile during the flight trajectory.



Figure 3. Assembly of projectile and barrel

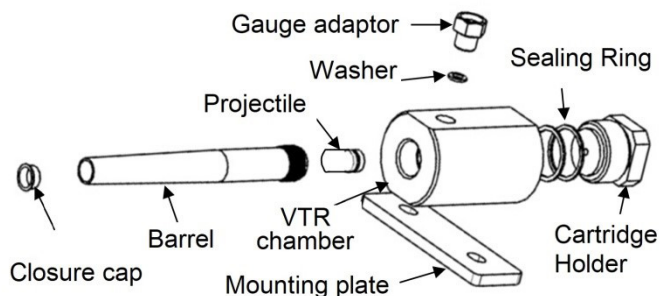


Figure 4. A 3D view of various parts of a VTR

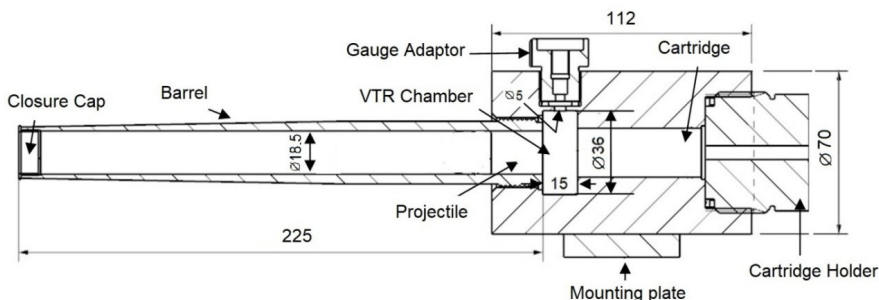


Figure 5. Engineering drawing of a VTR, showing the cartridge and hole (5 mm) for pressure take off where the pressure sensor is fitted (all dimensions are in mm)

Propellant pressure measurement and projectile muzzle velocity should be accurately measured. This will help to determine the acceptability of the propellant before use in an actual weapon, either in the static or dynamic mode. The projectile muzzle velocity and the pressure generated by the cartridge ensure perforation of the target after conducting various trials.

3 Description and Function of the Cartridge

3.1 Description

The cartridge for the disrupter consists of case and end cap-foil assembly. The case has a squib located centrally at one end. The end cap is soldered with foil. The case and end cap are both made of brass. The foil is made of copper. The case

is filled with a pyrotechnic composition as booster (aluminium and potassium perchlorate) and propellant as the main charge. The booster and propellant are separated by felt material. The cartridge has internal threads to accommodate the end cap-foil assembly. Figures 6 and 7 illustrate the cartridge engineering drawing, and a model with its detailed parts. The internal diameter of the cartridge case is 17 mm and the length is 35 mm. This is the space available for combustion of the propellant inside the cartridge. The outer diameter, total length and step diameter of the cartridge are 20, 53 and 22.5 mm, respectively.

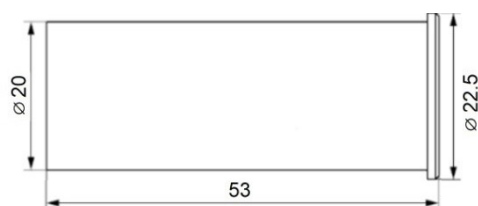


Figure 6. Engineering drawing of the cartridge (all dimensions are in mm)

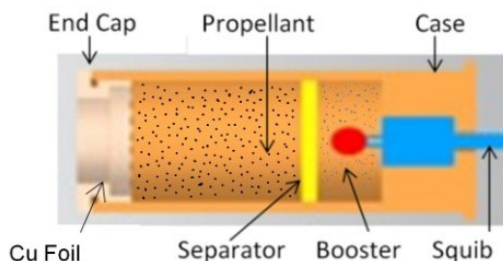


Figure 7. A model and its detailed parts

3.2 Function

Initiation of the cartridge is a thermal process in which a small resistance element, *i.e.* bridge wires are heated electrically. Its temperature is sufficient to cause deflagration of the pyrotechnic composition in contact with it. The bridge wire is heated, thus igniting the highly sensitive composition. This will further initiate the booster. The initiation of the booster finally ignites the propellant. The burning of the propellant generates gas pressure in the case, which ruptures the copper foil. The gas pressure thus generated is utilised to create the water-jet through the disruptor weapon. Here the chemical energy of the propellant is converted to the kinetic energy of the gas and acts on the projectile.

4 Materials and Methods

4.1 Propellant composition

Table 1. Chemical composition and physical properties of double base propellant spherical ball powder ammunition [25]

Component	Content [wt.%]
Nitrocellulose (NC)	85.3 Nitration (13% N)
Nitroglycerine (NG)	10.05
Dibutyl phthalate (DBP)	3
Diphenyl amine (DPA)	0.95
Calcium carbonate	0.5
Graphite	0.2
Physical properties	
	Value
Propellant shape	Spherical grains
Density	1.55 g/cm ³
Force constant	950 J/g
Average diameter	0.483 mm

Table 2. Chemical composition and physical properties of the double base NGB 051 propellant

Component	Content [wt.%]
Nitrocellulose (NC)	57.8 Nitration (12.75% N)
Nitroglycerine (NG)	39.85
Carbamite	1.7
Mineral jelly	0.4
Graphite	0.25
Physical properties	
	Value
Propellant shape	Graphite square flake
Density	1.65 g/cm ³
Force constant	1200 J/g
Web	0.15 ±0.02 mm
Length	1 mm

Double base propellants were used as materials in the experiments. The chemical composition and physical properties of the double base propellants are given

in Tables 1 and 2, respectively. The types of propellants used for testing the measurement of the pressure at the exit of the cartridge and the projectile velocity are shown in Figures 8(a) and 8(b), respectively.



(a)



(b)

Figure 8. Spherical ball powder propellant (a) and double base propellant NGB 051 (b)

A VTR was utilised to determine the cartridge pressure at its exit.

5 Experimental

5.1 Test arrangement for measurement of the pressure by the data acquisition system

The experimental test arrangement consisted of the VTR, high speed camera and data acquisition system. The pressure sensor and charge amplifier were the essential parts of the data acquisition system. A high speed camera was placed in a perpendicular direction to the motion of the projectile so as to track its trajectory. The frame per second and visibility for the motion of the projectile was adjusted for the camera.

The VTR was designed, fabricated and tested in the laboratory. The data acquisition system for the pressure measurement system comprises of a cartridge, gauge adaptor, VTR and Yokogawa scope corder DL 850E. It has a 12 bit module with a sampling rate of 10 MHz and charge amplifier. The measurement chain comprises of a pressure sensor, charge amplifier and output from the scope corder. Figure 9 illustrates the measurement chain. The cartridge was initiated on application of 24 V DC. Gases were generated on burning of the propellant. This acts as a working fluid against the projectile. A hole of 5 mm diameter was drilled through body of the VTR as a pressure take off point. Volume of approximately 15 cm³ was available (length 15 mm and internal diameter 36 mm) for expansion of the gases ahead of the projectile. A pressure sensor was screwed into the body in a radial direction perpendicular to the axis of the VTR body. It converts pressure into electrical signal. This signal is being small and is further amplified by a laboratory charge amplifier. Charge mode pressure sensor, laboratory charge amplifier and scope corder are connected by low noise cable. The pressure sensor was selected to have a fast response, small size, durability, hermetically sealed construction, measurement range 15000 psi, sensitivity 0.39 pC/psi and a rise time of $\leq 1.0 \mu\text{s}$.

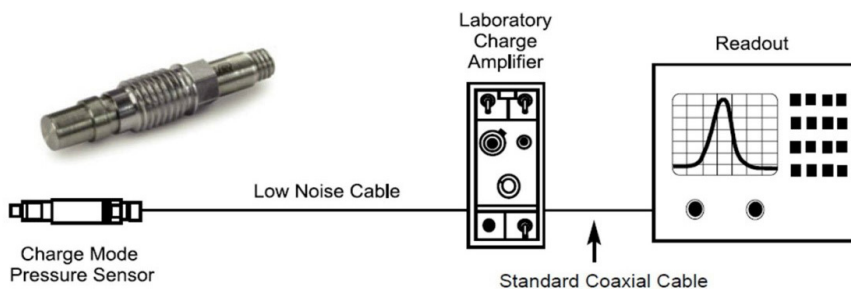


Figure 9. Measurement chain having charge mode pressure sensor, laboratory charge amplifier and output from scope corder

5.2 Test arrangement for measurement of the velocity using high speed photography

The role of the propellant is to push the projectile out of the barrel. The propellant occupies the space in the gun chamber immediately behind the projectile. It is usually a solid energetic material that upon the application of a suitable energetic stimulus rapidly transforms into small gaseous molecules. Due to the rapid volumetric expansion, the projectile is accelerated through the barrel [26]. Projectile velocity measurement is one of the important parameters associated with armament research studies. The velocity measurement near the muzzle of the barrel is an essential pre-requisite for the determination of the projectile velocity. Figure 10 demonstrates the experimental arrangement for measurement of the velocity of the projectile using high speed photography. A high-speed camera is able to take the image exposures at more than 5000 frames per second (fps). It is used for recording fast-moving objects as a photographic image(s) onto a storage medium. This camera is widely used for scientific research, military testing and evaluation, and in industry. Various methods such as Doppler RADAR, photocell, flash radiograph and high speed camera are available. The velocity of the projectile can be calculated if the time interval is measured over a known distance. A time interval counter with a suitable start/stop circuit gives the time measurement very accurately.

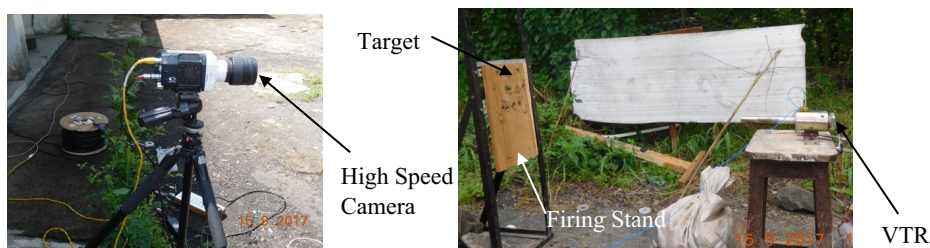


Figure 10. An experimental arrangement for the measurement of projectile velocity using high speed photography. It consists of a camera, VTR and target for arresting the projectile using a firing stand

Figures 11 and 12 depict the clear distinction between the two arrangements, *i.e.* VTR and water-jet disruptor. The various events related to the VTR firing are illustrated in Figures 11(a) and 11(b). Figure 11(a) shows the firing of the VTR without water in which the projectile will exit from the barrel. Figure 11(b) shows the projectile moving towards the target. All of these events were captured using high speed photography.

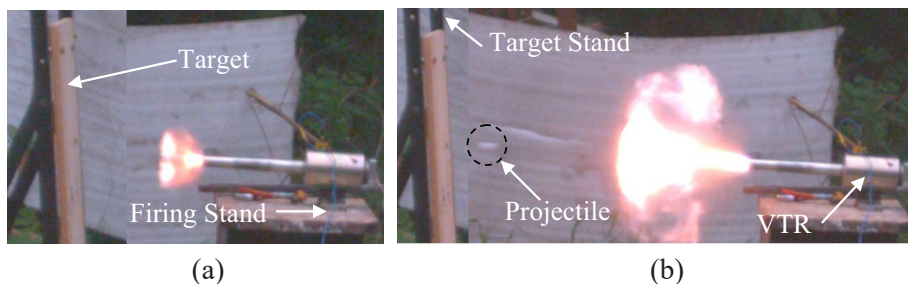


Figure 11. Firing of the VTR (a) and projectile moving towards the target (b)

The various events related to the water-jet disruptor firings are illustrated in Figures 12(a) and 12(b). Figure 12(a) shows the firing of a water-jet disruptor with water, in which the projectile becomes camouflaged with water mist. Figure 12(b) shows the interaction of the water-jet and projectile on the target.

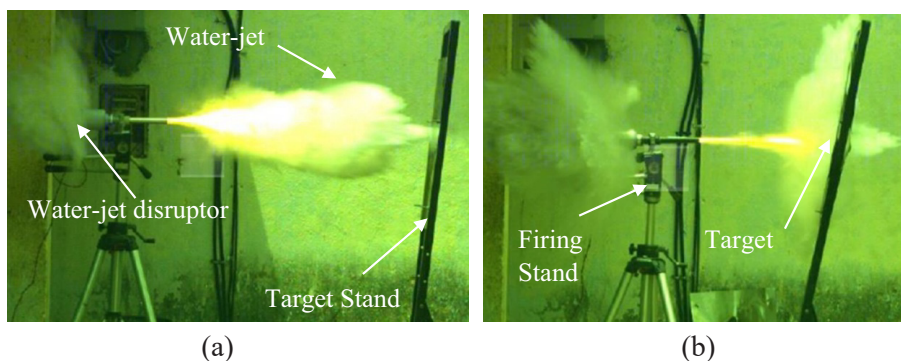


Figure 12. Firing of the water-jet disruptor (a) and interaction of the water-jet and the projectile (b)

6 Results

6.1 Theoretical determination of the projectile velocity

The relation between velocity and internal pressure acting on the projectile is given by Equation 1. The subscripts *i* and *o* represent the inlet and outlet conditions. This velocity is obtained using Bernoulli's equation with the following assumptions [27]:

- There is steady flow of fluid, *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 ($W_s = 0$).
- 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 $y_i = y_o$.

$$m_i \left[e_i + \frac{P_i}{\rho_i} + \frac{V_i^2}{2} + gy_i + Q \right] = m_o \left[e_o + \frac{P_o}{\rho_o} + \frac{V_o^2}{2} + gy_o + W_s \right] \quad (1)$$

$$V_o \text{ or } V_{th} = \sqrt{\frac{2P_i}{\rho}} \quad (2)$$

where P_i is the internal pressure generated by the propellant burning and acting on the projectile and can be determined as explained in Paragraph 6.2 and ρ = projectile density (material construction, nylon) = 750 kg/m³.

6.2 Estimation of internal pressure (P_i)

The internal pressure generated inside the cartridge case can be determined by using the following relation [28]:

$$P_i = \frac{FC}{V} \quad (3)$$

where F (950 J/g) and C (3 g) are the force constant and charge mass of the spherical ball powder propellant, and V is the total volume available (23 cm³) for expansion of the gases, which includes the VTR volume and the cartridge volume. The calculations for volume and pressure are illustrated below.

Cartridge volume = Area \times Length

$$\text{Cartridge volume} = \frac{\pi}{4} d^2 \times l \quad (4)$$

where d is the internal diameter ($d = 17$ mm), length ($l = 35$ mm) is the inside length available for expansion of the gases after propellant burning and π is 3.14. Substituting these values into Equation 4, gives a cartridge volume of 7.94 cm³.

For the VTR chamber, the internal diameter ($d=36$ mm) and length ($l=15$ mm) is the inside length available as shown in Figure 5. Substituting these values into Equation 4 gives a VTR chamber volume of 15.2 cm³.

Adding both volumes *i.e.* cartridge and chamber volume, gives the total volume available for expansion, *i.e.* approximately 23 cm³. Putting this value into Equation 3, gives an internal pressure of the order of 123.91 MPa for spherical ball powder. This is the theoretical pressure.

The same exercise is repeated for NGB 051 propellant as explained above, to determine the internal pressure. Substituting values of F (1200 J/g), C (3 g) and V (23 cm³) in Equation 3, the theoretical internal pressure for NGB 051 propellant works out as 156.52 MPa.

7 Discussion

The turbulent stream of gases after combustion of the propellant follows certain distance as the projectile leaves the barrel. Immediately at the muzzle end, the projectile path is tracked by high speed photography. Typical graphs for spherical ball powder ammunition and NGB 051 propellant for distance vs. time and velocity vs. distance of the projectile are shown in Figures 13 and 14, respectively. These graphs were obtained by an Excel programme and pixels from frame to frame. As the time increases the projectile velocity increases. From the graph, it is clearly observed that the projectile velocity is maximum at the muzzle end of the barrel.

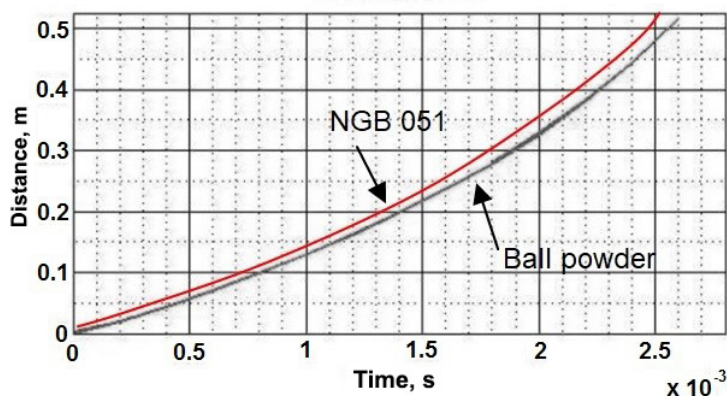


Figure 13. Distance vs. time

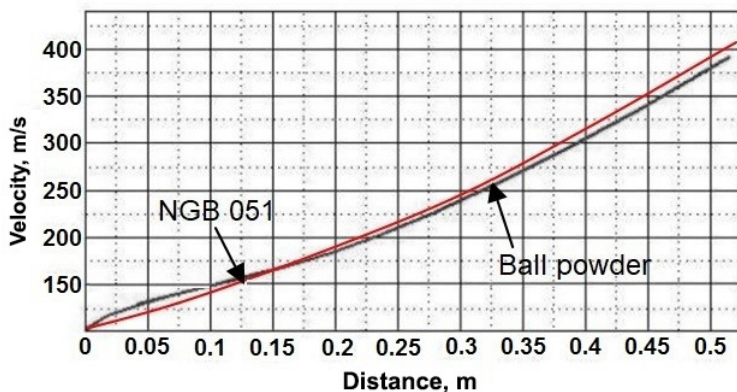


Figure 14. Velocity vs. distance

The pressure and velocity parameters were generated by firing the cartridges in a VTR under ambient conditions. The evaluation technique for the measurement of pressure and velocity was explained in Section 5. The parameters for spherical ball powder and NGB 051 propellants are given in Tables 3 and 4, respectively. Considering the losses and assuming the combustion of the propellant is similar to the burning of fuel in an internal combustion (IC) engine, this gives an actual pressure from 39.26 to 50.12 MPa for spherical ball powder in the VTR. The standard deviation for the maximum pressure is 3.24 MPa. These losses are due to friction between the barrel and the projectile, heat retained by the cartridge case, heat to the propellant and propellant energy imparted to the burning of the propellant. The theoretical projectile velocity varies from 323.56 to 365.58 m/s. The experimental projectile velocities varied from 333.52 to 384.23 m/s. The percentage error between the experimental and theoretical projectile velocity is less than 7. The standard deviation for theoretical and experimental projectile velocities varied from 12.57 to 13.88 m/s.

Table 3. Performance parameters (spherical ball powder)

Round	P _{max} [MPa]	Theoretical projectile velocity [m/s]	Experimental projectile velocity [m/s]	Percentage error [%]
1	42.781	337.76	361.91	6.67
2	40.84	330.01	343.21	3.84
3	39.26	323.56	333.52	2.98
4	41.21	331.50	353.87	6.32
5	50.12	365.58	384.23	4.85
6	43.78	341.68	362.8	5.82
7	42.76	337.67	360	6.20
8	46.12	350.69	366.60	4.33
9	44.91	346.06	364.82	5.14
10	47.01	354.04	367.12	3.56
Min.	39.26	323.56	333.52	–
Max.	50.12	365.58	384.23	–
Mean.	43.87	341.85	359.80	–
Standard deviation	3.24	12.57	13.88	–

Table 4. Performance parameters (NGB 051)

Round	P _{max} [MPa]	Theoretical projectile velocity [m/s]	Experimental projectile velocity [m/s]	Percentage error [%]
1	62.6	408.57	415.16	1.58
2	60	400	409.43	2.30
3	61.42	404	412.13	1.97
4	59.3	397.65	408.52	2.66
5	57.23	390.65	403.54	3.19
6	63	409.87	418.32	2.01
7	59.8	399.33	407	1.88
8	58.7	395.64	406.91	2.76
9	57.87	392.83	404.12	2.79
10	56.8	389.18	401.23	3
Min.	56.8	389.18	401.23	–
Max.	63	409.87	418.32	–
Mean.	59.67	398.77	408.63	–
Standard deviation	2.14	7.09	5.33	–

Considering the losses and assuming that combustion of the propellant similar to burning of fuel in an internal combustion (IC) engine, this gives an actual pressure from 56.8 to 63 MPa for NGB 051 propellant in the VTR. The standard deviation for the maximum pressure is 2.14 MPa. The theoretical projectile velocities varied from 389.18 to 409.87 m/s. The experimental projectile velocities varied from 401.23 to 418.23 m/s. The percentage error between the experimental and theoretical projectile velocities is less than 3. The standard deviation for the theoretical and experimental projectile velocities varied from 5.33 to 7.09 m/s.

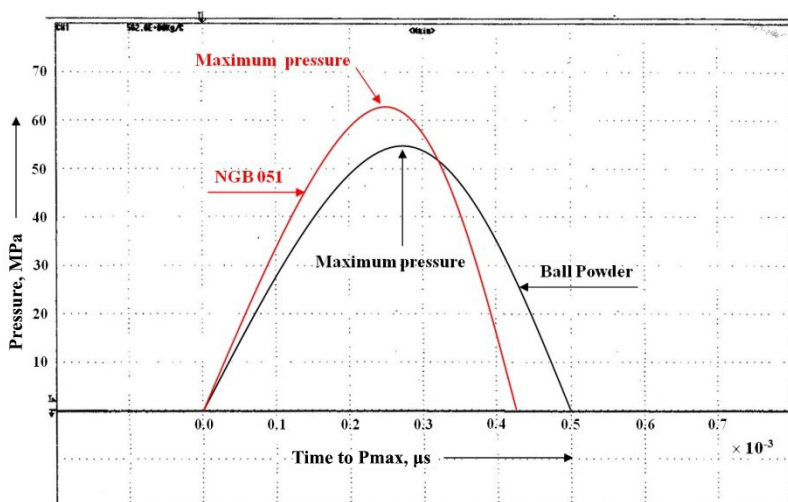


Figure 15. Firing curves for spherical ball powder ammunition and NGB 051

One of the firing curves, obtained for spherical ball powder ammunition (black colour) and NGB 051 (red colour) propellant are superimposed over each other in Figure 15. Although the pressure-time profile has a sharp peak, the time axis is plotted in μs to expand the pressure plot. Completion within $0.5 \mu\text{s}$ makes the event instantaneous. The time taken for burning NGB 051 propellant is less than that for spherical ball powder propellant. From the Tables 3 and 4, it can be observed that the pressure for spherical ball powder propellant is less than that for NGB 051 propellant in all cases. This is due to the greater force constant for NGB 051 propellant. As the combustion of the propellant takes place inside the VTR, the pressure acts on the projectile. The pressure rises and the projectile starts its motion inside the barrel. The pressure reaches its maximum value. As the projectile moves in the forward direction through

the barrel, the pressure starts to fall as shown in Figure 15. The fall in pressure is due to the increase in volume inside the barrel. The final pressure after leaving near the muzzle end of the barrel is above atmospheric pressure. At the exit end of the muzzle, the projectile has maximum velocity.

The gas pressure and muzzle velocity measurements over time were analysed. The projectile velocities were recorded using high-speed photography. The United Kingdom Defence Standard describes the procedures to be used for assessing the ballistic performance of gun propellants [29]. The maximum projectile velocities for spherical ball powder and NGB 051 propellants were measured experimentally as 384.23 and 418.32 m/s, respectively. The maximum pressures for spherical ball powder and NGB 051 propellants were measured as 50.12 and 63 MPa. The maximum pressure recorded in the VTR shows that they are consistent. Propellant parameters such as maximum pressure, force constant, vivacity and burning rate are determined by combustion of a propellant in a closed vessel (CV). Meysmans *et al.* [30] studied the ballistic parameters, and demonstrated the influence of vessel size at the same loading density using propellant for small arms in a CV.

From Tables 3 and 4, it may be observed that the theoretical projectile velocity is less than the experimental values. The percentage error is less than 10%. This validates both the experimental and the theoretical projectile velocities. The estimated pressures, experimental and theoretical are closely matched with each other. Furthermore, the variation in the maximum pressure and projectile velocity is due to the propellant gas expansion. Manual measurements may also lead to errors during the measurement of these events by a high speed camera. This is due to the short stand-off distance, *i.e.* 0.5 m between the target and the velocity test rig. Theoretical values pertaining to projectile velocities are less, as frictional and drag forces are not taken into account.

The basic parameters in a VTR using a data acquisition system have been generated by mounting pressure sensor to measure the internal ballistic parameters of the cartridges used in a disruptor weapon. This kind of internal ballistic evaluation technique related to the gas generator plays a vital role during development, qualification testing of armament systems, before offering them to users and the final production of the cartridges.

8 Conclusions

A VTR has been successfully designed and fabricated for use in the laboratory to determine projectile velocities using a high speed camera. The pressure

generated by the cartridge can be conveniently measured using a data acquisition system. This paper describes a novel method for dynamic pressure and velocity measurements, for evaluating the performance parameters of a double base propellant using a VTR. Pressure measurement in a VTR is one of the most demanding measurements for selection of the propellant for a particular weapon. Therefore the performance of a water-jet disruptor critically depends upon its combustion characteristics including pressure, temperature sensitiveness burning rate, spatial distribution of energy release, temperature and species concentrations of the propellant. The velocity of the projectile is dependent on the rate at which the gas is produced by the burning of the propellant. It is dependent on the amount of chemical energy released. Thus novel method for pressure - velocity measurement related to a power cartridge for a water-jet disruptor has been successfully established.

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