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Experimental analysis of ballistic parameter evaluation of power cartridge in vented vessel for water-jet application

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Abstract

The present study deals with the evaluation of ballistic parameters of power cartridge in vented vessel (VV) for water-jet application using statistical methods. VV is test equipment which approximately simulates the motion of projectile in dynamic condition. Power cartridges are basically known as pyrotechnically or propellant actuated devices (PADs) utilized in disruptor to create a high velocity jet of water. Because of fast burning characteristics, high burning rate, density and easy ignition characteristics, it quickly develops both products of combustion, high pressure and temperature gases. This acts as a dominant force during propellant combustion in the cartridge case. The high velocity water-jet aids in destroying the suspected improvised explosive devices (IED's) effectively. To evaluate the performance parameters, VV was designed, fabricated and tested in the laboratory. The vessel body is provided with orifice or vent of 5 mm diameter through which combustion gases are allowed to flow. The gas pressure generated by the power cartridge was measured using the pressure transducer fitted over the vented vessel body. It is paramount and an essential task for determination of correct pressure inside a vessel. This parameter simulates the motion of projectile inside the barrel in which change of volume occurs. The purpose of this study is to generate and measure the maximum pressure and rise time for maximum pressure of the cartridge by single base propellant in VV. The use of this evaluation method helps in understanding the behaviour of the propellant and acceptance of the propellant lot for cartridge production. An experimental study involves a burning of known mass of propellant inside VV at hot and cold conditions. Single base propellants with 3 g mass and pyrotechnic 0.5 g are used in VV firing. The experimental results revealed that the maximum pressure (P_{max}) in hot is more than that of cold condition, whereas time for maximum pressure is less in hot than that of cold condition. This paper presents an experimental finding carried out for ballistic performance parameters evaluation using data acquisition system and the statistical data for disruptor weapon at hot and cold temperature. The existing work was dedicated to evaluate the performance of the cartridge inside the VV. This research study reported that it is good agreement for the experimental trials considering performance evaluation of power cartridge in dynamic mode.

Keywords: ballistic, vented vessel, power cartridge, performance evaluation, propellant

1. Introduction

The closed pressure vessel testing were exclusively utilised for decades to predict the behaviour of various propellant. Such type of vessel holds the gas pressure or liquid higher than atmospheric pressure[1]. This closed vessel study also helps to investigate the combustion strength and grain geometry of the propellant[2, 3]. The power cartridges are known as the pyrotechnically actuated devices which would generate the gases when suitably initiated. They are typical initiators in which the propellant combustion takes place for generating the gas in short duration to perform various mechanical tasks. The power cartridges have numerous applications in escape aid system for an aircraft, stage separation in rockets and space and destruction of suspected IEDs using high velocity water-jet. The explosion using hydrogen in vented vessel is confined and is very complex as it involves many parameters[4]. The explosion in vented vessel is generally recommended to avoid accidents in industrial domain and defence application. The combustion products help to discharge to safer distance and location by means of vent. Experimental study was performed to examine the deflagration of pressure attenuation of LPG-air mixture[5]. Further, this study using numerical and experimental in spherical vessel ducted into vented vessel was carried out by Yuan et al.[6]. The problem of explosion mitigation through a vented vessel which connected to a duct was pointed by Ponizy' and Veyssiere[7]. A flow through duct allows fast combustion gases evacuation. A limited work on burning / explosion of propellant in vented vessel (VV) was addressed in the open literature as research related work classified in nature.

This current research article describes the performance evaluation technique of cartridge by burning single base propellant in the VV through vent at hot and cold conditions. This is the important stage to ensure the performance parameters of the cartridge to simulate gas motion through that particular vent or orifice. The maximum pressure indicates that the gas energy which is responsible for destruction of suspected IEDs. The propellant combustion gases after venting out is not studied seriously in defence research area concerning other important applications. In this present research paper, a general study of the propellant gases venting through orifice or vent problem is attempted.

1.1 Applications of VV

There are numerous applications of VV in industrial sector and defence. Some of VV technique are used for following purpose –

- To measure the performance parameters of main seat ejection cartridges such as maximum pressure and time taken to reach half the value of maximum pressure during design, development and testing[8].
- To evaluate the burn rates of propellants, for quality checks and acceptance during bulk production, performance evaluation during new development before induction into services.
- Life prediction and assessment, life extension and acceptance criteria of imported defence store.
- VV testing provides the data on the burn rate behaviour of energetic materials at different temperatures.
- Diurnal cycling and ballistic assessment to provide details on any degradation in the performance of the energetic material[9].
- To simulate gas flow through a particular vent to understand the propellant burning behaviour for operating another propellant actuated device or a specific system.
- Propellants testing in VV are conducted in condition of high loading densities in order to understand the nature of combustion of gun propellants under high pressure impossible to obtain in closed vessel tests.

1.2 Assumptions

In this manuscript, an attempt is made to evaluate the performance of the power cartridge. The important following assumptions were invoked to study the experimental results.

- The propellant gas behaves like real gas
- The ratio of specific heats is polytropic expansion
- The propellant gases temperature (T) is depends on pressure. The burning rate of the propellant is different at the different temperatures
- The energy loss is neglected to the vessel walls due to convection and conduction and pressure is varying at every instant as the gases are passing through orifice throughout the vessel being a dynamic mode
- When venting takes place, only unburned gases are vented out. The final gas pressure after achieving the maximum pressure is always above the atmospheric pressure
- The flame temperature of a single base propellant is range of 2500 to 3000 K[10]

2. Description and function of power cartridge

2.1 Description of power cartridge

The cartridge for disrupter consists of case, end cap-foil assembly. The case is having a squib at the centre of the cartridge. The other end of cartridge has end cap-foil assembly. End cap is soldered with foil made up of copper. The case and end cap both are made of brass material. The cartridge is filled with a pyrotechnic composition and propellant. Figures 1 (a) and (b) show the images of the cartridge and assembly parts in detail.

2.2 Function of power cartridge

As electrical energy is supplied to squib, it gets ignited. Squib once ignited, initiates the booster. The initiation of booster initiates the propellant. The burning of the propellant generates gas pressure in the case which ruptures the foil. This gas pressure released from cartridge acts against the water column held by projectile made up of nylon material. It gets sheared off and generates high speed water-jet through disruptor weapon.

3. Materials & test apparatus

3.1 Propellant composition

The method for performance evaluation of cartridge using VV comprises of burning of weighted propellant sample. The propellant is circular shape with average diameter of 0.18 mm. It comprises of NC 97.2 % (13.2 N), DBP 1.8 % and DPA 1 %[3] as stabiliser and calorimetric value is 3348 J g^{-1}. The gun powder is surrounded by the squib. The ingredients of gun powder composition consist of Potassium nitrate, Carbon & Sulphur.

The images of single base propellant along with SEM photograph used for testing in the power cartridge are depicted in Figures 2 (a) and (b).

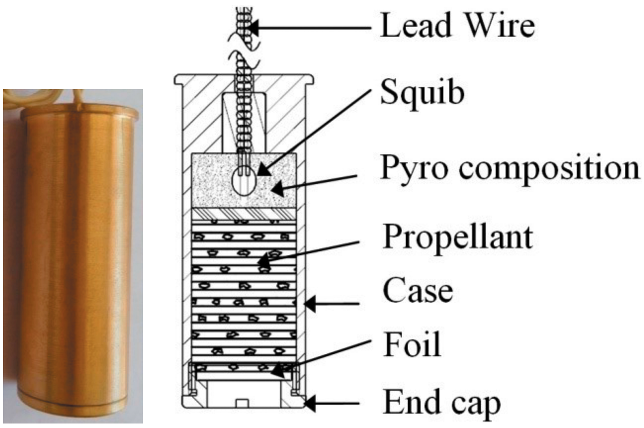
4. Experimental technique

4.1 Preparation for firing in VV

An experimental procedure comprises the following instruments and accessories

- A vented vessel (VV) with a volume 150 cc
- A pressure transducer
- Yokogawa Scope Corder DL 850E (12 bit module with sampling rate of 10 MHz) and
- Charge amplifier
- Power supply (24 V DC)

Figure 3 depicts schematics of VV and experimental apparatus utilised during the vented vessel firing. It is cylindrical in shape with internal diameter 40 mm and effective length 120 mm. This method is extensively used to test for evaluating the performance of pyro cartridge. The cartridge is loaded inside the breech chamber. A pressure transducer is fitted to the VV body in a radial direction perpendicular to axis. The bridge wire as a means of ignition is the part of the cartridge. It is electrically ignited using a suitable power source. The ignition of bridge wire causes to initiate pyrotechnic composition and the propellant. On burning of the propellant, gases were generated allow to pass through orifice or vent having diameter 5 mm. The location of vent is right angle to position of pressure transducer. The gas pressure is sensed by the pressure transducer. It generates the signal and passes to an amplifier. This signal is collected by an oscilloscope so as to generate pressure and time history profile on the oscilloscope screen. The cartridges are filled and properly weighed with 3 g single base propellant fired in VV at hot (45°C) and cold conditions (−26°C). The pyro composition i.e. gun powder 0.5 g used in the filling. It was fitted in radial direction and perpendicular to the axis of a body. The transducer converts the pressure into voltage, which gets amplified by an amplifier. The result was recorded in the form of maximum pressure *vs*. rise time i.e. (*P*-*t*) history graph.



(a) (b)

Figure 1 (a) Image of the cartridge; (b) Sketch for Cartridge details.

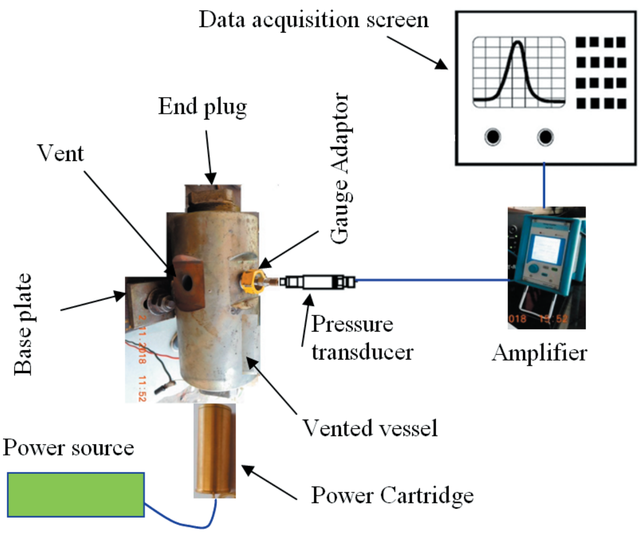
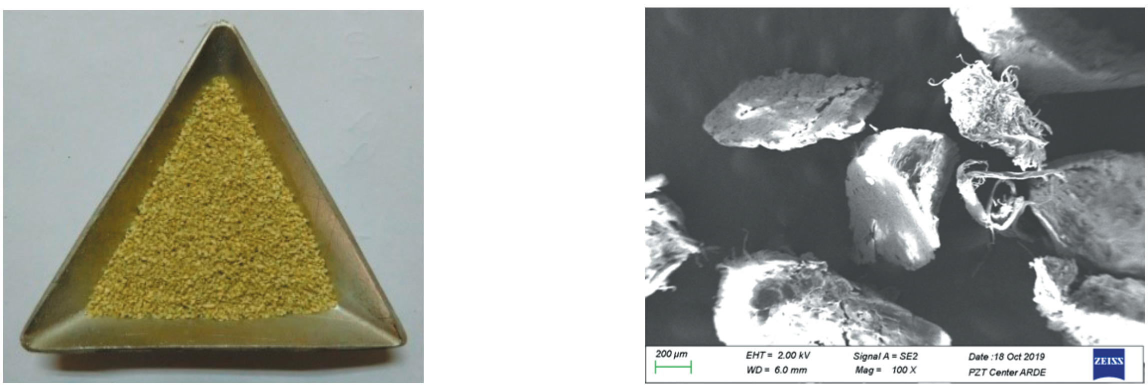


Figure 3 Schematic diagram of an experimental set-up showing VV, charge amplifier and scope- corder.



(a) (b)

Figure 2 (a) Single base propellant; (b) SEM of Single base propellant.

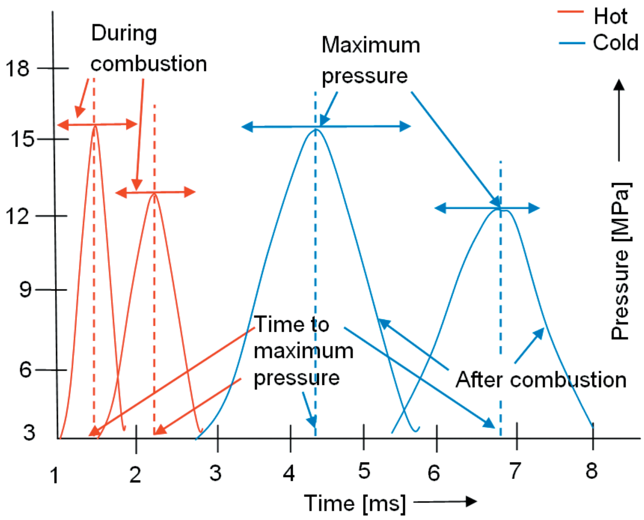


Figure 4 Pressure time history for single base propellant in hot and cold conditions.

Figure 4 illustrate the graphical representation of maximum pressure and rise time to maximum pressure at hot and cold conditions. The maximum and minimum values of the parameters are selected from Table 1.

The hot and cold conditions are differentiated by red and blue colours. The various regions during combustion phases and after combustion were indicated. The initial regions are at the beginning of the start of ignition of propellant. The final pressure is at the end of combustion of the propellant and this pressure is always above the atmospheric pressure. The engineering drawing of VV with important features with tolerances is represented at Figure 5. The design of test vessel is based on thick cylinder theory[11].

5. Analysis of test results and discussions

5.1 Performance evaluation in VV

The performance evaluation data of cartridge for single base propellant is generated by firing 15 Nos. of cartridges each in VV at hot and cold temperatures are given in

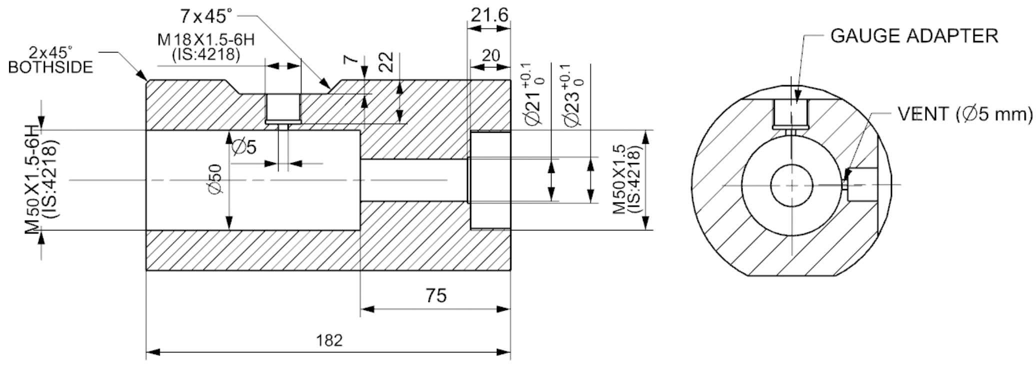


Figure 5 The engineering drawing of VV with important features with tolerances.

Table 1 Performance Parameters (Single base propellant).

Round	Hot (45 ⁰C)		Cold (−26 ⁰C)	
	P_{max} [MPa]	Time to maximum Pressure [ms]	P_{max} [MPa]	Time to maximum Pressure [ms]
1	13.54	6.76	13.84	5.76
2	14.84	4.2	12.76	6.23
3	13.90	5.85	13.52	7.93
4	15.01	4.67	12.53	6.93
5	14.15	3.88	14.92	5.67
6	13.19	2.15	14.34	5.98
7	15.49	3.69	12.89	7.15
8	14. 51	4.57	13.56	7.89
9	14.78	4.79	13.89	6.45
10	13.97	4.82	14.27	5.12
11	15.45	3.82	12.98	6.45
12	14.15	1.45	15.34	4.12
13	13.78	5.23	14.13	5.15
14	15.64	1.46	13.19	8.21
15	14.87	2.65	14.23	7.14
Mean	14.482	3.999	13.759	6.412
*Std Dev	0.775	1.535	0.807	1.158
Min	13.19	1.45	12.53	4.12
Max	15.64	6.76	15.34	8.21

Table 1. Statistics of parameters are determined and encapsulated below.

*Standard deviation

From the above table, it is observed that, in hot conditions the maximum pressure generated by this cartridge using single base propellant varies from 13.19 to 15.64 MPa, whereas time to $P_{\max}$ varies from 1.45 to 12.53 ms. The standard deviations for pressure and time to $P_{\max}$ are 0.775 and 1.535 respectively.

In cold conditions, the maximum pressure generated by this cartridge using single base propellant varies from 12.53 to 15.34 MPa, whereas time to $P_{\max}$ varies from 4.12 to 8.21 ms. The standard deviations for pressure and time to $P_{\max}$ are 0.807 and 1.158 respectively.

The time in case of hot condition is less than cold condition and pressure is more in hot condition than cold condition. This is due the propellant already gained some temperature in hot condition as pressure is directly proportional to temperature. Hence the response time is less as compared to cold conditioning. All the cartridge cases containing the propellant samples are placed in conditioning temperature for minimum period of six hours and immediately fired in the VV with minimum temperature loss and with minimum delay. Further from figure 4 it is observed that noticeable ignition delay in hot condition is less than cold condition.

5.2 Theoretical pressure estimation

Theoretically, the maximum pressure achieved in VV is determined using Equation (1) and it depends on the propellant burn rate and venting rate.

$$P_{max} = \textit{Burn rate of propellant / Venting rate} \tag{1}$$

Burn rate of propellant (r) is expressed as

$$r = \beta\, P_{max}^{\alpha} \tag{2}$$

Here

α = pressure index

β = burn rate coefficient

In Equation (1) the venting rate is the function of vent diameter and velocity of leaving gases. The venting rate is dependent on pressure. The pressure in VV is varied with the time after began it venting. This can be expressed as

$$m_v = C_d \times A \times v \times \rho \tag{3}$$

Where

m_v = Mass flow rate or venting rate of products of combustion propellant gases [kg s^{-1}]

A = Area of the vent [m^2]

v = Velocity of gases [m s^{-1}]

Velocity of gases can be computed using Bernoulli equation for incompressible fluid in isochoric condition as.

$$v = \sqrt{\frac{2P}{\rho}} \tag{4}$$

where

ρ = Density of products of combustion [g m^{-3}]

Putting value of v in Equation (3)

$$m_v = C_d A \sqrt{\frac{2P}{\rho}} \times \rho$$

$$m_v = C_d A \sqrt{2\rho P}$$

For a specific vent size design, coefficient of discharge (C_d) can be established using a following relationship

$$C_d = \textit{Actual discharge / Theoritical discharge} \tag{5}$$

Applying low of conservation of mass i.e. mass entering (m_e) into the system is equal mass generation (m_g) minus mass venting out or leaving (m_v) the system.

$$m_e = m_g - m_v \tag{6}$$

The total release rate (q) during combustion can be obtained by multiplying the combustion enthalpy (h_{comb}).

$$q = m_v \times h_{comb} \tag{7}$$

Knowing all the parameters and using Equation (1) the theoretical pressure can be determined. The maximum pressure achieved in VV firing is the resultant of vent size and velocity of gases. The relationship between venting rate / mass flow rate and pressure is not linear. The location of vent is kept away from the cartridge side so as protect the equipment bursting and damage to the pressure transducer due to pressure oscillations developed by combustion gases.

6. Conclusions

In this study, the overview of results showing the performance evaluation in terms of pressure-time measurement of power cartridge utilised in VV was explained. This article gives the information about the performance evaluation method of power cartridge in water-jet application *i.e.* maximum pressure and rise time to maximum pressure are determined by propellant burning in the VV. This manuscript discussed about the performance evaluation method of the power cartridge using single base propellant to generate the pressure profiles within the VV. The performances parameters are determined in VV at hot and cold conditions. The purpose of this paper is to study the behaviour of propellants at different conditions with test chamber having a hole or orifice. Further, this study helps in developing a method of choice of 'safe' vent areas to release the gas pressure. This VV technology is widely used to vent out explosive gases in industrial domain to protect the equipment[12]. The provision of vent to the vessel help to reduce the over pressure generated by power cartridge. Therefore selection of vent and its location plays a crucial role to measure ballistic parameters such as maximum pressure and time related to power cartridge. It is important to note that vent or orifice works as a pressure relieving device to avoid overpressure and protect installation and lives in case of mishaps.

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