The present study deals with combustion study for comparison of power cartridge in closed (CV) and semi-closed vessel (SCV) for water disruptor application using statistical methods. The cartridges are fired in the test vessels such as CV and SCV. CV is perfectly leak proof from all sides. SCV is provided with vent 5 mm diameter keeping the same volume as that of CV. To evaluate the comparative internal ballistic performances, the firings of cartridges are carried out in CV and SCV. The gas pressure generated by the power cartridges are measured using the pressure transducer fitted over the body. It is vital task to understand the effect of vent on maximum pressure inside a test vessel. The motivation behind this experiment is to assess the maximum pressure developed and respective time inside SCV to simulate the motion of projectile to some extent through barrel. The internal ballistic parameters are evaluated in CV and SCV. The percentage drop in pressure and time are calculated. From this study, it is inferred that pressure drop in SCV is 16 percentage to that of CV. Further, an experiment revealed that pressure drop in CV is 1.2 times of SCV.

1. Introduction

The closed vessel (CV) technology is exclusively utilised for decades to predict the burning behaviour of various propellants. The power cartridges are known as the propellant or explosive actuated devices which would generate the gases when suitably initiated. They are typical gas generators in which the propellant combustion takes place for generating the gas in short duration to perform various mechanical tasks [1]. Mainly cartridges are filled with single or double base propellant, pyrotechnic composition and gun powder. The propellant combustion is a very complex phenomenon. All the propellants manufactured for the defence applications are required to meet the stringent specifications requirements considering the chemical, physical properties, shape and the internal ballistic parameters. The responsibilities for independently testing samples of such propellants are to ensure that they meet those specifications after manufacture. In conventional weapon, the aim of propellant combustion with respect to the cartridge is to obtain the performance parameters to cause the required damage [2,3]. The internal ballistic evaluation of a given quantity of the propellant takes into account the determination of the propellant mass and the muzzle velocity. These parameters are evaluated from the mean relative values of vivacity and force constant. Ballistic level calculations and a variety of constants are called as an increment factor [4]. The general design principle is that the maximum pressure generated by the propellant burning inside the cartridge should not exceed the yield strength of the material. Therefore, it is very important to know the maximum pressure so as to ensure its safe use [5]. This research article describes the comparison of internal ballistic performance evaluation.
technique of cartridge by burning double base propellant in CV and Semi-Closed Vessel (SCV) with same volume at hot and cold conditions.

1.1 Applications of CV

The test related to power cartridge, in principle the test results can be applied to the combustion of gas propellant in CV. These techniques are used for the following purpose -

(a) To measure the internal ballistic parameters of the propellant and performance prediction of pyrotechnic composition
(b) To compare the burn rates of standard and test propellants, for quality checks and acceptance during bulk production, performance evaluation during new development before induction into services [6].
(c) Life prediction, assessment, life extension and acceptance criterion of defence store [7].
(d) CV testing provides the data on the burn rate behaviour of energetic materials at different temperatures
(e) Compared with the gun systems, CV data could be obtained at lower loading densities and thereby lower the pressures
(f) Diurnal cycling and ballistic assessment to provide details on any degradation in the performance of the energetic material [8].

1.2 Applications of SCV

SCV techniques are used to allow the outflow of gas through vents after reaching a certain pressure level. The need for power cartridge tests in SCV is carried out for the following purpose -

(a) To measure the internal ballistic 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 [9].
(b) Life prediction and assessment, life extension and acceptance criterion of imported defence store
(c) To simulate gas flow through a particular vent to understand the propellant burning behaviour for operating a another propellant actuated device or a specific system
(d) Propellants testing in SCV 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 CV tests.

2. Literature Survey

Clive et al. has conducted the experiments to evaluate the burning rate of polymer-bonded explosives (PBX) as a function of pressure [9]. Combustion characteristics and development for Zirconium Potassium Perchlorate using a numerical simulation inside CV was performed by Doo-Hee et al. [10]. Force constant, burning rate and vivacity of gun propellants are determined by CV techniques [11]. The burning rates are different for different propellants, and depend on the physical properties as well as chemical composition. In chemistry, burning rate is a measure of the linear combustion rate of propellant. It is measured in length such as "mm/second". The burn rates are affected by pressure and temperature. Burn rate is an important parameter especially in the area of propellant because it determines the rate at which combustion gases are generated. The propellant burn layer by layer and releases the energy by deflagration process which is surface burning phenomenon. The flame temperature of double base propellant is in between 2600°K - 3600°K [12]. Yilmaz et al. reported that strand burner is utilised to measure the linear burning rates of solid propellants at different pressure and temperature [13]. Leciejewski has carried out the comparative micro and conventional CV trials as per STANAG 4115 for a gun powder and single base propellant [14-15]. It also helps to determine force constant, vivacity and burn rates of the propellant under given temperature. Gun propellants firing in CV at various loading densities were carried out by Mehta et al. to assess the internal ballistic parameters [16]. The findings of this experiment show that the propellant burn rate at a given pressure is independent on the propellant loading densities. As the loading density increases, pressure increases. While dealing with R and D activities, defect investigations and inspection of gun propellants. CV evaluation is popularly utilised in conducting static trials in place of actual dynamic firing of the system. This activity is safer, quicker and cheaper for the gun propellant. Jakub, et al. carried out CV
test which exhibits the variation in velocity of cloud propagation [17-19]. The gun powder was used in ignition where plasma was compared. Divekar et al. reported that the thermal studies of triple base gun propellants having CL20 in CV which signifies improvement in energetic compositions. The authors further conducted study on web size variation of double base propellants in CV. This study brings out that increasing web size of propellant grain decreases the maximum pressure (Pmax) [20-21]. Bin et al. had deliberated the pressure of propellant in a CV with dissimilar loading densities using state principle [22]. Norbert et al. reported modifications in Vieille’s law to explain the temperature dependence of combustion or the burn rate of porous propellants using simplified heat flow in the solid phase [23]. An annexe of CV method was introduced by Vittal. It helps to determine the burn rate of propellants with pressure range varying from 9.8 to 75 MPa [24,25]. In this experiment, test propellant and standard propellants were compared. The gas products works as a fluid on the vessel walls. Internal ballistic parameters assessment for gun propellants through experiment and CV modelling was reported by Oliveira [26,27]. Parate et al. described the design analysis of CV using various theories of failures experimentally and FEM techniques [28].

Measurement of internal ballistic in SCV using power cartridge has a very less available literature. However there were some references cited in the open access to conduct simulations studies related to explosions. In order to avoid the accident due to explosion in industry venting of explosion using CFD was reported [29, 30]. Further, this study using numerical and experimental in spherical vessel ducted into vented vessel was carried out by Yuan et al. [31]. Peak pressure estimation in a spherical vessel using a properly vent design produced by hydrocarbon-air explosion was discussed by Michael et al. [32]. The author reported that flame velocity was utilised to explain the effect of flame acceleration. Under a given service operating conditions a safe engineering design for pressure vessels such as closed or semi-closed vessel was provided [33].

3. Description and function of power cartridge

3.1 Description

A disrupter power cartridge is made up of end cap-foil assembly and case. An electrical squib is located in the middle of the cartridge. End cap-foil assembly is screwed at the other end of cartridge. Foil is soldered with end cap. The material for construction for end cap and case are brass material. The propellant (3 g) and gun powder (0.5 g) are filled in the cartridge. Fig. 1 (a) and (b) show the image of the cartridge and assembly parts in detail.

![Image of the cartridge](image1.png)

**Figure 1(a) :** Image of the cartridge [34]

![Sketch of cartridge details](image2.png)

**Figure (b) :** Sketch of cartridge details

3.2 Function of power cartridge

On application of an electrical energy, squib gets ignited. It further initiates the gun powder which further initiates the propellant. The propellant on burning develops the gas pressure which ruptures the foil. This gas pressure is released by the cartridge, work against the water column inside the barrel of water disruptor. Nylon projectile gets sheared off and creates high speed water through disruptor.

4. Materials and test apparatus

4.1 Propellant composition
To determine internal ballistic parameters using CV and SCV comprises of burning of weighted propellant sample. The chemical composition and physical properties of double base propellant are given in Table 1 and 2 respectively. The gun powder composition is a mixture of Potassium Nitrate, Carbon and Sulphur.

Table 1: Chemical composition of the double base propellant (JSS 2003) [35]

| Ingredients         | Composition (wt %) |
|---------------------|--------------------|
| Nitrocellulose (NC) | 57.8 %             |
| Nitroglycerine (NG) | 39.85 %            |
| Carbamite           | 1.7 %              |
| Mineral Jelly       | 0.4 %              |
| Graphite            | 0.25 %             |

Note: Nitration (12.75 % N)

Table 2: Physical properties of the double base propellant

| Physical properties | Values          |
|---------------------|-----------------|
| Propellant shape    | Square flake    |
| Co-volume           | 0.9316 cc/g     |
| Density             | 1.65 g/cc       |
| Web                 | 0.15 ± 0.02     |
| Propellant mass     | 3 g             |
| Calorimetric value  | 1200 cal/g      |

The images of double base propellant with Scanning Electron Microscope (SEM) used for combustion study inside CV & SCV of power cartridge is depicted in Figure 2.

Figure 2: Double base propellant Square flake (left photo & SEM image)

5. Experimental procedure

5.1 Preparation

An experimental procedure is comprises a CV and SCV, pressure transducer, Yokogawa scope corder DL 850E (12 bit module with sampling rate of 10 MHz) and charge amplifier. The CV is cylindrical in shape with internal diameter 40 mm and effective length 120 mm. Figure 3 depicts schematics of CV, SCV and experimental apparatus utilised during the firing. CV is extensively used to find out the internal ballistic parameters of electrically initiated pyro cartridge. The cartridge is loaded inside the breech chamber of the test vessel. A pressure transducer is fitted to the test vessel body in a radial direction perpendicular to axis. The bridge wire as ignition system forms the integral part of the cartridge. It is electrically ignited using a suitable power source with 24 V DC power supply. The ignition of bridge wire causes to ignite the gun powder and subsequently the propellant. On burning of the propellant, the pressure acts on the walls of cartridge case and foil. Due to high gas pressure and temperature, foil gets ruptured. The gases are further expanded inside the vessel. The gas pressure was concealed from all the sides. This pressure is sensed by the pressure transducer. It generates the signal
and passes to an amplifier. Signal generated was very small in nature; an amplifier amplifies the output voltage. This signal is collected by data acquisition so as to generate pressure and time profile on the screen. The point of intersection on x-axis gives the rise time corresponding to maximum pressure and intersection on y-axis indicates the maximum pressure. The consequence of ballistic parameters such as maximum pressure vs. rise time i.e. (P-t) graph was recorded. The rate of electrical voltage generated was proportional to the change in applied pressure as an input.

The same test vessel is used as SCV in which gases are passing through vent having 5 mm diameter. The hole is provided in a perpendicular direction with gauge adaptor which acts as vent. This hole is covered with closure plug, then the same SCV works as CV.

![Figure 3](image_url)

**Figure 3**: An experimental set-up showing CV, SCV, charge amplifier and scope-corder [36]

Figures 4 and 5 illustrates the comparison for graphical representation of internal ballistic for double base propellant at hot and cold conditions in CV and SCV. The CV and SCV conditions are differentiated by *red* and *blue* colours. The various regions during combustion and after combustion, initial pressure, maximum pressure and final pressure are clearly depicted. The maximum and minimum values of ballistic parameters for CV and SCV at hot conditions are shown at Figure 4.

The maximum and minimum values of ballistic parameters for CV and SCV at cold conditions are shown at Figure 5.

The sequences of events as depicted in Figures 4 and 5 are -

- On application of current, there was a noticeable delay before explosive train starts. A tiny quantity of highly sensitive explosive detonates to produce the flame. This ignites the pyrotechnic composition thereby igniting the propellant.
- The pressure rises inside the cartridge and rupture the foil as it exceed the design pressure.
- The propellant produces the gas faster than the volume. Therefore the pressure inside the cartridge increases rapidly. At this point the highest pressure is reached as indicated. After reaching the maximum pressure, the increase in the volume is faster than the propellant can fill it. So the pressure drops slightly than maximum point. This is due to heat loss to the vessel by conduction and convection. The pressure in CV slightly decreases. Nevertheless, in SCV the final pressure is just above the atmospheric pressure.
The pressure is decreasing after achieving the maximum pressure. It is due to heat loss to vessel and expansion of gases after complete propellant burning. Songqi Hu et al. conducted the experiment by propellant burning in a closed bomb [37]. The author concluded that with the increase in the pressure, heat loss and temperature difference shows a decreasing pattern. The propellant burning rate
decreases with increase in peak pressure. The shorter is the burning time, less is the heat loss. This is attributed to heat loss due to convection and conduction to the walls. Conversion of chemical energy to gas energy utilised for generation of water disruptor system.

6. Estimation of Internal Pressure \( (P_i) \)

Internal maximum pressure generated in the CV can be estimated using well known Nobel and Abel equation given below.

\[
P_i = \frac{F \Delta}{(1-\eta \Delta)}
\]

\( \Delta \) is density of gas produced : ballistically called as “loading density”, \( \eta \) is “co-volume” as equal to \( \frac{1}{\delta} \) where, \( \delta \) is density of propellant. This is the equation of state of the gas in the gun.

Where \( F = 1200 \) J/g. \( F \) is constant called as “force” of propellant or specific energy. This is the energy released by the decomposition of unit weight of propellant and expressed as

\[
F = P_i \times V = n R T
\]

The force can be determined experimentally by burning a charge of propellant in a closed chamber \((i.e., at \text{constant volume})\) and measuring the maximum pressure produced along with suitable cooling corrections. To do this requires knowledge of \( \eta \) which can be determined simultaneously by firing a series of charges of different masses and measuring the corresponding maximum pressures.

It has the dimensions of energy per unit weight. This equation is used as the performance parameter for gun propellants, where

\[
V = \text{volume} \\
n = \text{number of moles of gas} \\
R = \text{universal gas constant} \\
T = \text{explosion temperature or adiabatic flame temperature}
\]

It is equal approximately to the internal energy of unit mass of the propellant gas at the adiabatic flame temperature and expressed as

\[
P_i = \int_{T_o}^{T} C_v dT
\]

The above equation (1), resemblance to VAN DER WAAL’S equation of state. The calculations for volume and pressure are illustrated below. The change in internal energy per unit mass of gas can be expressed as \( C_v (T_o-T) \) where \( C_v \), is an average value of the specific heat of the gas at constant volume averaged over the temperature range, \((T_o-T)\). This energy is used in heating the gun and in imparting kinetic energy to the projectile, the gas, and moving parts of the weapon. The quantity \( C_v \) \((T_o-T)\) is called the specific energy or potential of the propellant.

Cartridge volume = Area \times \text{Length}

\[
\text{Cartridge volume} = \frac{\pi}{4} d^2 \times l
\]

Where \( d \) is the internal diameter \((d=17 \text{ mm})\) and length \((l= 35 \text{ mm})\) is inside length available for expansion of gases after propellant burning. The \( \pi \) is Greek symbol and its value is 3.14.

Substituting these values in equation (4), gives cartridge volume = 7.94 cc

For closed vessel, internal diameter \((d=40 \text{ mm})\) and length \((l= 120 \text{ mm})\) is inside length available.
Substituting these values in equation (4) gives CV volume as 150.796 cc. The volume of CV is measured using mass of water occupied and confirmed with the scale marked beaker.

Adding both the volumes i.e. cartridge and chamber volume, it gives total volume available for expansion i.e. 158.736 cc (say 159 cc approximately). Putting this value in equation (1), gives internal pressure of the order of 22.64 MPa for double base propellant. This is the theoretical pressure.

7. Analysis of test results and discussions

7.1 Performance evaluation in test vessels

The internal ballistic parameters data of cartridge for double base propellant are generated by firing 10 Nos. of cartridges each in CV and SCV at hot and cold temperatures are given in Table 3 and Table 4 respectively. The cartridges are condition to min 6 hours temperature before the firing.

Table 3. Internal Ballistic Parameters in CV

| Round | Hot (45°C) | Cold (-26°C) |
|-------|------------|--------------|
|       | Pmax (MPa) | Time to maximum Pressure (ms) | Pmax (MPa) | Time to maximum Pressure (ms) |
| 1     | 18.021     | 3.54         | 15.45      | 6.23         |
| 2     | 17.513     | 4.12         | 16.5       | 5.45         |
| 3     | 17.238     | 4.54         | 16.1       | 5.12         |
| 4     | 17.128     | 5.12         | 16.7       | 5.18         |
| 5     | 17.212     | 4.82         | 16.8       | **4.23**     |
| 6     | 18.34      | 3.74         | 16.65      | 6.37         |
| 7     | 18.123     | 4.18         | 15.01      | 7.13         |
| 8     | **18.356** | **3.41**     | 15.612     | 6.23         |
| 9     | 18.327     | 3.84         | 16.23      | 5.23         |
| 10    | 18.012     | 3.98         | 15.8       | 6.18         |
| Mean  | 17.827     | 4.129        | 16.085     | 5.68         |
| *Std Dev | 0.501 | 0.552 | 0.602 | 0.869 |
| Min   | 17.128     | 3.41         | 15.01      | 4.23         |
| Max   | 18.356     | 5.12         | 16.8       | 7.13         |

Comments of internal ballistic parameters in CV testing

For considering CV performance at hot conditions, the maximum pressure generated by this cartridge using double base propellant varies from 17.128 to 18.356 MPa, whereas time to Pmax varies from 3.41 to 5.12 ms. The standard deviations for pressure and time to Pmax are 0.501 and 0.552 respectively. In cold conditions, the maximum pressure generated by this cartridge using double base propellant varies from 15.01 to 16.8 MPa, whereas time to Pmax varies from 4.23 to 7.13 ms. The standard deviations for pressure and time to Pmax are 0.602 and 0.869 respectively.

Comments of internal ballistic parameters in SCV testing

For considering SCV performance, at hot conditions, the maximum pressure generated by this cartridge using double base propellant varies from 15.4 to 13.58 MPa, whereas time to Pmax varies from 3.69 to 5.75 ms. The standard deviations for pressure and time to Pmax are 0.555 and 0.662 respectively.
Table 4. Internal Ballistic Parameters in SCV

| Round | Hot (45°C) | Cold (-26°C) |
|-------|------------|--------------|
|       | Pmax (MPa) | Time to maximum Pressure (ms) | Pmax (MPa) | Time to maximum Pressure (ms) |
| 1     | 14.51      | 3.83         | 13.8       | 6.89         |
| 2     | 14.56      | 4.2          | 12.56      | 6.25         |
| 3     | 13.9       | 4.85         | 13.43      | 7.22         |
| 4     | 13.58      | 5.75         | 12.23      | 7.63         |
| 5     | 14.54      | 3.88         | 14.45      | 5.16         |
| 6     | 13.6       | 5.23         | 14.38      | 5.82         |
| 7     | 15.4       | 3.69         | 12.89      | 7.63         |
| 8     | 14.15      | 4.57         | 13.56      | 7.15         |
| 9     | 14.2       | 4.79         | 13.89      | 6.14         |
| 10    | 13.8       | 4.82         | 14.27      | 5.65         |
| Mean  | 14.224     | 4.561        | 13.546     | 6.536        |
| *Std Dev | 0.555 | 0.662        | 0.772      | 0.845        |
| Min   | 13.58      | 3.69         | 12.23      | 5.16         |
| Max   | 15.4       | 5.75         | 14.45      | 7.45         |

In cold conditions, the maximum pressure generated by this cartridge using double base propellant varies from 14.45 to 12.23 MPa, whereas time to Pmax varies from 5.16 to 7.45 ms. The standard deviations for pressure and time to Pmax are 0.772 and 0.845 respectively.

The pressure time parameters are evaluated at hot (+45°C) and cold (-26°C) conditions using data acquisition system. The basic parameters in CV and SCV are generated as there is no direct method available to measure internal pressure of cartridge used in disruptor weapon. This kind of evaluation technique related to power cartridge plays a very important role in understanding the propellant behaviour in CV and SCV. From above statistical data, it is observed that the average pressure in hot is more than that of cold condition. However the time to maximum pressure is less in hot than that of cold condition. The standard deviation for maximum pressure and time corresponding to maximum pressure has increasing trend in hot than cold conditions.

7.2 Pressure drop estimation

The pressure drops between CV and SCV at hot and cold conditions are estimated for maximum parameters. The maximum pressure realised experimentally by this propellant in CV and SCV are 18.356 and 15.4 MPa in hot condition.

The percentage pressure drops can be determined using equation (1) as -

$$\text{Percentage pressure drop} = \left[ \frac{P_{\text{max, CV}} - P_{\text{max, SCV}}}{P_{\text{max, CV}}} \right] \times 100$$  \hspace{1cm} (3)

The percentage pressure drops are estimated as 16.103 in hot condition and 13.988 in cold condition. The above exercise is repeated for time to maximum pressure. The percentage drops in time are estimated as 10.95 in hot and 4.3 in cold condition.

The maximum pressure achieved in SCV depends on propellant burn rate, vent size and venting rate.
Burn rate of propellant \( r \) is expressed as

\[
 r = \beta P_{\text{max}}^\alpha
\]  

Here
- \( \alpha \) = pressure index
- \( \beta \) = burn rate coefficient

In equation (4) the venting rate is the function of vent diameter and velocity of leaving gases. The venting rate is dependent on pressure. The pressure in SCV is varied with the time after began it venting. This can be expressed as

\[
m = A \times v \times \rho
\]  

Where
- \( m \) = Mass flow rate or venting rate (kg/s)
- \( A \) = Area of the vent (m²)
- \( v \) = Velocity of gases (m/s)
- \( \rho \) = Density of products of combustion (kg/m³)

The maximum pressure achieved in SCV firing is the resultant of vent size and velocity of gases. The relationship between venting rate / mass flow rate and pressure is not linear.

Ratio of pressure drop is expressed as

\[
\text{Pressure drop ratio} = \left[ \frac{\nabla P_{\text{CV}}}{\nabla P_{\text{SCV}}} \right] = \frac{18.356}{15.4} = 1.2
\]

Thus the pressure drop in CV is 1.2 times than that of SCV.

8. Concluding remarks
In this study, the combustion of power cartridge are evaluated in CV and SCV. The test related to power cartridge, the test results in principle can be applied to the combustion of gas propellant in CV and SCV. The percentage pressure drops were calculated and it varies from 13.988 to 16.103. Similarly the percentage drops in time varies from 4.3 to 10.95. Thus from this study, it is inferred that pressure drop in SCV is 16 percentage to that with CV with a vent size of 5 mm in diameter. From the above experiments it was observed that pressure drop in CV is 1.2 times than that of SCV. The experimental pressure is less than theoretical pressure. This was attributed due to heat loss by convection and conduction to the vessel. This was reported by Parate and et al. [38]. This article explained about the evaluation of internal ballistic parameters such as maximum pressure and rise time to maximum pressure of power cartridge used in water disruptor application with CV and SCV techniques. Pressure measurement in CV is one of the most demanding measurements as a part of internal ballistic parameters and behaviour study for the different propellants. Maximum pressure is the basic parameters on which design of power cartridge is based. Experimental method is usually used to measure this physical quantity. Thus the performance evaluation related to power cartridge is established by conducting various experimental trials for double base propellant. CV evaluation using propellant is a well established technique in the laboratory and being used for determination of propellant characteristics used in power cartridges for many applications.
Internal ballistic parameters determination of propellant depends upon the following factors, the most significant being –

- CV or SCV volume
- Size of the vent
- Burning rate, force constant, shape and size of propellant

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