Evaluation of Internal Ballistics of Multi-Perforated Grain in a Closed Vessel

B. A. Parate, C. P. Shetty

***Abstract*—**This research article describes the evaluation methodology of an internal ballistics of multi-perforated grain in a closed vessel (CV). The propellant testing in a CV is conducted to characterize the propellants and to ascertain the various internal ballistic parameters. The assessment of an internal ballistics plays a very crucial role for suitability of its use in the selection for a given particular application. The propellant used in defense sectors has to satisfy the user requirements as per laid down specifications. The outputs from CV evaluation of multi-propellant grain are maximum pressure of 226.75 MPa, differentiation of pressure with respect to time of 36.99 MPa/ms, average vivacity of 9.990×10^{-4}/MPa ms, force constant of 933.9 J/g, rise time of 9.85 ms, pressure index of 0.878 including burning coefficient of 0.2919. This paper addresses an internal ballistic of multi-perforated grain, propellant selection, its calculation, and evaluation of various parameters in a CV testing. For the current analysis, the propellant is evaluated in 100 cc CV with propellant mass 20 g. The loading density of propellant is 0.2 g/cc. The method for determination of internal ballistic properties consists of burning of propellant mass under constant volume.

***Keywords*—**Burning rate, closed vessel, force constant, internal ballistic, loading density, maximum pressure, multi-propellant grain, propellant, rise time, vivacity.

I. Introduction

THE evaluation of an internal ballistics of multi-perforated grain of the propellant in a CV is essential to determine the various parameters and its behavior at ambient condition [1]. The propellant under study is single base propellant. This propellant is used in the propellant actuated device (PAD) for releasing an externally carried store i.e. bomb from parent aircraft. Multi-perforated propellant configuration is evaluated in CV for the assessment of their ballistic parameters. The propellant composition is extruded through die and punch [2]. The multi-perforated propellant grain is evaluated in 100 cc CV at a loading density of 0.2 g/cc and pressure-time profile is extracted, using piezoelectric crystals, through in-house developed data acquisition system (DAS). From thermo-chemical parameters of the combustion of propellant, performance parameters in terms ballistic are obtained and from pressure-time profile of CV, rate of rise of pressure, force constant, burning rate coefficients and vivacity are calculated. The burning performance of propellant in CV plays an important role in interior ballistics. To understand the combustion process in the actual system, the effect of geometry at constant volume needs to be evaluated to predict the dynamic combustion performance of multi-perforated propellant.

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II. Test Apparatus and Materials

The following materials and methods are used for the evaluation of internal ballistic of multi-perforated propellant grain:

(a) Multi-perforated propellant grain
(b) Closed Vessel (CV)
(c) Firing mechanism
(d) Data acquisition system (DAS)
(e) Pressure transducer

A. Propellant Selection

Multi-perforated configurations have more significance for gun propulsions, as they give progressive burning profile comfortably. In bomb release application, the part of the entire energy is imparted to ejector release unit (ERU) fitted below aircraft wings. The gas energy generated by propellant burning provides a jerk or thrust so as to provide a positive clearance between the release store and parent aircraft. This definitely needs a propellant configuration, where the amount of gas generation continues to rise. High gas evolution is possible only when the burning surface area continues to rise. This needs a progressive burning profile. Since the gun propellants are manufactured by extrusion technique and their outer diameters are also very small, the progressive nature of burning can be attempted by this configuration alone.

Multi-perforated propellant configuration is mostly utilized in gas generating situations. It has more importance in the gun propellant technology. In this technology, inhibition is never applied and the propellants burn at all the exposed surfaces. The salient features of this configuration are mentioned below.

- This configuration has a very high progressivity ratio that is reflected in pressure-time.
- This configuration is used in cartridge actuated devices (CAD), impulse cartridges, ejector release cartridges (ERU) and seat ejection devices.
- This configuration is suitable for small devices and accordingly, dimensions are limited. Use in bigger devices will lead to very high-pressure rise.
- This propellant has smaller web availability and burning time is generally very short.
- This configuration has very high volumetric loading (90-95%) and chamber volume is sufficiently filled with the propellant.
- Manufacturing of this configuration requires perforations, which are created by either mandrel or drilling.
- The production rate of this configuration is slow.
- The ignition system design for this configuration becomes critical as the combustion gases are allowed to pass

through multi-perforated holes during propellant burning. Since perforations are invariably not interconnected, the flame spread in each of the perforation takes place independently.

- The web between any two nearest holes and between any outer holes and periphery is the same. This gives a sudden end of progressivity.
- Multi-perforated propellant grain gives progressivity in uninhibited conditions.

A typical multi-perforated propellant configuration during combustion inside the cartridge is shown in Fig. 1. Fig. 1 A shows the seven holes configuration. It depicts initial configuration, which contains one central perforation and six perforations on the pitch circle. During combustion, the outer diameter of the propellant shrinks and the holes diameter expands. The directions of combustion of different burning surfaces are illustrated in Fig. 1 B. All six holes are equidistant from each other and also with the central hole. The outer diameter shrinks and meets the external six holes at the same time when the central hole touches the external six holes as shown in Fig. 1 B. This is the first web transition. The simultaneity of convergence of all the burning surfaces restricts various dimensions. Only two cross-sectional parameters, namely (i) outer grain diameter (radius, R) and the hole diameter (radius, r) are needed. There are six holes concentric with one center hole of the propellant. The propellant is consumed in length direction also. Till the first transition, the propellant is a single piece; but after this, propellant is divided in unconnected 12 pieces: six inner slivers and six outer slivers. Inner slivers are consumed first and this is denoted as second web transition. After the second web transition, only outer slivers remain as illustrated in Fig. 1 (c); at the third web transition, the entire propellant is consumed [3]. So, for multi-perforated propellant grain, three web transitions are defined - first the beginning of sliver formation, second is consumption of the outer sliver (convex triangle), the third is the consumption of the outer sliver (convex-concave triangle). This configuration is characterized by two diameters- one is grain diameter (D) and hole diameter (d). Outer radius ($R = D/2$), hole radii ($r = d/2$), propellant density (ρ) and length (L). The various web transitions of the propellant grain can be estimated as:

- Initial propellant weight = $\rho \Pi L [R^2 - 7r^2]$ = 0.5 g (for multi-perforated propellant grain)
- Initial burning surface area = $2 \Pi (R+7r) L$ = 490.51 mm^2

$$\textit{First web transition}, w_1 = \frac{(R - 3r)}{4}$$

$$\textit{Second web transition}, w_2 = \frac{(R - r)}{(2\sqrt{3}) + r}$$

$$\textit{Third web transition}, w_3 = \frac{(R^2 - r^2) + (r + w_1)[4r + 4w_1 - 2R\sqrt{3}]}{2(R + r) - 2(r + w_1)\sqrt{3}}$$

For illustration numerical analysis of actual propellant dimensions R = 3.8 mm, r = 1.45 mm, L = 9.2 mm, ρ = 1.5 g/cc, w_1 = 0.447 mm, w_2 = 0.757 mm, w_3 = 1.265 mm, initial propellant weight 0.48 g, initial burning surface area is 490.51 mm^2.

Before 0.447 mm web is consumed, all the holes are completely circular.

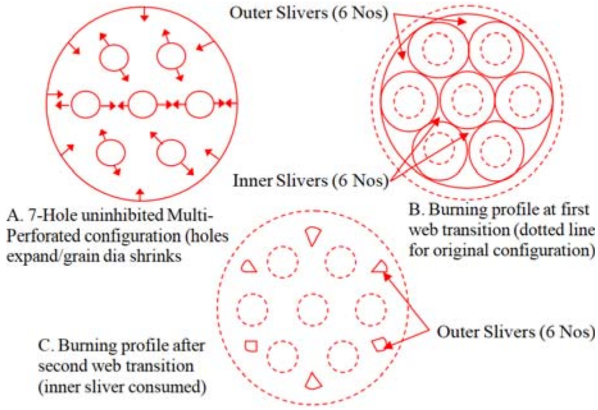

Fig. 1 Multi-perforated propellant burning

The basic chemical composition and physical properties of a multi-propellant grain that is used for the CV firings are indicated in Table I.

TABLE I
BASIC CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF MULTI -PROPELLANT GRAIN [4]

Chemical Composition			Physical properties of multi-propellant grain		
Nitro-cellulose	:	90 ± 1%	OD	:	7.6 mm
			Mean Web	:	1.45 ± 0.02 mm
Di-Nitrotolune	:	5 ± 0.1%	Length	:	9.2 mm (Nominal)
Di-butyl Phthalate	:	3 ± 0.5%	Density	:	1.50 g/cc
Di-phenylamine	:	1.3 ± 0.15%	Shape	:	Hepta-tubular
K_2SO_4	:	0.7 ± 0.15%	Mean hole diameter	:	0.67 mm

Fig. 2 illustrates the photo of a multi-perforated propellant grain utilized in the experimental trial.

Fig. 2 Photo of a multi-perorated propellant grain

III. EXPERIMENTAL CV ARRANGEMENT

An experimental set-up consists of closing plug, firing electrode, cotton bag containing gun powder, propellant, tourmaline crystal, lock nut, release valve assembly, gauge block, brass sealing rings, liner, plasticine earth pin, vessel body and firing block. The vessel body withstands a maximum temperature of 1500 ºC for a few milliseconds and is designed for 300 MPa. Design as well as testing of high pressure CV is as simple as design of any thick cylinder. Lames equations are used to design CV. The material of construction of the CV is stainless steel that is subjected to a high temperature and pressure. The thickness of CV is based on the pressure level. A very high factor of safety is considered. The length to diameter ratio is generally made 1:1. This is to ensure that heat loss through walls is restricted and at the same pressure gradient along the length of combustion chamber is negligible. This avoids oscillations due to pressure wave generation inside CV. Generally, minimum of 2.7 on tensile strength or 1.6 on yield strength is the recommended factor of safety. The design should be such that vessel is subjected to around 40-50% of the strength at the peak levels of applied load (here pressure).

As a CV is subjected to frequent firings, therefore it is provided with a thin layer of metallic liner inside CV, which faces combustion gases. The liner can be replaced after certain number of usages. This is to avoid replacement of complete vessel after certain number of usages to make the system economically viable. A liner thickness of 10-20 mm is generally preferred. However, due allowance is given for accommodation of the liner material inside the main vessel body.

End closures of CV also needs separate attention as they house various operational gadgets. As far as end closures are concerned, possible failure mode is shearing of threads at peak load. Material construction of these end blocks is softer and they have a tensile strength of 1000 MPa. Shearing strength is generally taken as two third of the tensile strength. One side of CV has release valve assembly to release the gases after the firing of the propellant. The other end has a firing electrode for ignition of the propellant. Tourmaline crystal is used for pressure measurement. Firing block contains firing line, which imparts initial flash for ignition of propellant. Both firing block and gauge block are screwed to the CV body with course pitch threads for adequate strength. Pitch of threads used are never less than 2 mm. Sufficient length of thread engagement is provided. Buttress thread is preferred for such applications. Threads are generally given lowest factor of safety compared to vessel design, so that first failure is always envisaged at threads. In addition to this, to safeguard vessel against shearing at the thread locations, vessel body is always made of a material harder than the material of construction of either of the blocks. Threads may be assumed to have tight tolerance without any mismatch or backlash. They are made at the internal diameter of the vessel and nominal diameter may be taken as nominal internal diameter of CV. Two extra threads are taken as engagement length.

The propellants are fired in CV at ambient conditions with loading density of 0.2 g/cc. Mass of propellant is taken as 20 g during firing. Small amount of gunpowder (1.2 g) is sealed in a cotton bag used to ignite the propellant. Fine nichrome wire is surrounded by gun powder bag. The fine nichrome wire is soldered across the firing pins. The internal diameter, outer diameter and inside length of CV are 49.5 mm, 75 mm and 53 mm respectively. The engineering sketch for CV and an image is shown in Fig. 4. This is ignited by passing a suitable current of the order of 3-5 A with an electrical circuit. The propellant is loaded in the vessel so as to keep in touch with gun powder bag. Gun powder initiates the propellant charge. As the propellant burns, generation of gas pressure takes place at a high temperature and because of confinement, pressure starts building in CV. A pressure measurement is carried out using data acquisition system which comprises a tourmaline pressure sensor (sensitivity 180 pC/MPa, frequency response is better than 10 MHz, size of crystal is 10×8 mm and colour black) and charge amplifier.

The main component of pressure gauge is transducer, which converts pressure into electrical signals for measurement and recording. The governing principle of such transducer is piezoelectricity. It is defined as an electric polarization produced by mechanical strain in crystal belonging to certain classes. The produced measurable polarization must disappear on removal of mechanical strain. This property is shown by some typical materials only.

Piezoelectricity is exhibited by natural crystals like quartz, tourmaline, Rochelle salt etc. Some of the artificially made materials like Lead Zirconium Titanate (PZT), Poly Vinyledene Fluoride (PVF), Barium Titanate etc. also exhibit the property. They can be used for measurement of pressure, strain, acceleration and similar physical properties. For measurement of the pressure in CV, there are two specific requirements. First one is a high level of pressures to which the crystal will be subjected during the firing and another is the response time. Quartz or tourmaline crystals will fulfill these requirements.

The pressure is sensed by tourmaline pressure sensor mounted onto the CV body. The input to the sensor is in the form of gas pressure. The tourmaline sensor converts this pressure into electrical signals for measurement and recording. For any transducer, three important parameters are monitored. First is sensitivity, which is defined as change in electric output per unit change in measured quantity. It is expressed in pC/MPa. The second parameter represents the deviation of output signal. Third important characteristic of piezoelectric crystal is repeatability, which represents independence of measurement from time. The output signal from the transducer is processed to give *P-t* profile. The dedicated software has provision to record, plot, analyze, store and retrieve the data for use. Charge amplifier produces a voltage an output proportional to an input charge. Sealant compression, gauge block and lubricant corrections are applied to correct the vessel volume. As the propellant burning takes place inside the vessel, gases are produced. Once firing is over, CV remains at high pressure and temperature.

The data obtained from CV can be used in the manufacturing of new propellants [5]. Divekar et al. studied the effect of the web size of double base propellant grains [6]. However, after the complete consumption of the propellant, there is no heat source. Because of heat dissipation, the combustion gases start cooling. Cooling results in shrinkage of gases, resulting in reduction in pressure in CV. These gases apply pressure on the walls of vessel. These records using DAS are properly stored in the computer. *P-t* profile after reaching the maximum pressure is slightly decreasing in nature. This heat loss is mainly due to convection and conduction to the walls of vessel [7]. This illustrates that the energy liberated by the propellant burning undergoes numerous conversions i.e., chemical energy to gas energy. Burning rates are determined by combustion of propellant in CV. Pressure must be brought to ambient pressure. For this purpose, release valve assembly is placed in gauge block for releasing gases from previous firing. The release valve assembly is nothing but spring loaded vent, which is opened to vent out the accumulated gases. It also acts as safety valve for situations where pressure inside vessel goes beyond designed pressure. After release valve is opened, all accumulated gases are liberated from the CV.

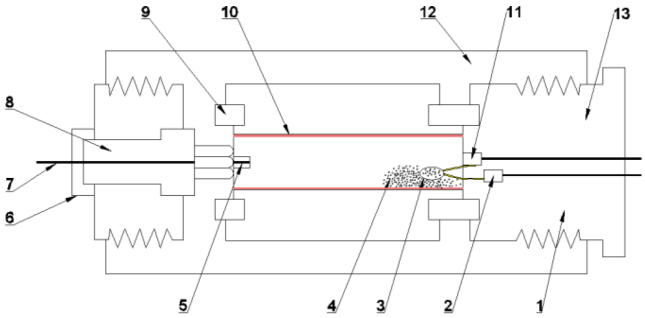

Fig. 3 Engineering sketch of the CV: 1. Closing plug, 2. Firing electrode, 3. Cotton bag containing gun powder, 4. Propellant 5. Tourmaline crystal, 6. Lock nut, 7. Release valve assembly, 8. Gauge block, 9. Brass Sealing ring, 10. Liner, 11. Plasticine earth pin, 12. Vessel body, 13. Firing block

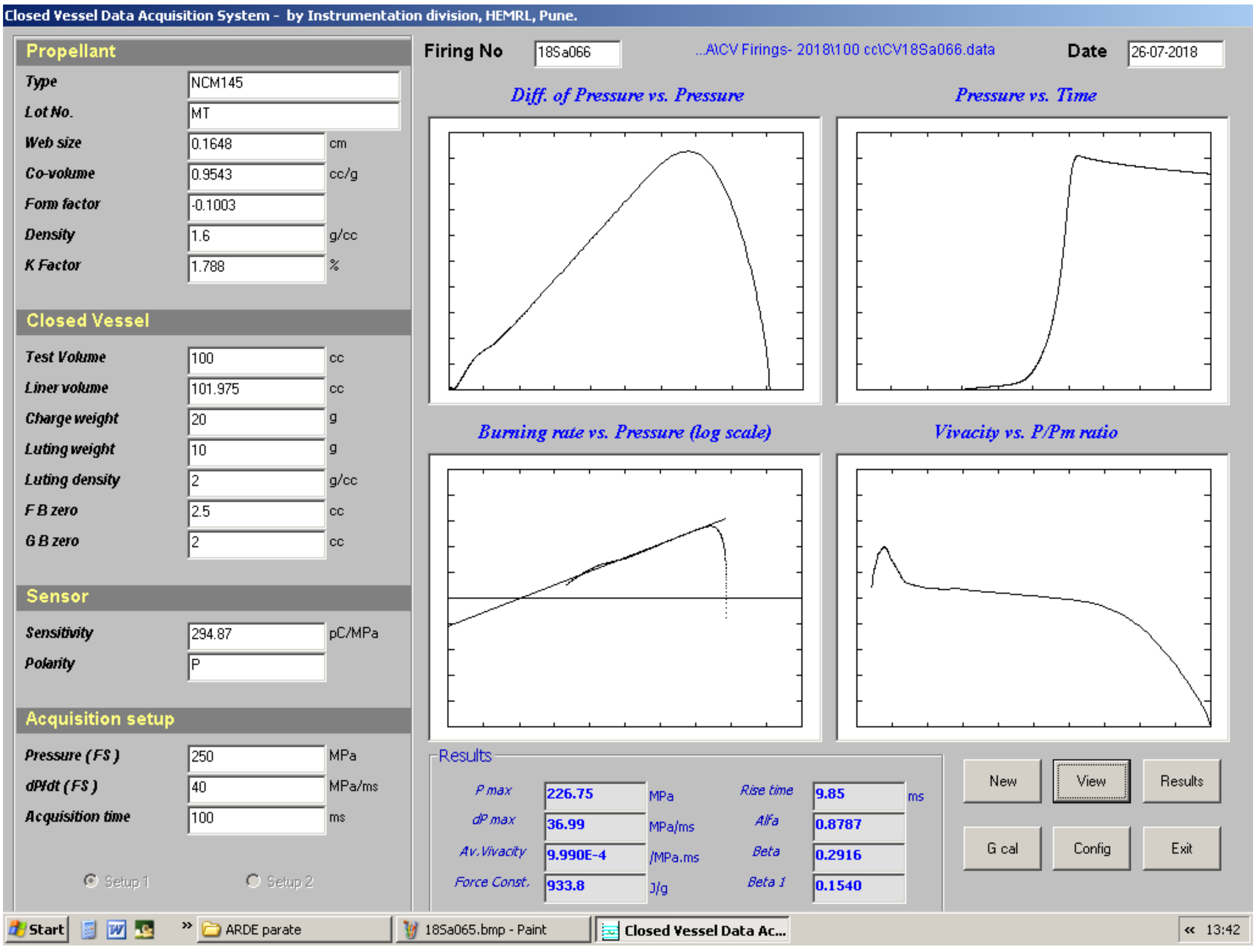

Fig. 4 Output from DAS

IV. Experimental Results and Discussions

Engineering sketch of the CV is shown in Fig. 3. The output from DAS is shown in Fig. 4. Maximum pressure and response time are the data obtained through DAS. The internal ballistic results obtained from DAS are given as:

- The output from CV evaluation of multi-propellant grain is maximum pressure 226.75 MPa
- Differentiation of pressure with respect to time is 36.99 MPa/ms
- Average vivacity is 9.990×10^{-4}/MPa ms, force constant 933.8 J/g, rise time 9.85 ms, pressure index 0.878 including burning coefficient 0.2916.

V. Concluding Remarks and Observations

The burn rate of the multi-perforated propellant is calculated from pressure time curve in closed bomb data by using the gas state equation. The internal ballistics of multi-perforated propellant grain in CV are addressed in this research article. The main objective of this paper is to determine the various ballistics parameters using a CV method. The following inferences are drawn from this article:

- A CV firing is considered a pre-requisite for the dynamic evaluation and is implemented to qualify the propellant through static laboratory proof without any complications of dynamic firing.
- The maximum pressure, force constant, burning rate, vivacity and burning rate coefficient of multi-perforated propellant grain are determined using a CV technique and they are found to be dependent on maximum pressure.
- CV evaluation is a diagnostic and definite tool to evaluate ballistic performance of multi-perforated propellants and the same is implemented in this paper.

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Conflict of Interests

It is hereby confirmed that there are no known conflicts of interest regarding the publication of this paper and no significant financial support for this work that could have influenced its outcome.

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He has reviewed as a reviewer in various international peer reviewed journals such as *Defence Science Journal*, *Defence Technology*, *International Ballistic Symposium* and *Journal of Modern Mechanical Engineering and Technology*, etc. He is the recipient of 'Armament award for the year 2006' in recognition of his outstanding contributions of saving in FE saving and self-sufficiency in reliance and timely supply of cartridges to Users which helps to avoid AoG (Aircraft on Ground) situation. He received the Pinaka award for production and timely supply of cartridges to IAF in the year 2019 in short notice. He received certificate and gold medal on the occasion of National Science day oration in year 2021.

He had the original idea for writing the manuscript and performed the experimental trials related to research activities. The author of this paper did the literature survey, participated in the writing of manuscript, planning, execution and analysis of this study. He wrote first draft of the manuscript.

Mrs. C P Shetty, Technical Officer 'C' is working at HEMRL, Pune. She has 34 years on experience with evaluation of gun propellants in closed vessel system at HEMRL, Pune. She has developed CVDAS and is responsible for installation of CVDAS at OF, Itarsi, OF, Bhandara, CF, Aruvankadu. Integration, calibration, reconfiguration and maintenance of these indigenously developed CVDAS has also been carried out by her. The piezo-electric crystal selection, gauge integration, integration with charge amplifier and DAS has been carried out by her at HEMRL.

She was involved in conducting the experiments, interpretation of results and proof reading of this manuscript.