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Effect of Loading Densities in Closed Vessel Tests on the Burning Rate of a Propelling Charge

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ABSTRACT

Closed vessel firing of gun propellant at different loading densities is conducted for evaluation of its ballistic parameters. Although in actual gun applications, loading densities are higher, but for closed vessel evaluation standard loading density is taken as 0.2 g/cc for interior ballistic calculations of guns. Closed vessel evaluation of standard triple-base propellant in hepta-tubular configuration with loading density varying in the range of 0.2 g/cc to 0.3 g/cc is conducted for the evaluation of salient ballistic parameters. It is observed that maximum pressure increases with increase in loading density of propellants. As loading density increases, rate of rise of pressure also increases. Accordingly, a rise in burning rate is also observed. However, the burning rate index (α) and coefficient (β) of the power law of burning ($r = \beta P^{\alpha}$) is found independent of loading density. The average values of these burning rate parameters are calculated as (α =) 0.78 and (β =) 0.45 for the studied propellant.

Keywords: Gun propellant, internal ballistics, closed vessel, burning rate, loading density

1. INTRODUCTION

Gun is an essential part of the artillery system for every country. Inside a gun, chemical energy of propellant is converted into kinetic energy of the projectile, which is projected at high velocity towards the intended target. Propellant releases energy by self-sustained chemical reaction and when it is suitably initiated, it burns at a controlled rate and generates large volume of gases at high temperature. This action generates high pressure inside the gun chamber, which accelerates the projectile inside the gun barrel. There exists two competing activities inside the gun barrel – first is release of gas by combustion of gun propellants, which is responsible for rise in pressure, and second is extra space (volume) created by movement of projectile, which reduces pressure. The pressure inside a gun barrel is a function of these two competing actions. Initially, rate of generation of gases exceeds extra volume created by movement of projectile and pressure rises rapidly. Subsequently, at the end of or after complete consumption of propellant, pressure inside gun barrel decreases. However, the projectile continues to accelerate, even when pressure inside gun barrel is reducing. Suitability of the gun propellant is decided by maximum pressure generated in the gun barrel and required muzzle velocity of the shot. Prediction of maximum pressure and muzzle velocity is possible from ballistic parameters of propellants, gun parameters and the burning rate of the propellants[1-2].

The burn rate profile of a propellant grain, i.e., the rate at which the surface of a burning propellant recedes, can be controlled by many factors like: chemical composition of propellant, ignition characteristics, size and shape of propellant grain, the number of perforations in each grain, loading conditions (charge weight variations), etc[3,4]. The burn rate increases as the pressure increases. The linear burning rate *vs* pressure behaviour of a gun propellant is represented with burn rate law. The most widely used burning law is expressed in exponential form and it represents dependence of burning rate of propellant on pressure. The burn rate *vs* pressure behaviour of a gun propellant is evaluated by firing propellant charges in closed vessel[5].

Closed vessel evaluation of gun propellants is a well-established technique by which experimental determination of propellant performance in the laboratory conditions can be conducted[6]. Instead of conducting dynamic firing inside gun when dealing with research, development, inspection, and defect investigations of gun propellants, a less expensive, quicker and safe process of closed vessel evaluation is generally adopted[7,8]. It consists of burning a known amount of propellant in a closed combustion chamber of known volume. The generated pressure is recorded using a piezo-electric pressure transducer. The pressure-sensitive element of the gauge is a gem quality tourmaline crystal. Dedicated software is used to process this pressure-time data to further calculate force constant, vivacity, and burning rate, burning rate constants of the propellant. Theoretically these values are used to calculate the maximum pressure and muzzle velocity developed by a known charge of the propellant in the gun[9,10]. The results obtained for a triple -base propellant is presented earlier by Divekar[11], *et al.*

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2. EQUATIONS USED

(i) The rate of change of pressure wrt time, i.e., *dP/dt* is obtained from pressure-time samples recorded from closed vessel firings of propellant grains.

dP/dt from digital *P* samples, $\frac{dP}{dt} = \frac{P_2 - P_1}{t}$

Force constant $F = P_m * \left(\frac{1}{\Delta} - \eta\right)\left(1 + \frac{K}{100}\right)$

where P = instantaneous Pressure in MPa; P_m = Maximum Pressure; *dP/dt* = Rate of change of pressure in MPa/ms; t = Sample rate (ms); Δ = Loading density (g/cc); η = Co-volume of the propellant gases (cc/g); K = Cooling correction factor applied to measured P_m due to the heat loss inside the closed vessel body.

(ii) The burning of propellant in a closed vessel is governed by
(a) the rate of burn law,
(b) the form function, and
(c) the equation of state[1,5].

2.1 The Rate of Burning

The propellant burns in parallel layers (Piobert's law). The rate of burning (R) is proportional to the pressure acting on the surface of the propellant (Veilli's law). This is given by the equation:

$$R = \beta.\, P^{\alpha} = -D.\frac{df}{dt} \tag{1}$$

where D = Web size (cm); α = Pressure index; β = Burning rate coefficient (cm/s/MPa$^{\alpha}$); f = fraction of web D remaining at a time (initially the value of f = 1 and as combustion takes place it becomes 0 (complete combustion occurs).

2.2 The Form Function of the Propellant

The form factor θ can be calculated from the geometry of the propellant grain and is given by

$$\varphi = (1-f)\,.\,(1+\theta f) \tag{2}$$

where φ = Fraction of charge burnt at any time; initially when no charge is burnt, the value of φ is 0 which increases to 1 after complete combustion; θ = Form factor.

Form factor is a representation of how surface area is varying at any instant during burning. For zero values of form factor, burning area remains constant throughout the burning of gun propellant. If form factor is positive, surface area decreases with burning, therefore exhibits regressive burning profile. If form factor is negative, surface area increases as burning progresses. Hence propellant grains with negative form factor exhibits progressive burning.

The change in fraction of charge burnt wrt the change in fraction of web remaining i.e. Differentiation of φ wrt f gives

$$\frac{d\Phi}{df} = \sqrt{((1+\theta)^2 - 4.\theta\Phi)} \tag{3}$$

2.3 The Equation of State

Since pressure inside the closed vessel is very high, ideal Nobel –Abel gas equation is modified with the normal Van der Waal equation of state, as given by

$$P\left[(V - 1 - \Phi).\frac{C}{\delta} - (\eta.\Phi.C)\right] = F.C.\Phi \tag{4}$$

where δ = density of propellant (g/cc); V is effective volume of closed vessel corrected with lubricant and sealant compression (cc); C is propellant charge weight (g); η= Co-volume of the propellant gases (cc/g); and F is force constant (J/g) defined as the energy imparted when 1 g of propellant is burnt.

When the propellant charge is fully consumed i.e. φ=1and maximum pressure P_m is achieved at this instant, then the Eqn. (4) becomes

$$Pm[V - (\eta - C)] = F.C \tag{5}$$

Dividing the Eqn (4) by Eqn (5)gives Fraction of charge burnt at any time

$$\phi = \frac{P}{Pm}[1 + b(1-\phi)]$$

$$\text{Or} \quad Pm[V - (\eta - C)] = F.C \tag{6}$$

where b is Co-volume correction factor

$$b = \frac{\left(\eta - \frac{1}{\delta}\right) * \Delta}{(1 - \eta\Delta)}$$

Differentiating Eqn. (6) gives the change of mass burnt with time and is calculated as

$$\frac{d\Phi}{dt} = \frac{dP}{dt.}\frac{(1 + b - b\Phi)}{Pm + bP} \tag{7}$$

From Eqns (3), (7), and (1), the rate of burning R (cm/s) can be written as

$$R = \beta.P^{\alpha} = -D.\frac{df}{dt} = -D.\frac{df}{d\Phi}.\frac{d\Phi}{dt}$$

$$R = \frac{dP_x}{dt} * \frac{(1 + b - b\varphi)}{(P_m + bP)_x} * \frac{D}{\sqrt{(1+\theta^2) - 4\theta\varphi}} \tag{8}$$

Or $\log R = \log \beta + \alpha \log P$

On logarithmic scale, burn rate and pressure are related as a straightline. When the values of log$R$ *vs* log$P$ are plotted, the gradient of the best fit straightline gives α, the pressure index value and the intercept point gives β, the burning rate coefficient.

3. EXPERIMENTAL SET UP AND TEST

Closed Vessel Firings of a triple base propellant were carried out at different loading densities. Loading density is defined as the ratio of propellant mass to chamber volume. The closed vessel volume was 700 cc and propellant charge weight taken was 140 g (loading density = 0.2 g/cc), 157.5 g (0.225 g/cc), 175 g (0.25 g/cc), 192.5 g (0.275 g/cc), and 210 g (0.3 g/cc), respectively. It is clear that exact chamber volume of a gun could not be simulated in CV, as it will need CV of different capacities, one for each type of gun. The volume of CV should be such that it should reflect the properties of propellant, adequately, with minimum amount of propellant.

Closed vessel of similar capacity (700 cc) is reported to be used for evaluation of gun propellants at TNO, Netherlands, also[12]. To some extent, the volume, selected for CV is justified. The propellant charge is ignited by a small amount (1.2 g) of gunpowder charge which is confined in a cotton bag. This gun powder bag is ignited by passing a current (3-5 Amp) through a short length of fine Nickel-chrome wire soldered across the firing pins[8].

The propellant grain considered for the study was a 7 hole multi-tubular cylindrical grain. The major energetic ingredient in the chemical composition of the triple-base propellant comprises nitrocellulose (NC), nitroglycerine (NG) and nitroguanidine or picrite (NQ). Stabilisers, flash reducer compositions are also added in very small part to increase the performance. The thermo-chemical and physical parameters of chosen triple base propellant are given in Table 1.

Table 1. Parameters of triple base propellant grain

Web size (cm)	**0.1320**
Form factor	-0.189
Density (g/cc)	1.66
K factor (cooling correction)	1.589

The inputs for closed vessel firings includes propellant parameters like charge mass, web size, density, co-volume and form factor. Another type of input parameter included vessel parameters like vessel volume and cooling correction. Cooling correction factor is applied to measured pressure due to the heat loss inside the closed vessel body. Vessel volume was also corrected for lubricant and sealant compression, gauge block and firing block corrections[8]. Major output was realized is in the form of Pressure - time profile. The recorded pressure-time profiles from CV firings at different loading densities are plotted in Fig. 1. The pressure-time data is the basic data output from firing a propellant. From this data, differential of pressure wrt time (*dP/dt*) was calculated and is represented in Fig. 2. Burning rate of propellant can be calculated for each instantaneous pressure using Eqn. (8). The generated burning rate versus pressure is plotted in Fig. 3. For the representation of burning rate law and for the calculation of burning rate coefficients, instantaneous values of burning rate versus pressure on log scale is generated. The values of log*R* are plotted against log*P* in Fig. 4 and the gradient of the best fit straightline gives α and the intercept is β.

4. RESULTS AND DISCUSSION

For different loading densities, closed vessel firing results are tabulated in Table 2. The graphs corresponding to different loading densities are shown in Fig. 1 and Table 3.

From Fig. 1, it is observed that higher the loading density, higher is the pressure generated. This is an obvious outcome. Higher loading densities mean more charge weight of propellant in the fixed volume (700 cc) of closed vessel, hence more gas energy is released after combustion. In addition to this, it is also observed from Fig. 1 that rate of rise of pressure also increases with loading densities. This means that the slope of differential pressure *vs* pressure increases with loading densities

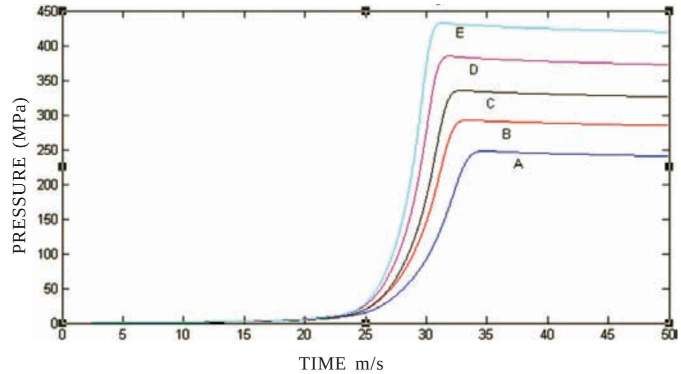

Figure 1. Pressure-time profiles for different loading densities.

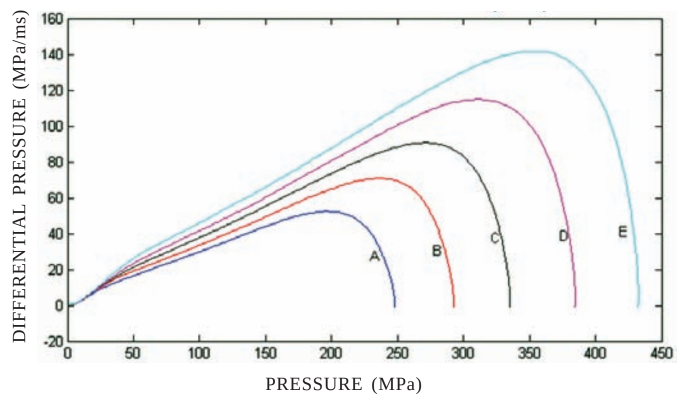

Figure 2. Variation of rate of change of pressure against pressure.

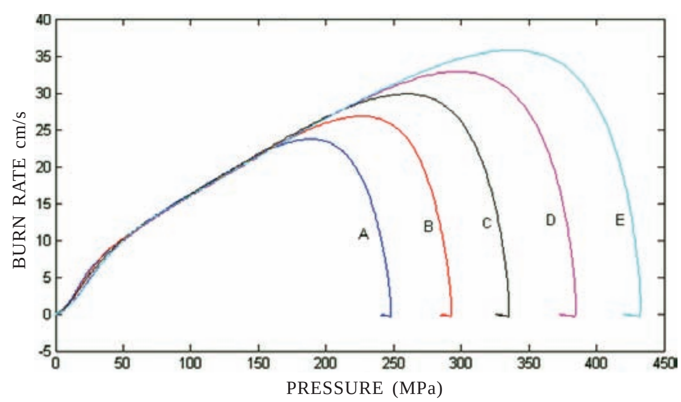

Figure 3. Variation of burning rate with pressure.

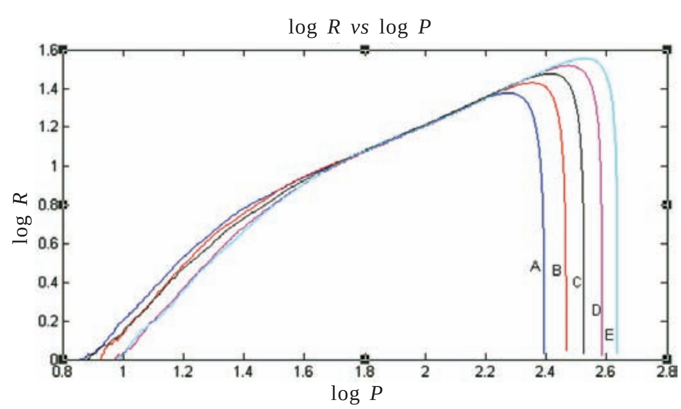

Figure 4. Variation of burning rate with pressure on logarithmic scale.

Table 2. Closed vessel (700 cc) firing results at various loading densities

Loading density (g/cc)	Charge weight (g)	Max pressure (MPa)	Rise time (ms)	Force constant (J/g)	Max differential pressure (MPa/ms)	Pressure index (α)	Burning rate coefficient (β)
0.2	140	247.9	6.72	1018.6	52.39	0.7941	0.4228
0.225	157.5	292.6	5.92	1042.9	70.67	0.7598	0.4829
0.25	175	335.25	5.35	1050.1	90.60	0.7730	0.4535
0.275	192.5	384.62	4.9	1069.4	114.78	0.7842	0.4199
0.3	210	432.6	4.42	1077.2	141.66	0.7559	0.4838

Table 3. Description of curves

Loading Density (g/cc)	0.2	0.225	0.25	0.275	0.3
Charge weight (g)	140	157.5	175	192.5	210
Description in Figure	A	B	C	D	E

as shown in Fig. 2. In fact, higher propellant quantity is not the only factor. When propellant weight is increased, number of propellant grain also increases. This increase is responsible for higher burning surface area and also higher rate of reduction in burning surface area. This is indirectly reflected by rate of rise of pressure (dP/dt). So, higher rate of rise of pressure represented more number of propellant grains, indirectly.

From the burn rate *vs* pressure curve (Fig. 3), it is seen that for higher loading density, peak pressure realised is higher. Higher peak pressure leads to higher burning rate of propellant. It was also observed from the firing curves that slope as well intercept on y-axis for Fig. 3 is invariant. This indicates applicability of the same burning rate law for all the loading densities. Same burning rate law in exponential form can be formulated for all five firing curves. From Figs 3 and 4, it was observed that there is not much significant change in the slope of burn rate versus pressure curve, and the slope of log R versus log$P$ curve for different loading densities. This means that burn rate of propellant at a pressure is independent of loading densities. Approximately the same pressure index (α) and burning rate coefficients (β) are achieved when charge masses are burnt with different loading densities[13,14]. Approximate burning rate (Table 2) for the propellant for loading densities from 0.2 g/cc to 0.3 g/cc is given by r (cm/s) = 0.43 x P (MPa)$^{0.76}$. As mentioned by Leciejewski[6], the closed vessel tests still remain the fundamental method for determining the form of the function $r(p)$ and the value of its coefficients.

5. CONCLUSIONS

Based on results of this study, the following conclusions can be made within the context of the study parameters.

- There appears to be little dependence of computed burn rate coefficients on the loading densities. The burn rate of propellant at a pressure is independent of loading densities.
- The higher pressures and the higher rate of rise of pressure at higher loading densities is due to the fact that higher loading densities mean more charge mass and more number of propellant grains inside the closed volume.
- There is not much change in the pressure index (α) and the burning rate coefficient (β) for different loading densities, as the slope of burn rate versus pressure curve remains almost the same.

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CONTRIBUTORS

Mrs Pragati Mehta is BE (Electronics and Communication) and is working as Sc 'C' in the closed vessel evaluation section of HEMRL, Pune. She has been involved with modelling and simulation of pressure development in closed vessel by firing gun propellants. She has developed in MATLAB complete software for data acquisition, gauge calibration, data retrieval, performance parameter calculation and comparison of different firings.

Mrs C.P. Shetty has 27 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.

Shri R.N. Pundkar has 32 years of experience with design, manufacturing, and testing with closed vessel system. Using indigenous materials, the complete CV system was fabricated and maintained to give consistent, reliable, and repeatable results. HE has also developed HPCV, where maximum peak pressure of the order of 782 MPa has been achieved.

Dr Himanshu Shekhar has done PhD in Mechanical Engineering and has 21 years of experience with processing, modelling, simulation and testing of propellants, explosives and pyrotechnics. He is currently Sc 'F' and Joint Director at HEMRL, Pune. He is recipient of *Young Scientist Award*, *Agni Award for Excellence in Self-Reliance*, and *Science Day Oration Award* from DRDO and is awarded with *Mr Engineer-2013* title by the Institution of Engineers. He has more than 100 research paper, 11 technical books, and has contributed one chapter in a book. He is Life Member of HEMSI and AeSI.