Defence Science Journal, Vol. 59, No. 5, September 2009, pp. 494-498

Design of Funnel Port Tubular Propellant Grain for Neutral Burning Profile in Rockets

Himanshu Shekhar

High Energy Materials Research Laboratory, Pune-411 021

ABSTRACT

Radial outward burning tubular propellant grain gives progressive burning profile, but trimming port at one end to conical form gives close to neutral burning profile. Though this configuration is easy to realize, but close-form burnback equation for performance prediction of such propellant geometry is not available. In this paper, close-form burnback equation for conically trimmed tubular propellant grain is developed. One propellant grain is also evaluated and performance matching to prediction by developed formulation is realised. Parametric study for different aspect ratio (*L/D*), diameter ratio (*d/D*) and slant angle (θ) is carried out for a typical configuration and variation is explained. The developed formulation is simple, handy, easy and quick.

Keywords: Propellant geometry, propellant grain, tubular propellant grain, neutral burning profile, mathematical formulation.

NOMENCLATURE

a	Burning rate coefficient
A_t	Throat area for the rocket motor
C^*	Characteristic velocity for the propellant composition
C_f	Thrust coefficient
d	Inner diameter of propellant grain
D	Outer diameter of propellant grain
F	Thrust generated by rocket motor
l	Straight length of the propellant port
L	Total length of the propellant
m_d	Rate of discharge of combustion gases from nozzle
m_g	Rate of generation of combustion gases
n	Burning rate pressure exponent
P	Pressure inside rocket motor chamber
r	Burning rate of solid propellant, $a \times P^n$
S_i	Initial burning surface area of propellant
S	Surface area of propellant geometry
t	Time elapsed
t_1	Time corresponding to web burnt w
w	Web burnt during motor operation
ρ	Density of propellant
θ	Slant angle of conical section at one end

1. INTRODUCTION

Design of a solid propellant grain was governed by ballistic, processing, and structural integrity requirements. Solid propellant burning surface recedes in the direction normal to the surface at any point of time and rate of propellant consumption depends on the initial burning surface and restricted boundary. Pressure-time, thrust-time, acceleration, velocity, and trajectory are decided by propellant configuration, and are largely a geometric consideration. Most of the time, it is preferred to have neutral burning profile, where burning surface area does not change during motor operation. For more lucid idea, neutrality factor was conceived and derived for different propellant configurations.[1] Neutral burning profile is generally obtained by end-burning cigarette mode-laterally, inhibited propellant or end-inhibited tubular propellant grains burning radially from inner and outer surfaces.[2] For star-shaped propellant port with different number of star points, the angle between tangents to the control burning surfaces for neutrality is also derived.[3] The current article derives a mathematical formulation for tubular propellant grains with one end internal port internally trimmed in a conical form.

2. MATHEMATICAL FORMULATION

Although several approaches for burnback equations are available in literature[4-6], but performance prediction of conical end port tubular propellant grain for neutrality is derived using close-form equations. The geometric features of the propellant grain are given in Fig. 1.

Propellant grain is assumed to be inhibited at lateral as well as at one end. Initial burning surface area is given by combination of a cylindrical and a conical section. Cylindrical section surface area is circumference times length of section, while conical surface area is projection of end surface area at an angle of θ. Initial burning surface area (S_i) is given by Eqn (1) as

$$S_i = \pi \times d \times l + (\pi/4) \times (D^2-d^2)/\sin\theta \qquad (1)$$

During motor operation, propellant was consumed in laterally outward direction, modifying internal diameter as well as length. For an instance, when web consumed is

Received 29 October 2008, Revised 16 March 2009

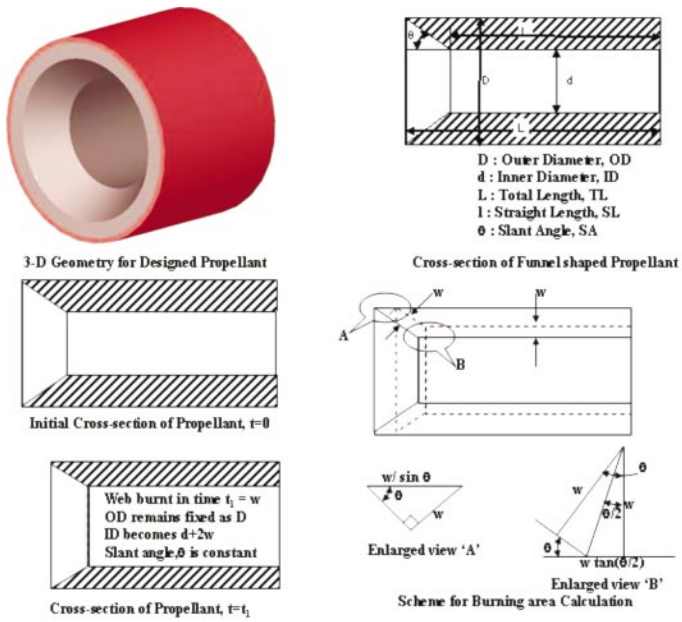

Figure 1. Salient parameters for conically trimmed tubular propellant grain.

w, outer diameter and slant angle during motor operation remains unchanged. Internal diameter increases from d to $d + 2w$. Conical section is affected by change in internal diameter only. Length of cylindrical section reduces as length of straight section reduces by $w \times \tan(\theta/2)$ as shown in Fig. 1. Incorporating both the parameters, burning surface area at $t = t_1$ corresponding to web burnt w is given by Eqn (2) as

$$S = \pi \times (d+2w) \times \{l - w \tan(\theta/2)\} + (\pi/4) \times \{D^2 - (d+2w)^2\}/\sin\theta \quad (2)$$

When propellant combustion in rocket motor chamber occurs, combustion gases are evolved. Rate of generation of combustion gases are given by Eqn (3) as

$$m_g = \rho \times r \times S = \rho \times a \times P^n \times S \quad (3)$$

After steady state condition is established, rate of generation of mass is equal to rate of discharge of combustion products from the rocket motor nozzle. Rate of discharge of combustion gases is given by Eqn (4) as

$$m_d = P \times A_t \times g / C^* \quad (4)$$

Equating rate of mass generation to rate of mass discharge, pressure corresponding to known web-burnt was calculated using Eqn (5) as

$$P = (a \times \rho \times C^* \times S / A_t \times g)^{1/(1-n)} \quad (5)$$

The calculation was conducted using web increment from zero web to complete consumption of propellant grain and adequate web burnt steps. For each web, corresponding surface area was generated using Eqn (2). Using Eqn (5) for each generated surface area, pressure generated in rocket motor chamber was calculated. Since burning rate coefficient and burning rate pressure exponent are known for a given propellant, therefore burning rate ($r = a \times P^n$) corresponding to each pressure was generated. Initially, time (t) was zero and web burnt (w) was also zero. For each increment in web (Δw), pressure generated in Eqn (5) gives instantaneous burning rate and time increment is obtained using Eqn (6). This time increment is added to earlier time to get current time. This algorithm helps in generation of pressure-time profile.

$$\Delta t = \Delta w / (a \times P^n) \quad (6)$$

For generation of thrust-time profile, pressure was converted to thrust using Eqn (7) as

$$F = C_f \times P \times A_t \quad (7)$$

Although simple mass-balance equation was employed in the formulation, but depending on actual configuration, combustion gas flow area to throat area must be compared to ensure absence of erosive burning. In the early phases of burning, before steady state burning profile sets-in on the propellant surface, unsteady ignition transition phase exists. During this phase, prediction by mass-balance equation alone is not sufficient to derive pressure-time and thrust-time profile. Propellant burning in conical section and in transition zone is two-dimensional and can have severe erosive burning. Additionally, longitudinal variations of thermodynamic parameters like pressure, temperature, and velocity also affect the pressure-time and thrust-time profiles. However, in the present formulation, derivations were restricted to generation of close-form burnback equation from geometrical considerations, which was in line with current state-of-the-art derivations for different propellant geometries.[5,6]

Since neutrality of configuration was a major concern for propellant grains, therefore derivative of burning surface area as given in Eqn (2) wrt web burnt was obtained from Eqn (2) as Eqn (8).

$$dS/dw = \pi\{2l - [d+2w] \times [\tan(\theta/2) + (1/\sin\theta)] - 2w\tan(\theta/2)\} \quad (8)$$

For neutral burning profile, burning surface area was constant and derivative of burning surface area wrt web burnt, close to zero was desired. The derivative, given in Eqn (8) shows that the derivative can be minimised by adjusting l, θ, and d parameters of the propellant grain.

3. FIRING RESULTS AND ANALYSIS

Solid propellant grain with essential geometric and ballistic parameters given in Table 1 was prepared and fired in a small motor.

Performance prediction was done and firing curve was obtained reasonably matching to the prediction as per close-form burnback equation developed. The comparison was reproduced in Fig. 2.

Since making a propellant grain with exact conical end was difficult and equally difficult was to maintain the sharp tip during inhibition and handling, therefore the propellant configuration used in static evaluation had blunt end, as shown in solid model of Fig. 1. It was depicted with dimensions in Fig. 2 also as inserts. Close

Table 1. Salient geometric and ballistic parameters of evaluated propellant

Parameters	Value
Grain outer dia, *D*	72 mm
Grain inner dia, *d*	40.5 mm
Straight length, *l*	46.5 mm
Slant angle, θ	34 degree
Propellant density, ρ	1.58 g/cc
Characteristic velocity, *C**	1360 m/s
Burn rate coefficient, *a*	6.448 mm/s
Burn rate exponent, n	0.114
Throat area, A_t	25.517

matching in value and shape to the reasonable level of accuracy was clear from Fig. 2.

For single-propellant configuration, one geometric parameter was varied at a time and prediction was made. A typical propellant grain with outer diameter of 50 mm, inner diameter of 10 mm, total propellant length of 200 mm, and slant angle of 9° was considered. For parametric variation, tubular burning area at extreme diameter was taken homogenising factor (π.50.200 = 31415.9 mm^2) for surface area and maximum web was taken homogenising factor (50/2-10/2 = 20 mm) for web burnt. First of all, aspect ratio (*L/D*) was varied from 2.6 to 10 and predicted profile was shown in Fig. 3. For lower aspect ratios, highly regressive profile was obtained, which becomes a progressive curve for high aspect ratios. Low aspect ratio gives higher initial burning area and lower final burning area. Neutrality was obtained for aspect ratio of 4.5.

To confirm neutrality, derivative of burning surface area has been plotted against fraction of web burnt in Fig. 4. It was clear that with changing *L/D* ratio, derivative moves in vertical direction on the plot. For lower aspect ratio, derivatives are negative, depicting a highly regressive burning area variation profile. Regressivity increases with fraction of web burnt. As aspect ratio increases, variation curve (in Fig. 4) shifts upward and for high aspect ratio of 10, all derivatives are positive, giving a progressive burning area variation profile. For aspect ratio of 4.5, variation profile was evenly distributed around zero value. During initial phases, it was slightly progressive, which became

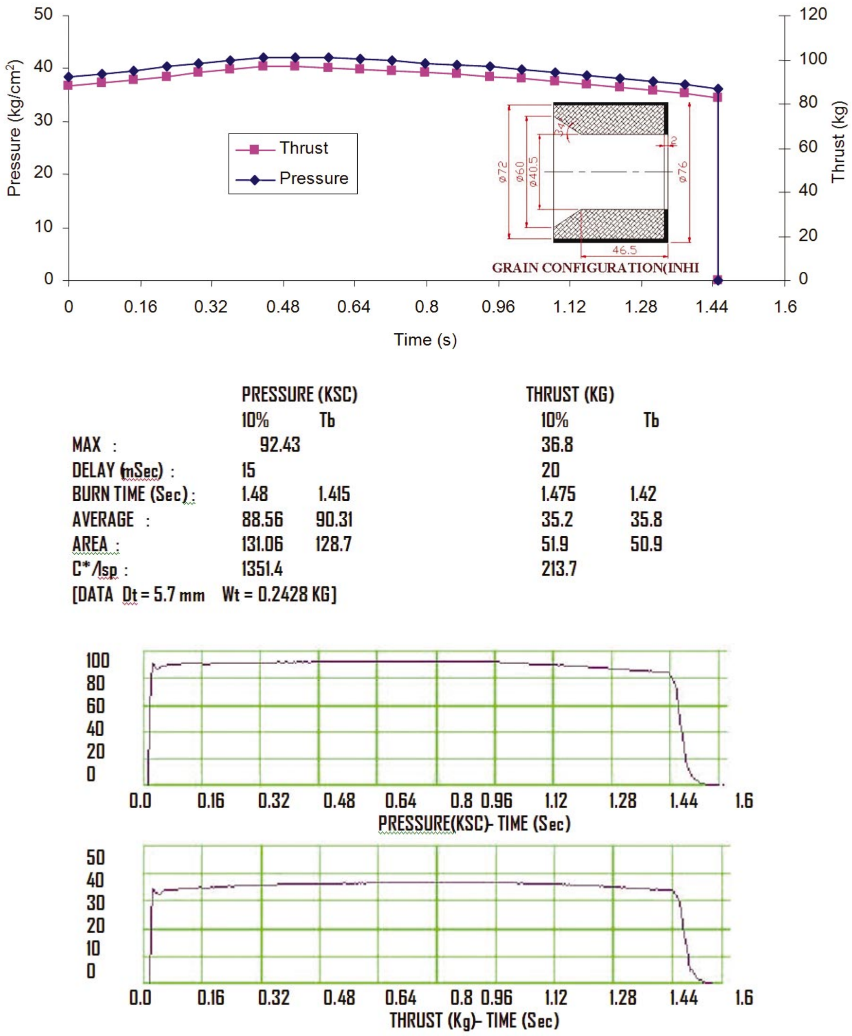

Figure 2. Predicted and realised firing profiles.

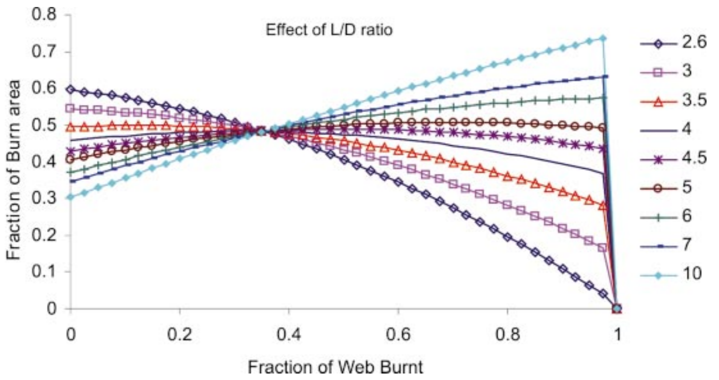

Figure 3. Nature of firing profile for different aspect ratios (*L*/*D*).

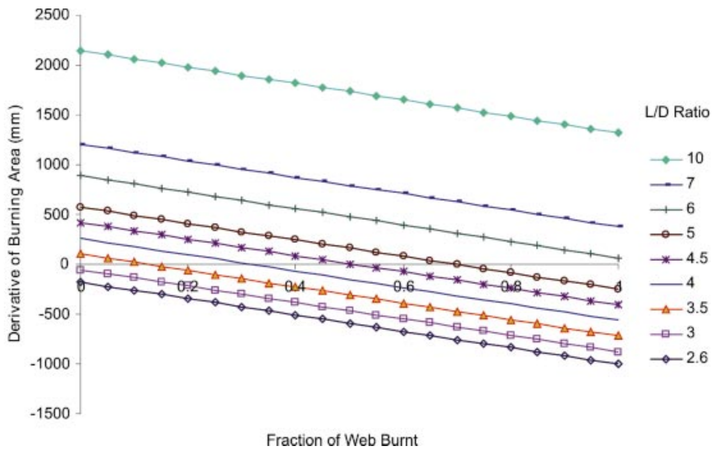

Figure 4. Variation of derivative of burning area with various aspect ratios (*L*/*D*).

regressive as burning progressed. So, this aspect ratio gives approximate neutral burning area variation profile for a given configuration.

Diameter ratio (*d/D*) of sample propellant configuration was considered as the next parameter and was changed from 0.1 to 0.7. It was obvious that higher diameter ratio indicates lower propellant weight. However, due to homogenisation, curve indicated in Fig. 5 shows the same ordinates. At lower diameter ratio, profile curled at both

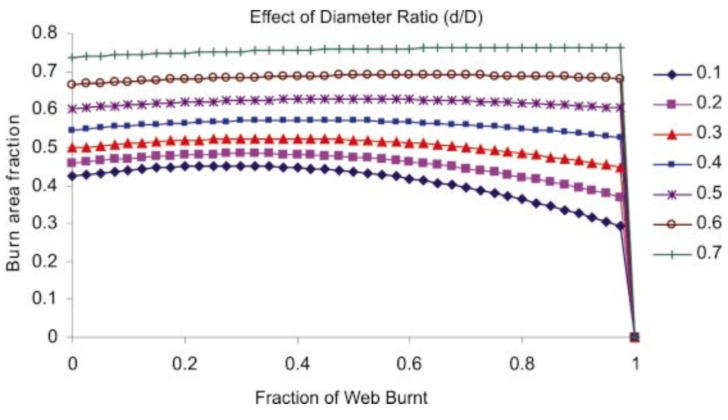

Figure 5. Nature of firing profile for different diameter ratios (*d*/*D*).

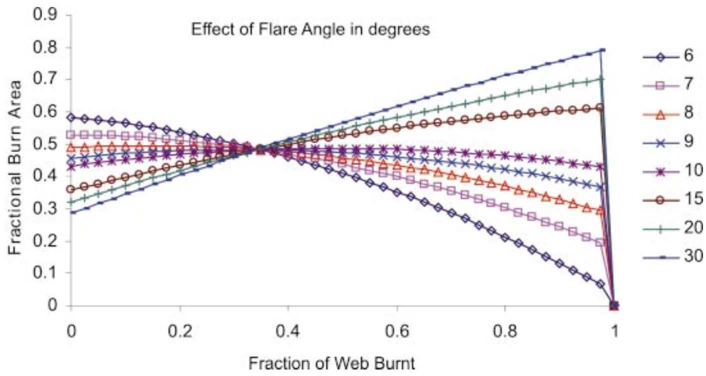

Figure 6. Nature of firing profile for different flare angles (θ).

the ends and maximum was obtained at the central portion. With increase in diameter ratio, this change in value led towards neutral burning profile.

Slant angle of the propellant configuration was changed from 6° to 30°, as shown in Fig. 6. At lower slant angle, more part of tubular propellant section was trimmed to make conical end and lower propellant weight was envisaged. At this geometry, regressive burning profile was obtained. When slant angle was increased, profile shifted towards neutrality, but central hump remained. For higher slant angle, profile became progressive. Neutrality was obtained for a slant angle of 10°.

Derivative of burning surface area was not depicted for all the parametric cases, but neutrality was ensured after achieving equal distribution of derivative curve on either side of zero slope. From parametric studies, it was clear that lower aspect ratio (*L/D*) and lower slant angle (θ) leads to regressive burning profile. Increasing both leads to neutral and further increase leads to progressive burning profile.

4. CONCLUSIONS

Laterally inhibited tubular propellant grain was bound to give a progressive burning profile, but trimming one end to conical form gives close-to-neutral burning profile. This type of configuration was conceived and close-form burnback equation for performance prediction has been evolved. A small propellant grain has been statically evaluated with performance matching to prediction. Different geometric parameters like diameter ratio, aspect (length to diameter) ratio and slant angles are varied for a typical configuration and effect on pressure-time profile evaluated. Simplicity of propellant configuration, close-form burnback equation for performance prediction, validation by static evaluation, and parametric studies make this design approach for neutral propellant grain unique, quick, and easy.

REFERENCES

1. Krishnan, S. Design of neutral burning star grains. *J. Spacecraft*, 1975, **12**(1), 60-2.
2. Solid propellant grain design and internal ballistics. NASA, 1972. Report No. NASA SP-8076.
3. Williams, F.A.; Barrere, M. & Huang, N.C. Fundamental

aspects of solid propellant rockets. Technivision Services Slough, England, October 1969. pp. 217.
4. Solid rocket motor performance analysis and prediction. NASA, 1971. Report No. NASA SP-8039.
5. Michael, A.; Willcox, M.; Quinn Brewster, K.C.; Tang, D. & Stewart, Scott. Solid propellant grain design and burnback simulation using a minimum distance function. *J. Prop. Power*, 2007, **23**(2), 465-75.
6. Michael, A.; Willcox, M.; Quinn Brewster, K.C.; Tang, D.; Stewart, Scott & Kuznetsov, Igor. Solid rocket motor internal ballistics simulation using three-dimensional grain burnback. *J. Prop. Power*, 2007, **23**(3), 575-84.

Contributor

Mr Himanshu Shekhar is an MTech in Mechanical Engineering from IIT, Kanpur, India, and is working as Deputy Director and is Head, Ballistic Group at High Energy Materials Research Laboratory, Pune. He has developed infrastructure for processing large size case-bonded solid propellant rocket motors and has processed several motors, which have been fired successfully. He has designed propellant grains for various applications. He is recipient of *Young Scientist Award*. He has more than 30 publications, and authored two books on Solid Rocket Propellants.