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Extension of the universal erosive burning law to partly symmetric propellant grain geometries

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ABSTRACT

This paper aims at extending the universal erosive burning law developed by two of the present authors from axi-symmetric internally burning grains to partly symmetric burning grains. This extension revolves around three dimensional flow calculations inside highly loaded grain geometry and benefiting from an observation that the flow gradients normal to the surface in such geometries have a smooth behavior along the perimeter of the grain. These are used to help identify the diameter that gives the same perimeter the characteristic dimension rather than a mean hydraulic diameter chosen earlier. The predictions of highly loaded grains from the newly chosen dimension in the erosive burning law show better comparison with measured pressure–time curves while those with mean hydraulic diameter definitely over-predict the pressures.

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1. Introduction

Two of the present authors (HSM and PJP) [1] presented a procedure based on non-dimensional considerations by which the data on erosive burning from more than ten investigators from different laboratories across the world on both double base and composite propellants could be brought into a simple relationship as

$$\eta = 1 + 0.023(g^{0.8} - g_{th}^{0.8})\mathcal{H}(g - g_{th}) \quad (1)$$

to within an accuracy of $\pm 10\%$. In the above equation, η is the ratio of burn rate with lateral flow to that without any flow (the classical erosive burning ratio $= r/r_0$), g is essentially the ratio of mass flux through the port to the mass efflux from the surface modified for size effects as $(G/\rho_p r_0)\,(\rho_p r_0 d_0/\mu)^{-0.125}$, where G is the mass flux through the port, $\rho_p r_0$ is the non-erosive mass efflux from the surface, g_{th} is the threshold value obtained from the plot of the data as 35 and $\mathcal{H}$ is the Heaviside step function that is introduced to indicate a critical flux below which there is no erosive burning. The basis of the equation is that fluid mechanics controls the erosive burning and while many details of the propellant like the composition, particle sizes in the case of heterogeneous propellants do matter with regard to the burn rate, the data from different sources has not shown any specificity on non-dimensional parameter plots. While one cannot intrinsically rule out the subsidiary effects, there was no specific trend in the data to suggest that. Earlier investigators used various dimensional parameters and missed out the principal effects even though the important effects are embedded in the equations that have been used for a long time. Hasegawa et al. [2] used X-ray absorption measurements for double slab motors (DSM) to get a curve fit for erosion law of the form given by Dickinson et al. [3]. Unfortunately, they have chosen to depart from dimensionless correlation above to a new correlation based on dimensional mass flux with inadequate justification. Because of this reason, they have used different constants for different size motors showing clearly inadequacy of the relationship that earlier literature is filled with. Recently, Topalian et al. [4] have chosen to study erosive burning in composite propellants ignoring the

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Nomenclature

A_p	local port area
G	mass flux through port
$\mathcal{H}$	Heaviside step function
P	grain perimeter
Re_0	Reynolds number defined as $\rho_p r_0 d_0/\mu$
U_{av}	average axial velocity
d_0	port diameter
g	modified mass flux ratio defined as $(G/\rho_p r_0)(\rho_p r_0 d_0/\mu)^{-0.125}$
g_{th}	threshold mass flux ratio (=35)
$\dot{m}$	mass flow rate kg/s
r	burn rate with lateral flow
r_0	burn rate without lateral flow
x	axial location
μ	coefficient of dynamic viscosity
η	erosive burning ratio
ρ	density of products of combustion
ρ_p	propellant density
τ_w	wall shear stress

underlying fundamental influence brought out in Mukunda and Paul[1] and seeking any possible deviations from the universal relationship. In fact, the comparisons in Ref. [4] are so limited that the data fit into the above correlation and no extra effects expected to be delineated in their work seem apparent.

In Eq. (1), the motor size effect comes in through the Reynolds number, $Re_0=\rho_p r_0 d_0/\mu$ with d_0 being chosen as the port diameter. This equation has been applied routinely to the design of highly loaded grains that have circular port and found to give predictions consistent with large size motor data from tests. When it is expected to be extended to more complex geometries, like star grains, one would normally use the hydraulic diameter given by $4A_p/P$, where A_p is the port area and P is the grain perimeter. This relationship was routinely used in propellant grain design at the defense laboratories. When this relationship was used for grain shapes having partly Finocyl shape [5], it *over-predicted* the pressure variation in the early part of the burn. Burn rate differences in a star point and recess locations of a star and other shapes have been discussed in Williams et al. [6]. This subject that has remained unaddressed till now because there has been no clear demand on these aspects from motor designers. It is the objective of this paper to address the complex flow through the slots of the grain and the central region that affect the heat flux to the grain in the interior regions through a rigorous calculation of three-dimensional internal flow through the grain and in this process, seek any possible revision of the universal burn rate law for non-axisymmetric shapes.

2. The motors studied

Two rocket motors are considered for the study here. Both have a cylindrical section towards the head end and a finocyl shape in the aft region. The details of the calculations of one motor are set out here. The results of the other motor are summarized. The details of the motors are shown in Table 1. The length-to-diameter ratio of the cylindrical portion is about 18 for the first motor and 26 for the second motor.

The first motor has a finocyl geometry whose cross section is shown towards the right side. The vertical lines drawn refer to the locations where the 3-d thermo-fluid information is extracted. As shown in Fig. 1 is another highly loaded grain with a strong possibility of erosive burning occurring in the cylindrical portion itself; it could also occur in the finocyl part.

3. The 3-d computational details

A symmetric geometry of 45° sector for Motor-1 has been considered for the simulation. The geometry with the boundary locations is shown in Fig. 2.

Table 1
Properties of the motors under study.

Parameter	Motor-1	Motor-2
Motor length, m	2.1	4.8
Port diameter, m	0.17	Varies from 0.31 to 0.49
Initial cylindrical segment, m	1.37	3.48
Finocyl transition zone, m	0.18	0.26
Number of webs in the finocyl	4	8
Finocyl minimum dia., m	0.08	0.13
Finocyl maximum dia., m	0.17	Varies from 0.28 to 0.37
Throat diameter, mm	45	176
Burn rate at 7 MPa and pressure index, n	6.5 mm/s and 0.25	19 mm/s and 0.38

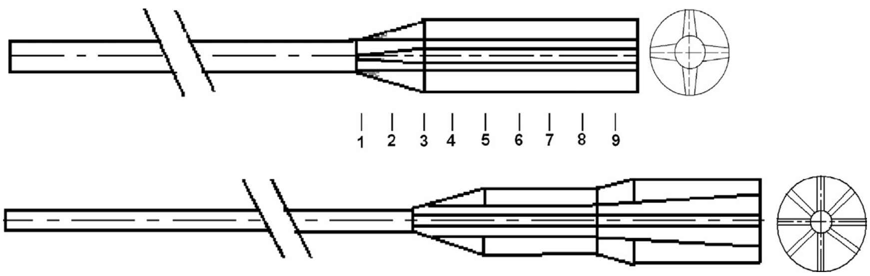

Fig. 1. Geometries of the two grains for Motor-1 (top) and Motor-2 (bottom); the first part is cylindrical and the aft part is finocyl with a transition region, the cross section shown on the right is of the aft end.

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