Theoretical Prediction of Erosive Burning Characteristics of Solid Propellant

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Theme

THE aim of this paper is to provide the designer of modern solid propellant motors with a successful theoretical basis for predicting the erosive burning effects that are already in the designing phase. This is done by means of modified Lenoir-Robillard formulas and theoretically determined unkown parameters. In up-to-date practice, a great deal of experimental investigation had to be done to define those constants. The application range of this theory has been extended on plateaunized propellants with negative erosion effects. The only experimental constants required by this method are the linear burning rate law and initial temperature sensitivity.

Contents:

The theoretical method is based on following assumptions:

1) The double-layer scheme of turbulent boundary layers has been accepted (turbulent core and laminar sublayer, neglecting end effects). For analyzing the problem, the semiempirical theory of turbulence has been applied with extension in case of mass injection into the boundary layer.

2) The effect of erosive burning appears when the flame front passes the boundary of the laminar sublayer and gets into the turbulent core.

3) The laminar sublayer thickness, when the blowing effect exists, is determined on the basis of the Van Dierst assumption which accepts, as a competent shear stress for determining the sublayer thickness, shear stress on the boundary of laminar sublayer, and turbulent core.

4) There is a critical value of the blowing parameter B_{cr} where the local coefficient of friction (with blowing effect) equals zero, $C_f/C_{f_0}=0$. In case of asymptotic, nonisothermic boundary layer this parameter is defined through the relations[5]

$$B_{cr}=b/(1+b/4)^{0,2} \tag{1}$$

$$b=\frac{1}{1-\psi}\left[\ln\frac{1+(1-\psi)^{1/2}}{1-(1-\psi)^{1/2}}\right]^2 \tag{2}$$

where ψ is temperature factor $\psi=T_s/T_c$.

5) The position of the flame front is determined on the basis of known temperature profiles in the gas phase obtained through the equation

$$\frac{d}{dx}\left(\lambda\frac{dT}{dy}\right)-m\,c_p\frac{dT}{dy}+\phi(T)=0 \tag{3}$$

6) Some of the propellants used have a change of pressure exponent in linear burning rate law (plateau and mesa effects), linear burning rate law of such propellant is given in Fig. 1. For such propellants we assume the following: a) the catalytic effect which causes plateau or mesa effect is noticeable only in the pressure range beyond p_t and, b) the effect of the catalyst asymptotically decreases, when velocity of combustion products increases. This means that in erosive burning conditions, propellant nonerosive burning rate has a value near the burning rate of nonplateaunized propellant and the entire calculations must be done using "plateau-free" burning rate law.

7) For composite propellant, Summerfield's theory has been accepted, and for double-base propellants, Zeldovič and Beljajev's theory. With respect to these theories we have the following equations for surface temperatures

$$T_s=2\sigma_p+Q_s/c_s+T_0 \tag{4}$$

for composite propellants, and

$$T_s=\sigma_p+Q_s/c_s+T_0 \tag{5}$$

for double-base propellants, where σ_p is the initial temperature sensitivity of burning rate, Q_s is the solid phase heat of destruction, c_s is the solid phase heat capacity, and T_0 is the initial temperature.

By using the described assumptions, the following formulas have been derived (Fig. 2)

$$r=r_0^*+r_e+r_p \tag{6}$$

where r_0^* is plateau-free linear burning rate; r_e is erosive burning rate based on the Lenoir-Robillard law[1]

$$r_e=(\alpha/d^{0.2})\,G^{0.8}e^{(-\beta\rho_s r/G)} \tag{7}$$

and r_p, the plateau burning rate based on the following formula:

$$r_p=(r_0-r_0^*)\,e^{(-G/\rho_s r\gamma)} \tag{8}$$

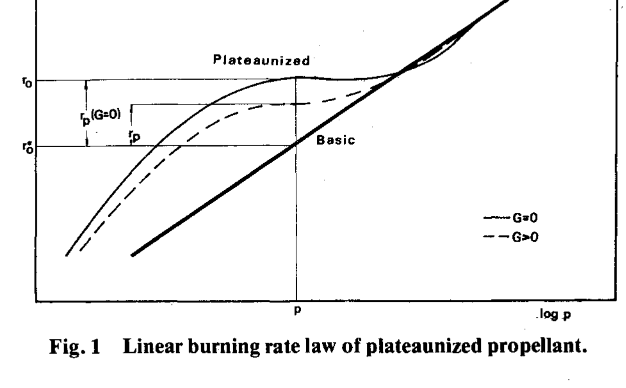

Fig. 1 Linear burning rate law of plateaunized propellant.

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Index categories: Combustion in Heterogenous Media; Fuels and Propellants, Properties of; Solid and Hybrid Rocket Engines.

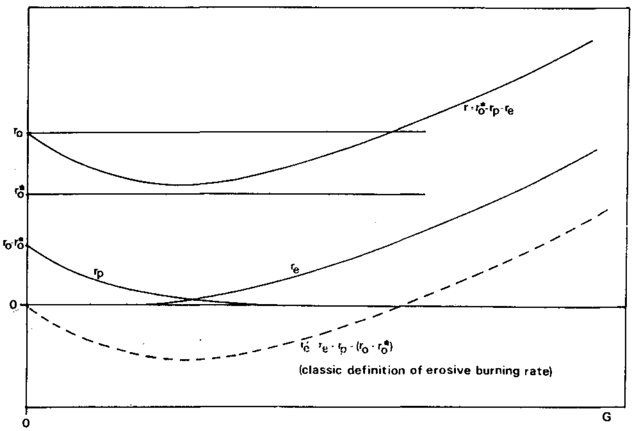

Fig. 2 Definition of burning rate components (classic and present theory).

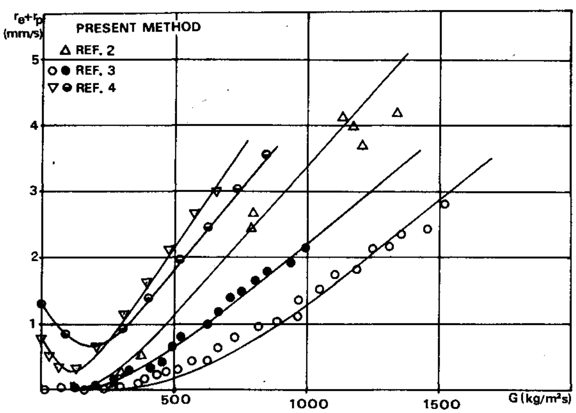

Fig. 3 Comparison with Wimpress,[2] Green,[3] and Dickinson, Jackson, and Odgers[4] experiments.

Parameter α is given by

$$\alpha = \frac{0.023\, c_p\, \mu^{0.2} Pr^{-0.667} \theta}{c_s\, \rho_s (0.5 + \psi/2)^{0.667}} \tag{9}$$

where c_p is heat capacity of combustion products at combustion temperature, Pr is the Prandtl number, $\theta = (T_c - T_s)/(T_s - T_0 - Q_s/c_s)$ flame temperature criterion, μ is the combustion products dynamical viscosity, ρ_s is the propellant density and $\psi = T_s/T_c$. T_s has been determined using Eqs. (4) or (5) and Q_s using the approximate formula

$$Q_s = 1{,}045{,}000(\mathrm{AP}) - 940{,}000(\mathrm{BI}) - 280{,}000(\mathrm{AL}) \quad (\mathrm{J/kg}) \tag{10}$$

where (AP), (BI), and (AL) are mass fraction of ammonium perchlorate, binder, and aluminium respectively. For double base propellants Q_s should be determined using the approximation

$$Q_s = 159{,}000 \ln(3000 r_0) \quad (\mathrm{J/kg}) \tag{11a}$$

where r_0 is in m/sec. Parameter β is defined by

$$\beta = B_{cr} \left[\frac{49}{(\theta'^{\,0.63} \ln\theta')^{1.1111}} + 0.45 \right] (r_0 d\, \rho_s/\mu)^{0.1111} \tag{11b}$$

where

$$\theta' = \theta\, c_p (0.5 + \psi/2)^{0.2}/c_s + 1 \tag{11c}$$

where d is the port diameter. B_{cr} should be determined using Eqs. (1) and (2). Parameter γ should be determined using the empirical formula

$$\gamma = \beta (r_0 - r_0^*)/r_0 \tag{12}$$

This method has been compared with the experimental data of numerous authors (Drašković, Heron, Wimpress, Green, Marklund and Lake, Dickinson, Jackeson and Odgers, and Peretz), and the agreement is very good. Some of the results are given in Fig. 3.

In conclusion we must point out that the uncertainty of initial temperature sensitivity has a great effect on the uncertainty of the final results of the method. However, using a limited amount of precise experimental data, good prediction can be made.

References

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