Technical Notes

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Experimental Investigation of Erosive Burning Solid Propellants

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Nomenclature

a = constant in burning-rate law
A_b = combustion surface area, m²
A_p = cross section of port area, m²
A_t = throat area, m²
C^* = characteristic velocity, m/s
C_F = thrust coefficient
e = web thickness of propellant grain, m
F = thrust, N
G_g = mass velocity of combustion gases, kg/m²s
Isp = specific impulse, s
K_n = A_b/A_t
L = length of propellant grain, m
n = exponential constant
p = static pressure, N/m²
r = burning rate, m/s
V_b = burning rate dependent pressure, m/s
V_e = erosive burning rate, m/s
α_1 = erosive constant ($cm^{2.8} \cdot kg^{-0.8} \cdot s^{-0.2}$), = 5.70
β = dimensionless exponential constant, = 53.0
ρ_p = density of propellant, kg/m³

Introduction

THIS paper presents experimental measurements of the erosive burning rate of composite solid-propellant grains having a star perforation. The erosive burning rate data were obtained using web burnout detectors on the outer surface of the propellant grain. These experimental results were compared with the predictions from the design procedure using the Lenoir and Robillard theory[1] supported by numerical analysis. The total burning rate r, including the erosion effects, is given by the following equation[2]:

$$r = V_b + V_e = ap^n + \alpha_1 G_g^{0.8}/L^{0.2} \cdot \exp[(\beta \cdot \rho_p \cdot r)/G_g]$$

A review of the available literature indicated that the Lenoir and Robillard theory has been quoted by some investigators[3,4] as suitable for general use and by others as even the best available.[5] Other authors[3] have identified weak points in the form, but the proposed alternatives also have their own weaknesses. As demonstrated later in this paper, the experimental results are in good agreement with the Lenoir and Robillard theory.

For the experimental procedures, rocket motors with different lengths and constant K_n were used to investigate the erosive burning. This method has the advantage that the erosive burning conditions are real and the influence of erosive burning on the motor performance parameters ($\bar{P}$, $\bar{F}$, Isp, C_F, and C^*) can be observed directly.

Experimental Procedures

The experimental investigation of the erosive burning rate was conducted using several modular rocket motors. Each module had a length of 0.488 m. Several assemblies of different numbers of module or half-length module were used to accomplish these tests (Fig. 1). The modular assembly was chosen as a practical means of obtaining different erosive burning conditions.

A total of 13 tests were conducted to provide the erosive burning data: five tests using a single module, three using dual-module motors, one using 2½ modules, three using 3 modules, and one using 3½ modules.

The rocket motors were loaded with 10 points star-shaped composite solid-propellant grains. The dimensions of the grains and geometry of the star perforation are indicated in Figs. 1 and 2. The basic composition of the solid propellant was ammonium percholorate, 70%; aluminum, 10%; binder (PBCT), 15%; and others, 5%.

All firing tests were performed at room temperature after conditioning the rocket motors for 24 h at 20°C. The burning rate was measured with web burnout detectors (0.2-mm-diam copper wires) distributed along the other surface of the propellant grain (Fig. 3).

Results and Discussion

Figure 4 shows the measured pressure and thrust vs time traces for a single-module configuration that is typical of the results obtained in all the tests. From these results the $\bar{P}$, $\bar{F}$, Isp, C_F, and C^* were obtained and are presented in Table 1. Also shown Fig. 4 and Table 1 are the predicted results from the design procedure calculations. A comparison of results shows good agreement as indicated by a maximum deviation of about 10%.

Figure 5 shows the effects of gas velocity on erosive burning of composite solid propellant. In this figure, the burning rate is plotted vs gas velocity and shows that the burning rate increases as expected, with increasing gas velocity for various lengths of propellant grains.

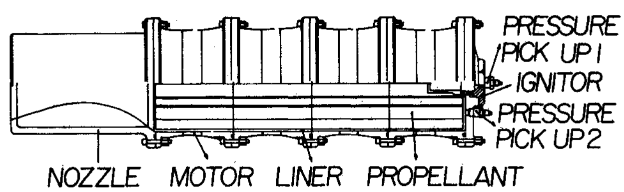

Fig. 1 Several assemblies of different numbers of rocket-motor modules.

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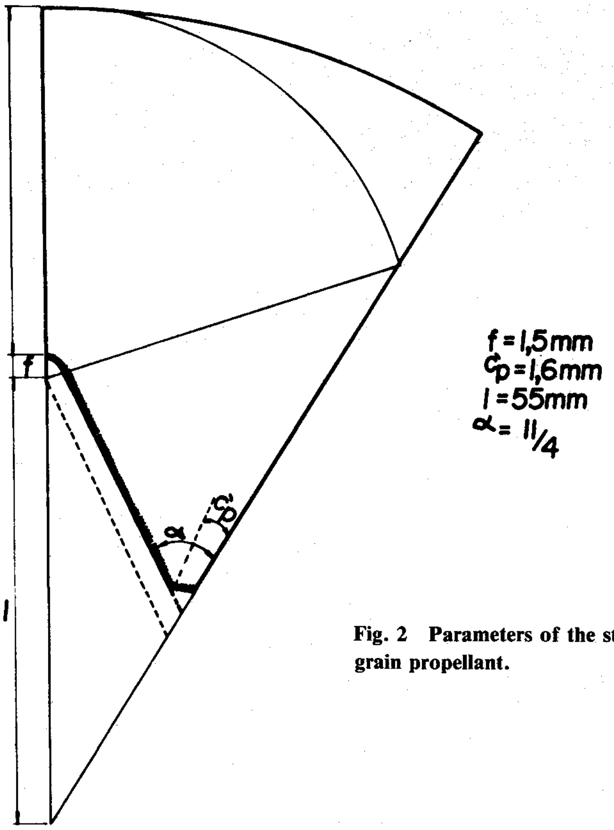

Fig. 2 Parameters of the star grain propellant.

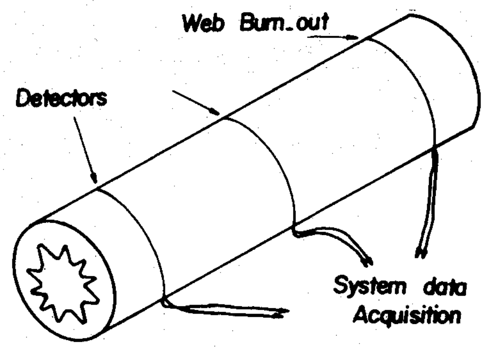

Fig. 3 Propellant with web burnout detectors.

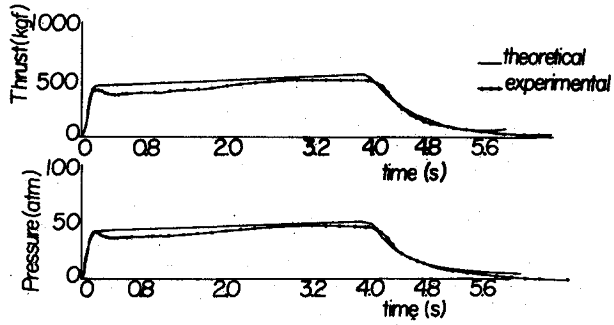

Fig. 4 Pressure and thrust as a function of time for single-module motor.

Table 1 Comparison of experimental and predicted results of performance to rocket motor of different lengths

Lengths of propellant	Types of results	Performance parameters						
		$\bar{P}, Pa \times 10^{-5}$	F,N	Isp, s	C_F	C^*,m/s	t_b,s	k_{nj}
$L = 0.488$ m (1 module)	Experimental	40.4	4191.4	194.0	1.52	1255.0	4.26	336.4
	Results[a]	44.80	4765.4	217.6	1.59	1347.1	4.20	
$L = 0.976$ m (2 module)	Experimental	41.9	8758.1	196.1	1.54	1253.0	4.11	336.4
	Results[a]	45.1	9451.6	211.3	1.53	1356.7	4.20	
$L = 1.220$ m (2½ modules)	Experimental	42.2	10678.5	193.6	1.49	1276.4	4.16	336.4
	Results[a]	45.4	11876.8	212.2	1.53	1361.3	4.20	
$L = 1.464$ m (3 modules)	Experimental	45.7	13802.0	199.2	1.48	1327.2	4.0	336.4
	Results[a]	46.4	14158.0	194.8	1.52	1199.0	3.80	
$L = 1.708$ m (3½ modules)	Experimental	33.1	13092.9	189.1	1.21	1326.4	4.64	284.5
	Results[a]	34.7	14106.7	184.4	1.26	1241.7	4.2	

[a]Predicted results.

Table 2 Comparison of predicted and experimental burning rate to rocket motor of different lengths

Lengths of propellant	Types of results	Burning rate						
		r_1	r_2	r_3	r_4	r_5	r_6	r_7
$L = 0.488$ m (1 module)	Experimental	5.20	5.13	5.32	—	—	—	—
	Results[a]	4.57	4.57	4.57	—	—	—	—
$L = 0.976$ m (2 modules)	Experimental	5.34	5.26	5.37	5.21	5.23	5.49	—
	Results[a]	4.65	4.65	4.65	4.65	4.65	4.65	—
$L = 1.220$ m (2½ modules)	Experimental	5.41	4.40	5.36	5.07	5.07	5.19	—
	Results[a]	4.64	4.64	4.64	4.64	4.65	4.65	—
$L = 1.464$ m (3 modules)	Experimental	5.63	5.37	5.48	5.55	5.67	5.61	5.82
	Results[a]	4.67	4.67	4.68	4.70	4.71	4.75	4.76
$L = 1.708$ m (3½ modules)	Experimental	4.97	3.85	4.56	4.62	4.97	4.79	5.37
	Results[a]	3.97	3.98	4.05	4.11	4.16	4.28	4.43

[a]Predicted results.

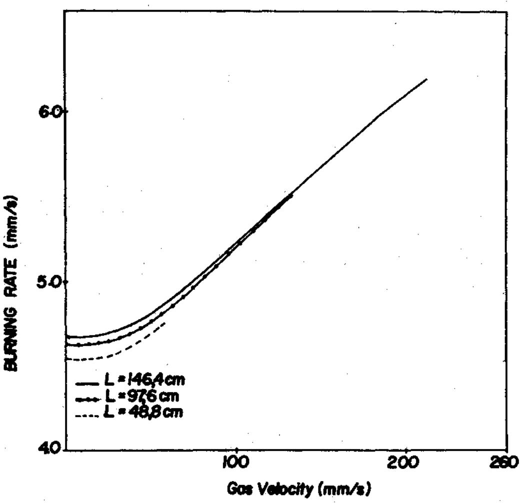

Fig. 5 Burning rate vs gas velocity data for various lengths of propellant.

The experimental method used to determine burning rate is accurate since previous experimental work[6] has not shown a temperature gradient across the propellant grain web. Thus, opening of burning detectors wires actually occurs only when the flame reaches each one, providing accurate results. Comparison of the experimental burning rate and predicted results from the design procedure, listed in Table 2, shows good agreement.

The analysis of the experimental results of rocket motors of several lengths indicates a small erosive burning effect. That is reasonable because the port-to-throat area ratio was high enough ($A_P/A_t<2$) although the gas velocity reaches values greater than 180 m/s (threshold velocity[7,8]).

It can also be seen that erosive burning causes a decrease in Isp, C_F, and C^* and an increase in the burning rates along the propellant grain length. It should be pointed out that in the designs tested here the erosive burning was relatively small, and it was possible to verify a quite small influence on the rocket motors parameters.

In this work the erosive burning effects obtained were small. Therefore, further work will be done in a regime where strong erosive conditions are likely to occur.

Acknowledgments

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Characteristic Times for Lean Blowoff in Turbine Combustors

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Introduction

IGNITION and blowoff within turbine combustors have been studied extensively in the last few years; correlations for these processes have been made with characteristic time models. A lean blowoff model developed by Plee and Mellor[1] uses fuel properties, combustor inlet conditions, and combustor geometries to define characteristic times that are combined to represent a limit for blowoff. The model was originally developed for simple geometries and later applied to can combustors.[2] More recently, the model has been extended to annular combustors—specifically the General Electric (GE) J85.[3] As shown by Jarymowycz and Mellor,[3] the slow evaporation of fuel altered the correlation technique from that used previously for can combustors.[2] However, this conclusion was based on limited GE blowoff data taken by Oller et al.[4]

The purpose of this Note is to utilize a more complete set of new J85 lean blowoff data obtained at the Naval Air Propulsion Center (NAPC) and thus continue the validation of the model's application to annular combustors. In addition, because the NAPC facility could not reproduce the combustor inlet conditions used in the GE tests, the model was used to scale the combustor conditions at NAPC. A blowoff limit equation recommended here correlating data for two can combustors as well as the GE and NAPC J85 data suggests that the model is able to characterize blowoff independently of combustor type and can be used to scale test conditions.

Background

The lean blowoff model defined by Plee and Mellor[1] uses three characteristic times to represent blowoff: a droplet evaporation time (τ_{eb}), a fuel ignition delay time (τ_{hc}), and a shear layer residence time (τ_{sl}). At the limit for lean blowoff, the residence time in the shear layer will equal approximately the sum of the droplet evaporation time and ignition delay time:

$$\tau_{sl} \sim \tau_{hc} + k \cdot \tau_{eb} \tag{1}$$

with k a constant weighting factor found by Plee to be 0.011 for a best-fit straight line.[5] Since the equations for the

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