World Academy of Science, Engineering and Technology
International Journal of Aerospace and Mechanical Engineering
Vol:7, No:9, 2013

Performance Investigation of Solid-Rocket Motor with Nozzle Throat Erosion

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Abstract**—**In order to determine the performance and key design parameters of rocket, the erosion of nozzle throat during solid rocket motor burning have to be calculated. This study aims to predict the nozzle throat erosion in solid rocket motors according to the thrust profile of motor in operating conditions and develop a model for optimum performance of rocket. We investigate the throat radius change in the static test programs. The standard method and thrust coefficient are used for adjusting into the ideal performance for conical nozzles. Pressure and thrust data acquired from the tests are analyzed to determine the instantaneous nozzle throat diameter variation throughout the test duration. The result shows good agreement of calculated correlation comparing with measured erosion rate data showing agreement within 1.6mm/s. Nozzle thrust coefficient loss is found approximately 24% form nozzle throat erosion during burning.

Keywords**—**Erosion, nozzle throat, thrust coefficient.

I. Introduction

THE performance of the rocket motor was partially depended on the rate of erosion of the nozzle materials originated by the hot gas flow during the operation. The performance and pressure of the rocket decreases with the erosion of the nozzle [1]. In this study, we investigate the relations between the erosion material and the operating condition of pressure in nozzle combustion chamber.

The chamber pressure directly related to the thrust is a function of the ratio of the burning surface to the nozzle throat area. For preliminary performance calculations, the throat area is usually assumed to be constant for the total burning duration. However, for accurate performance prediction, it is necessary to include the erosion of the nozzle material, which causes an increase of the nozzle throat area [2]. Ablative materials are designed to insulate the nozzle metallic housing and provide the internal contour necessary to expand the combustion gas. Erosion of nozzle material is caused by the complex interaction between the high-temperature high-velocity gas flow, the chemically and mechanically eroded during motor operating conditions. The enlargement of the throat area reduces the chamber pressure and the thrust as total impulse. Hence, the nominal performance of the motor decreases and the resulting performance reduction must be evaluated by designers. Erosion is maximum at the throat region, but it also occurs in the regions upstream and downstream of the throat section. Performance reduction can be determined by very expensive and time consuming full scale firing tests [5].

Moreover, the simulations of erosion as a function of ablation test material, hot flow gas temperature, and hot flow gas pressure are determined.

II. Materials and Methods

Normally, nozzles convert thermal energy of gas into kinetic energy. Nozzle performance is characterized by thrust generated from high pressure fluid [3].

The throat sections of nozzles typically regress significantly causing a reduction of the expansion area during burn. We determine the throat area and the throat radius changes by model equation calculation.

The materials investigated are refractory metal, graphite and reinforced-fiber material. In this case, nozzle inserted material is obtained from DTI. The graphite is inserted in to the throat nozzle and the metal is at divergent and convergent section of nozzle. These inserted materials from DTI [4] are conducted to determine the performance of rocket nozzle.

In several references and course materials used for rocket calculation, determining the actual thrust coefficient of the ideal thrust coefficient is simply multiplying by the nozzle divergence correction factor. The standard method [7] is used to correct the ideal thrust coefficient and the theoretical specific impulse to the actual thrust coefficient and the delivered specific impulse. The standard method that presents thrust coefficient ($C_{F,act}$) based on the measured thrust and the corrected chamber pressure is divided by the nozzle divergence correction factor (λ) and the calculated ideal thrust coefficient (C^o_F) to determine the experimentally measured CF efficiency factor (η_F).

$$F = C_{F,act} A_{th} p_c \quad (1)$$

$$C_F^0 = \sqrt{\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left[1-\left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right]} + \left(\frac{P_c-P_\infty}{P_c}\right)\varepsilon \quad (2)$$

$$\varepsilon = \frac{A_e}{A_{th}} \quad (3)$$

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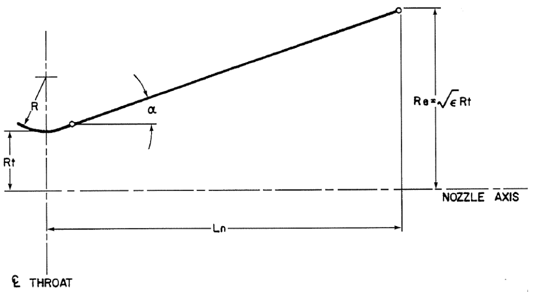


Fig. 1 Typical Design for a Conical Nozzle with a Rounded Throat

$$\lambda = \frac{1}{2}(1 + \cos \propto) \tag{4}$$

$$\eta_F = \frac{C_{F,act}}{\lambda C_F^o} \tag{5}$$

The designer can specify the chamber pressure profile by modifying the geometry of rocket DTI used in this study shown in Fig. 2. Fig. 2 presents the thrust and chamber pressure time for DTI. The nozzle drawing is divided in two parts, the main metal part of the nozzle, and the graphite throat inserted shown in Fig. 3. Several rocketeers use this type of design with a conical convergent section. A rounded throat and a conical divergent section with rounding of the corners between the sections are more efficient and most high performance solid rocket motors.

This procedure is used throughout the test program in order to determine the throat area and the throat radius change calculation by the flow equation. The flow equation method consists of the following instantaneous throat area for conical nozzle in (6) [6].

$$A_t(\theta) = \frac{\left(\eta_{c*,I} c^*_{th-eq}\right)\dot{W}_t(\theta)}{g C_d(\varphi P_{c,i})} \tag{6}$$

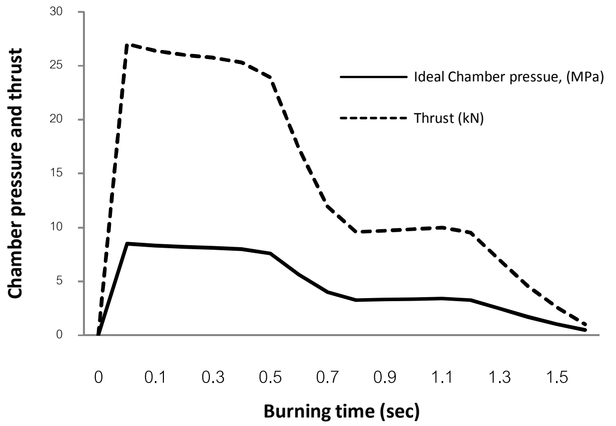
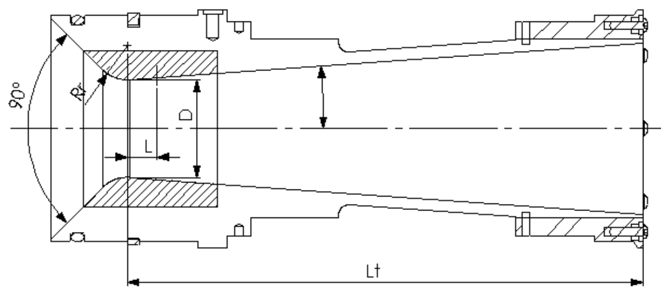


Fig. 2 The chamber pressure and thrust design for DTI rocket



p_c(design) = 11MPa	ε = 3.09	Nozzle CF correction: η_F = 0.99
HTPB/AP/AL	Straight-cut throat	c* = 1595
γ=1.2	Throat L/D = 0.1	Throat material: Graphite D1
Conical Divergent section	Nozzle performance	ablation rate : 0.1mm/s
Half angle = 4 deg	Divergence correction: λ = 0.9988	

Fig. 3 Nozzle parameters for DTI

Thrust and chamber pressure time for DTI rocket test motor presents in Fig. 4. The chamber pressure data is measured using pressure transducers at the head end of the motor. The thrust and chamber pressure time response during the burn is analyzed using the standard method and corrected the measured chamber pressure to the actual chamber pressure. This can determine the actual thrust coefficient and calculate the ideal thrust coefficient based on the actual chamber pressure and atmospheric pressure, and calculation of the measured CF efficiency factor (ηF).

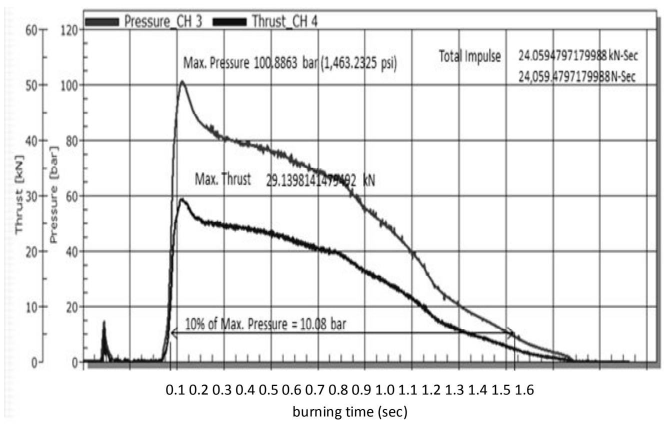


Fig. 4 Thrust and Chamber Pressure Time response of DTI rocket

The analysis for the DTI test motor is an example of manual calculation at selected points along with thrust and chamber pressure time response to determine representative values for the thrust coefficient and CF efficiency factor.

IV. RESULTS

Fig. 5 presents the results of erosion rate calculated by the flow equation and Fig. 6 shows the experimental data obtained from DTI rocket. The chamber pressure and thrust data is measured using chamber pressure instrument and load cell mounted in the forward bulkhead of the motor. The C_F efficiency factor from (5) for the thrust curve is plotted versus time show in the Fig. 7. The C_F efficiency factor (η_F) for DTI test motor nozzle is approximately 0.76, representing a 24% loss in thrust coefficient, which is a fairly value and indicates performance for the nozzle.

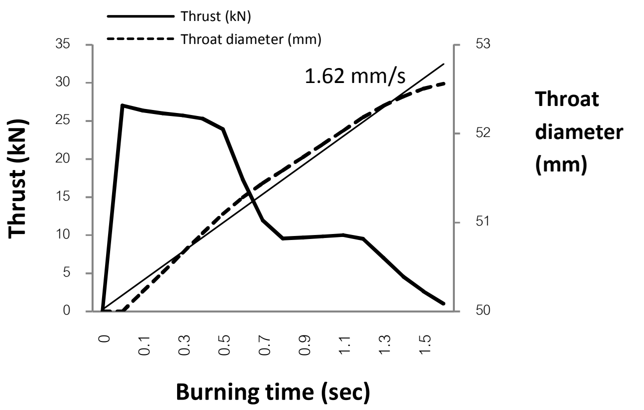


Fig. 5 Model thrust time and throat diameter for DTI rocket

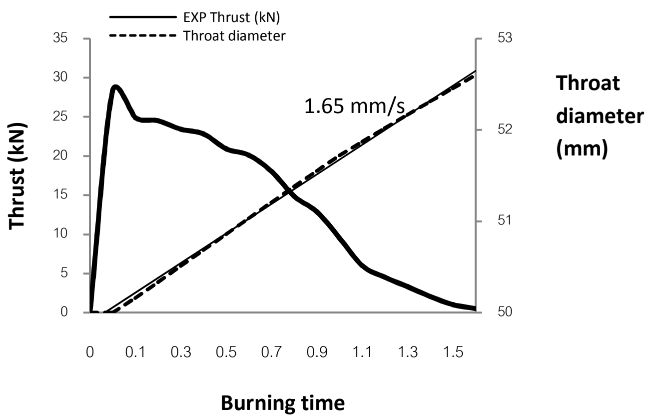


Fig. 6 Experiment thrust time and throat diameter for DTI rocket

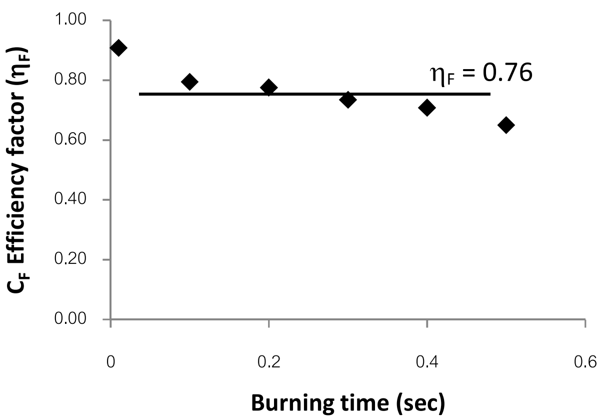


Fig. 7 C_F Efficiency Factor (η_F) versus time for first 0.5 seconds of thrust curve for DTI rocket

V. Conclusion

A model for classic equation to predict erosion of nozzle materials shows good agreement with experimental data. Modeling has been widely used to analyze nozzle erosion in solid propellant rocket motors. Erosion of nozzle throat is characterized by chamber pressure and burning time. Analysis of the erosion behavior for varying chamber pressure shows the known linear dependence of the throat erosion rate on the chamber pressure.

The thrust coefficient losses are significantly higher than most high power and experiment that rocketeers have performed thrust coefficient calculation assuming no losses beyond divergence losses (equivalent to a C_F efficiency factor (η_F) =1.0). The actual thrust coefficient loss is found approximately 10% (a CF efficiency factor (η_F) =0.90) for the round throat and the divergence correction factor design is $\alpha = 15^o$, for which λ = 0.983. However, conical nozzles are excessively long for large expansion ratios and suffer additional losses caused by flow separation. A bell-shaped nozzle is therefore superior because it promotes expansion while reducing length.

A mathematical model is developed to predict the erosion rate of nozzle exposed to a hot gas flow that affects the erosion rate significantly. However, the developed model has been able to predict the erosion rate as a function of the rocket performance.

Acknowledgment

This study is supported in part by Chemical Engineering and Metallurgy Laboratory, research and Development Department, The Defense Technology Institute (Public Organization), Bangkok, Thailand.

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