JOURNAL OF PROPULSION AND POWER
Vol. 23, No. 5, September–October 2007

Technical Notes

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Thrust Termination Dynamics of Solid Propellant Rocket Motors

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DOI: 10.2514/1.26576

I. Introduction

ACTIVE thrust termination or reversing of a separating motor are ways to facilitate the staging process and improve the performance of a multistage rocket [1–4]. This is done by opening a secondary nozzle located on the motor head and causing rapid depressurization of the motor chamber. During a rapid change in the chamber pressure the burning rate becomes a nonlinear function of pressure and its time rate of change. The strong dependence of the solid propellant burning rate on the chamber pressure results in a transient nonlinear behavior that may cause premature dynamic extinguishment of the motor. Solid propellants' transient burning and extinguishment during rapid pressure change have been the subject of a number of studies and several transient burning models have been developed [5–8]. Zeldovich has proposed a comprehensive model based on the unsteady rate of heat transfer to the propellant surface and the time rate of change of the temperature distribution in the solid propellant [6]. This model requires specification of many experimentally determined parameters. The transient burning rate model proposed by Von Elbe and McHale is easy to implement and requires instantaneous pressure and its time rate of change for the regression rate prediction [5]. References [1,2] studying motor transient behavior have used a control volume approach for the gas dynamic simulation of the motor's internal ballistics. However during the active thrust termination (or reversing) process there is a considerable pressure variation along the motor port and there is a rapid propagation of expansion waves, through the thrust termination nozzles. These expansion waves play an important role in the transient thrust behavior and a more comprehensive flow model should be used for the internal ballistics' simulation.

II. Numerical Solution Procedure

The conservative vector form [9] of the Euler equations with a quasi-one-dimensional flow assumption based on the problem geometry and a calorically perfect gas assumption for the working gas are used to formulate the problem. The burning rate of the solid propellant is modeled using the $\mathrm{d}p/\mathrm{d}t$ model proposed by Von Elbe and McHale [5]. This burning rate model is given as

$$r = r_o\left[1 + \psi\left(\frac{n\alpha_p}{Pr_o^2}\right)\frac{\mathrm{d}P}{\mathrm{d}t}\right] \qquad r_o = ap^n \tag{1}$$

Here r, and r_o are the transient and steady propellant burning rates, respectively. Discretization of the governing equations is done using a finite volume approach. The convective flux is then calculated using Roe's scheme [9]. Appropriate boundary conditions are applied at the nozzle exit according to the instantaneous flow regime. At the motor head, solid wall boundary conditions are applied before the opening of the secondary nozzle lid.

III. Analytical Thrust Reverse Estimate

Throat and exit diameter of the secondary nozzle should be selected according to the desired reverse thrust level. An approximate method to predict the nozzle geometry for creation of a specific amount of reverse thrust is developed using a control volume approach. The reversing process is usually applied near the end of the motor operation interval, at which time there are no erosive burning effects and we can assume uniform flow properties in the combustion chamber. The equations can be found in [10]. The pressure term in the thrust relation is neglected. It is assumed the propellant burning area is almost constant during the reversing process. Using the relation $T_f = -\beta T_i$ between the motor thrust just before initiation of thrust reversing (T_i) and its thrust after completion of reversing (T_f), and also assuming equal expansion ratio for main and secondary nozzles, the following simple relation is obtained:

$$\beta = \left(1 + \frac{A_{t2}}{A_{t1}}\right)^{\frac{1}{n-1}}\left(\frac{A_{t2}}{A_{t1}} - 1\right) \tag{2}$$

This shows that the thrust ratio (β) is a function of the nozzles' throat area ratio (A_{t2}/A_{t1}) and the pressure exponent (n) in the burning rate equation. This result is obtained under a steady state assumption and ignores any transient behavior. A drastic increase of the secondary nozzle throat area may cause a high pressure drop rate that would lead to a dynamic propellant extinguishment.

IV. Numerical Results and Discussion

The case of a secondary nozzle designed to produce thrust reversing was analyzed and the thrust ratio of the secondary nozzle to the main nozzle was determined and compared with the theoretical results. Next, the case of a secondary nozzle designed to produce thrust termination was considered. The motor under consideration has a cylindrically perforated grain with the grain length of 0.8 m, perforation diameter of 0.1 m, and web thickness of 0.02 m. The main nozzle throat diameter is 0.06 m and its exit diameter is 0.12. The secondary nozzle throat diameter is 0.08 m and its exit diameter is 0.16 m. The secondary nozzle lid is opened at the motor operating pressure of 90 bar. The gas constant for combustion gases is $318\ \mathrm{J/(kg \cdot K)}$, $\gamma = 1.21$, and the combustion gases flame temperature is 2800 K. The propellant physical and burning rate characteristics are given as $\rho_p = 1700\ \mathrm{kg/m^3}$, $a = 0.005\ \mathrm{m/s}$, $n = 0.4$, $\psi = 2$, and $\alpha_p = 1.294\mathrm{E}{-7}$.

The pressure and thrust time history for the thrust reversing case are shown by Figs. 1 and 2. Figure 1 indicates that there is a rapid depressurization after the secondary nozzle lid is removed. However

Received 16 July 2006; revision received 16 February 2007; accepted for publication 1 April 2007.

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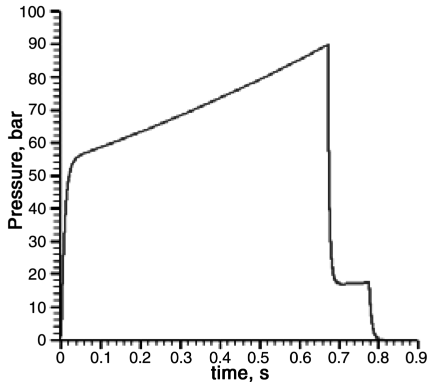

Fig. 1 Pressure history for reversing case.

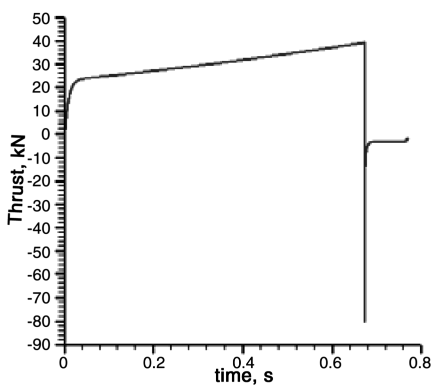

Fig. 2 Thrust history for reversing case.

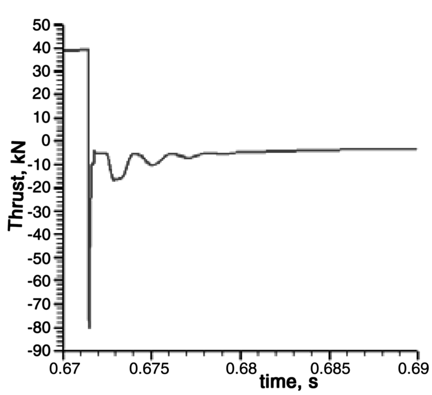

Fig. 3 Thrust history for reversing case.

there is no extinguishment and the motor achieves a new equilibrium at about 18 bar. The thrust time history shows that the motor thrust undergoes an abrupt and drastic drop from 39.2 kN to about −83 kN and recovers to about −4.86 kN. It is noted that $\beta = 0.124$. The analytical relation Eq. (2) predicts the value of 0.142 which is about 14% larger that the value obtained from the transient simulation of the motor. Figure 3 shows the detailed oscillatory behavior of the motor thrust. The oscillatory thrust behavior is due to the expansion wave that travels from the secondary nozzle exit back into the motor. At the instant of the removal of the secondary nozzle lid there is a large pressure difference between the motor exit pressure and the ambient pressure which creates a considerable reverse thrust. The knowledge of maximum level of instantaneous reverse thrust and the duration of the transient behavior of the motor during the thrust reversing process can be very valuable to the rocket designer. If the objective of the motor designer is to extinguish the propellant burning and terminate the forward thrust, the throat area of the secondary nozzle must be increased to a value that would create such a rapid depressurization that an automatic propellant extinction would follow. To study the effects of the nozzle geometry change on the dynamics of the motor thrust we examined three different secondary nozzle geometries for the same motor. Taking the geometry already discussed as the reference case, in the first case the secondary nozzle throat diameter was increased from 0.08 to 0.12 m and its exit diameter was increased from 0.16 to 0.24 m. The ratio of the exit to the throat areas of the main and secondary nozzles was kept constant and equal to the reference case. For the second case the secondary nozzle throat diameter was increased from 0.08 to 0.12 m but its exit diameter was kept constant to 0.16 m. For the third case the secondary nozzle throat diameter was increased to 0.13 m and its exit diameter was changed to 0.20 m. Table 1 summarizes the cases considered in this study.

Table 1 Results summary

	Ref. case	Case 1	Case 2	Case 3	Case 4
D_{e1}/D_{t1}	12/6	12/6	12/6	12/6	12/6
D_{e2}/D_{t2}	16/8	24/12	16/12	20/13	13/13
T_f, kN	−4.86	−6	−4.7	0	0
$T_{\max}$, kN	−83	−233	−87	−152	−52

It is observed that the motor does not thrust terminate for the first and the second case, but the third geometry results in thrust termination. The 50% increase of the nozzle throat diameter would increase the equilibrium reverse thrust to about 6 kN, which is a modest 20% increase. This is consistent with the analytical result obtained, which indicates that there is a maximum achievable level of equilibrium reverse thrust due to enlargement of the nozzle throat area. This conclusion is reconfirmed for the second case where the equilibrium reverse thrust and the peak transient reverse thrust are almost the same as the reference case in spite of a 50% increase of the throat diameter and the same exit area as in the reference case.

The significance of the nozzle exit area can be seen by comparison of the peak transient reverse thrust in the first case to that of the reference case. To avoid undesirable transient reverse thrust it is recommended to decrease the exit diameter or eliminate the diverging part of the secondary nozzle. It is most interesting to note that even though the equilibrium reverse thrust is zero in the third case, there is a large transient reverse thrust. The transient reverse thrust has reduced in the divergenceless nozzle case (case 4).

V. Conclusions

Analytical and numerical results indicate that there is a maximum achievable level of equilibrium reverse thrust due to enlargement of the secondary nozzle throat area. Further enlargement of the secondary nozzle throat area would result in thrust termination. However in a thrust termination process, even though the final equilibrium thrust is zero, there is a large transient reverse thrust. To minimize this undesirable transient reverse thrust, the diverging part of the secondary nozzle should be reduced or eliminated.

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