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IGNITION DELAY AND UNSTEADY TEMPERATURE EFFECTS ON IGNITION PEAK OF SOLID ROCKETS

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ABSTRACT

The coupled and the uncoupled effects of the ignition delay and the unsteady combustion gas temperature on ignition peak of high velocity transient motors are examined with the help of a two dimensional Navier-Stokes solver. It has been observed through the parametric studies that the altered variation of the ignition delay will alter the transient temperature growth history and the flame spread mechanism, which in turn alter the pressure spike of identical solid rockets. It has been inferred that the altered variation of both the chamber pressure-rise rate and the ignition temperature will alter the ignition delay and thereby the overall starting transient history of solid rockets. It has been concluded that the solid rocket motor designers should have a bearing on the pressure and pressurization rate prior to ignition for achieving repeatability of starting transient history in solid motors with the same propellant formulation and geometry.

NOMENCLATURE

C_h = Stanton number
P_c = chamber pressure
q_w = wall heat flux
T_c = combustion gas temperature
T_g = chamber gas temperature
T_{ig} = propellant ignition temperature
T_{pi} = initial propellant surface temperature
T_{ps} = propellant surface temperature
T_f = flame temperature
t = time
t_{ig} = ignition delay
U_∞ = free stream velocity
λ_{pr} = thermal conductivity of the propellant
ρ_∞ = density (free stream value)
α_{pr} = thermal diffusivity of the propellant

INTRODUCTION

Several models have been developed over the past six decades to characterize the starting transient of solid propellant rockets [1-6]. Even though these models have been helpful in interpreting many fundamental processes on starting transient, the understanding of motor to motor variation of ignition peak (pressure spike) of solid rockets essentially with non-uniform port is not fully understood. Though the previous temporal model [7, 8] has been able to demonstrate the motor to motor variation of ignition peak in low velocity transient (LVT) motors with uniform port to a certain extend, this model could not demonstrate the same successfully in high velocity transient (HVT) motors with non-uniform port due to the multi dimensionality of the flowfield. A motor with a high-throat to port area ratio ($A_t/A_p > 0.56$) and relatively high length to diameter ratio ($l/d = 10.0$), can be treated as a high velocity transient motor.

The motivation for the study emanates from the need to explain the phenomena or mechanism(s) responsible for the variation of the starting transient and the pressure spike in identical motors (i.e., same grain configuration, nozzle throat area and propellant formulation), essentially with non-uniform ports, during the static tests and the actual flights of solid rockets. In

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these motors inconsistent variations of ignition delay have been noticed [7]. Many of the earlier analyses on starting transient have been arrived at a solution after making an assumption of constant combustion gas temperature in a rocket chamber. This simplification is not sufficiently valid for transient period owing to the fact that the combustion gas will follow a definite temperature growth history from the ignition temperature to flame temperature. It has been reported through the previous connected papers [7, 8] that this temperature growth history depends upon the coupled effect of pressure and pressure-rise rate prior to ignition. This coupled effect is increasingly important in the case of solid rockets of same class but with different ignition delay because ignition delay is a function of pressure and pressure-rise rate prior to ignition (induction period) in solid rockets. Note that induction period will set the environment for ignition.

In this paper the coupled and the uncoupled effects of ignition delay and the unsteady temperature effects on HVT motors have been examined.

NUMERICAL METHOD OF SOLUTION

The unsteady temperature effects have been included in the previous papers, those dealing with combustion instability experiments [9, 10]. In this analysis a definite combustion temperature (T_c) growth history from ignition temperature (T_{ig}) to flame temperature (T_f) is approximated as [7, 8],

$$T_c = \frac{T_f}{1+\left(\frac{T_f - T_{ig}}{T_{ig}}\right) e^{-\theta(t-t_{ig})}} \qquad (1)$$

Where

$$\theta = \left(\frac{1}{P_c}\frac{dP_c}{dt}\right)_{induction} = \frac{1}{t_{ig}}\log\left[\frac{T_{ig}(T_f - T_{pi})}{T_{pi}(T_f - T_{ig})}\right]$$

This temperature growth history (Eq.1) is included in the two-dimensional Navier Stokes solver for predicting the starting transient of solid rockets. This code solves unsteady Reynolds-averaged thin-layer Navier-Stokes equations by an Implicit LU-Factorisation time integration method. It uses state of the art numerical methods like upwind differencing with Van Leer flux vector splitting which are necessary for getting good quality time accurate solutions for practical configurations. The system of governing differential equations with boundary conditions is solved using the finite volume method. The viscosity is determined from the Sutherland formula. A global time step is employed for getting time dependent solutions. The employed numerical scheme is essentially the same as used in our previous work [11, 12]. An algebraic grid generation technique is used to discretise the computational domain. In this analysis, an ideal igniter gas flow with constant velocity (= 700m/s) and specific heat is assumed. Initial propellant surface and non-propellant (nozzle) wall temperatures are prescribed. At the solid walls no-slip boundary condition is imposed.

The following ordinary differential equation is used for the determination of propellant surface temperature.

$$\frac{dT_{ps}}{dt} = \frac{4\alpha_{pr} q_w^2 (T_g - T_{ps})}{3\lambda_{pr}^2 (T_{ps} - T_{pi})(2T_g - T_{ps} - T_{pi})} \qquad (2)$$

The wall heat flux q_w is evaluated $\left(C_h = \frac{q_w}{\frac{1}{2}\rho_\infty U_\infty^3}\right)$ using the Navier-Stokes solver. Note that the related formula (Eq. 2) has been used by Peretz et al., [2] for calculating the propellant surface temperature using the integral method [13]. In their model instead of computing q_w the convective heat transfer coefficient h_c has been taken as an empirical relation.

The burn rate is computed based on the local pressure of the cell ($r = aP_c^n$). Normal velocity due to propellant burning is evaluated using the burn rate, propellant density and gas density ($V_n = r\rho_p/\rho_g$) Tangential velocities are specified as zero. Erosive burning is deliberately ignored for identifying the unsteady temperature effects on pressure spike and the starting transient history of solid rockets separately.

The ignition criterion, adopted in this analysis, is that a point on the propellant surface ignites when it attains the prescribed T_{ig} value. The model describes thus the process of flame spreading along the propellant surface, which starts at first ignition and ends when the entire surface is ignited. The solution is obtained by solving the Eq. (2) simultaneously with the governing equations for gas phase to yield the propellant surface temperature at any calculated time and position. Once the propellant surface reaches the ignition temperature Eq.1 will be enabled to describe the transient temperature growth history from the ignition temperature to the flame temperature. Note that many of the earlier analyses, variation from the ignition temperature to the flame temperature is considered as instantaneous. In the present parametric studies different temperature growth histories have been obtained by altering the propellant ignition temperature (T_{ig}). Once T_{ig} and T_f are fixed (when $t = t_{ig}$, $T_c = T_{ig}$ and when $t \rightarrow \infty$, $T_c = T_f$) the temperature growth history will depend upon the variation of θ (see Eq. 1).

In this study, different practical port configurations with two-dimensional nozzles have been considered. The baseline values are taken from Ref. (2) for AP composite propellant ($T_{ig} = 700^oK$, $\alpha_{pr} = 0.1875 \times 10^{-2}$ cm^2/s, $\lambda_{pr} = 0.9 \times 10^{-3}$ cal/cm-sec-^{o}K). In the present analysis altering the propellant ignition temperature has altered ignition delay.

RESULTS AND DISCUSSION

The ability of the code to make an accurate prediction of starting transient history is sensitive to the initial condition, combustion temperature growth history and the heat transfer from the gas to the propellant surface. It has been observed through the parametric studies that the altered ignition delay will alter the transient temperature growth history and thereby the flame spread mechanism, which in turn alter the pressure spike and the starting transient history of identical solid rockets.

As stated earlier, in this study different ignition delay has been obtained by altering the ignition temperature. Initially variations in the flame spread pattern and the starting transient histories with different ignition temperatures have been examined in SRMs with uniform port, without considering the combustion temperature growth history (i.e., sudden change of T_c from the ignition temperature to the flame temperature). It is observed that the altered ignition delay will alter the flame spread and the starting transient. It is inferred that when the ignition delay is small the spread rate will be high and the correspondingly pressure spike will be high.

Another attempt has been made to compare the coupled effect of the ignition delay and the unsteady temperature effects on pressure spike and the starting pressure transient of solid rocket motors with uniform port. The combustion temperature growth histories, corresponding to the different ignition temperatures, have been included in the model to examine these effects.

In all the cases, the different temperature growth histories at the different axial locations are observed. These differences are attributable to the difference in ignition time. It has been observed that flame spread and the starting transient histories are further altered by the different combustion temperature growth histories. The interesting flame spreading phenomena apparent in this study is that the relatively low spread rate in comparison with the previous case (i.e, without considering the temperature growth history). However, pressure spike is found relatively high. The differences in the flame spread pattern and the starting pressure transient with different temperature growth histories can be explained as follows. The altered variation of the combustion gas temperature history will alter the combustion gas density and the heat flux distribution (after the first ignition) along the axis, which in turn alter the normal velocity due to propellant burning and the flame spread pattern respectively. As a result pressure spike and the overall starting pressure transient of solid rocket motors will alter. Having proven this logical concept the next step is to examine these effects in a conventional solid rocket motor with non-uniform port.

A typical case of a solid rocket motor with divergent port is considered in this study to establish the present findings. In all the cases considered in this study it has been concluded that the altered variation of ignition temperature and the combustion temperature growth history will alter the flame spread, pressure spike and the overall starting pressure transient history of solid rocket motors.

The detailed parametric studies indicate that the motor to motor variations of pressure spike is mainly attributable to the altered pre-ignition ballistics. It is perceptible from the transient temperature model (Eq.1) that any coupled variation of pressure and pressurization rate prior to ignition will alter the combustion temperature growth history, which in turn alter the flame spread and the overall starting transient history. These theoretical studies are also demonstrating the importance of inclusion of ignition delay as an input variable for the accurate prediction of pressure spike of solid rocket motors.

It is conjectured from these studies that apart from the variation of the transient temperature growth history, altered variation of ignition delay will alter the flame spread mechanism by that the starting transient history. This is more pronounced in solid rocket motor with non-uniform port. Note that *a prior* knowledge of the effect of ignition delay on pressure spike will be helpful for the rocket motor designer to design the motor with minimum expensive testing.

As reported earlier [7] there are test results of identical motors with almost same pressure spike with different ignition delay. Note that this will not contradict the proposed theory owing to the fact that, the variation of the constant θ is negligible when the ignition delay is relatively large. It shows that at higher values of ignition delay almost same pressure spike occurs because the transient temperature growth history will not alter much at higher values of ignition delay due to the negligible variation of θ ($= f\ (1/t_{ig})$) It may be noted here that when the actual ignition delay is large slight error in predicting the ignition delay will not alter much the magnitude of the pressure spike prediction.

It has been concluded that the solid rocket motor designers should have a bearing on the pressure and pressurization rate prior to ignition for achieving repeatability of starting transient history in solid motors with the same propellant formulation and geometry.

The discussion on the basic cause of the altered variation of the ignition delay on identical solid rocket motors is beyond the scope of this paper.

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