Studies on Pre-Ignition Heat Flux Distribution in Solid Propellant Rockets with Non-Uniform Ports

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Abstract—Numerical studies have been carried out using a k-epsilon turbulence model to examining the igniter characteristics and the port geometry on flow separation, reattachment and pre-ignition propellant surface heat flux distribution in idealized solid propellant rocket motors with non-uniform ports. We observed through parametric analytical studies that with the same inflow conditions and propellant properties, heat flux histories and ignition time sequences are different for different port geometries. We also observed that the altered variations of the igniter characteristics will alter the heat flux distributions and the flame spread mechanism in solid rockets with identical port geometry. The numerical results presented in this paper with dummy motor test run made it possible to examining a number of factors, which are important in the ignition transient studies of solid rocket motors with port expansion configurations. We conjectured that more accurate description of the gas phase to the propellant surface heat transfer process is required for the better prediction and control of the starting transient of solid propellant rockets with non-uniform ports.

Keywords— flame spread, heat flux, ignition transient, solid rocket.

I. INTRODUCTION

A detailed picture of the internal flow during the starting transient/ignition transient of solid rocket motor is of interest for several reasons in addition to the motor performance itself. The prediction and control of the pressure and pressure-rise rate during the starting transient period of operation of solid rocket motors (SRMs) with non-uniform ports is of topical interest. For instance, dual-thrust motors (DTM) with a single chamber necessarily have non-uniform port geometry. The starting transient prediction of such motors is still an elusive problem. The starting transient comprises of a complex series of inter-related physical processes. An analysis of starting transient requires a detailed knowledge of its three different phases, viz., induction interval/ignition delay, flame spread and chamber filling period. Among the three different phases the second phase, the flame spreading process is one of the important physical processes in the initial portion of the thrust or the starting transient. Since the flame-spreading rate determines the instantaneous ignited fraction of the total surface area available for combustion, the gas generation rate or the chamber pressure are strongly dependent upon it. Therefore the accurate prediction of flame spread through a solid rocket motor with non-uniform port is very critical for its starting transient prediction.

Paul and Lovine [1] and several others [2]-[18] have demonstrated the role of flame spread rate in determining the starting transient of solid rocket motors. Indeed the rate of pressure rise can, to a certain extent, be controlled by altering the surface conditions governing the flame spread. In most cases the flame spreading observed over solid propellant is continuous. However, discontinuous flame spreading has also been observed in some laboratory experiments of Perez et al. [2] and Raghunandan et al., [3]. Perez et al., found that the flame-spreading rate increases with increasing igniter mass-flow rate and decreasing throat area. The discontinuous flame spreading has been attributed to enhanced radiation heat-transfer, delayed reaction in the gas phase, enhanced convective heat transfer, and local surface-roughness condition. Indeed the actual cause may be a combination of the four causes, as succinctly stated by Kumar and Kuo [4].

The mechanism of flame spread apart from being dependant on the thermal characteristics of the propellant, is influenced by the heat-transfer process, which in turn depends on the flow, ambient conditions, and propellant geometry. Normally, flame spread mechanism is assumed to be smooth or continuous. Through a series of theoretical and experimental studies Raghunandan and Sanal Kumar et al., [10] - [18] reported conclusively that in certain class of SRMs with non-uniform ports, secondary ignition can occur far downstream of the step. This is very likely to be within the recirculating flow region. The secondary ignition gives rise to two additional flame fronts, one of which spreads backward at a relatively lower velocity, presumably as a result of low reverse velocities present in the separation zone. This phenomenon is likely to play an important role in the starting transient of solid propellant rockets with non-uniform ports. The process of flame spread through such a port, which is an input to any model, remains obscure [18]. Note that predicting the exact location of the secondary ignition and modeling the flame spread is of notable technical interest to the aerospace industry. Literature review reveals that though several studies have been reported on flame spread over backward facing step there are no generalized model available in open literature for the prediction of flame spread through a solid rocket motor with non-uniform ports [18]. In this connected paper parametric analytical studies have been carried out to...
examining the flame spread pattern on dummy solid rocket motors with non-uniform ports.

II. NUMERICAL METHOD OF SOLUTION

Numerical simulations have been carried out with the help of a validated unsteady two-dimensional standard k-epsilon turbulence model using pressure based 1st order implicit scheme. The ability of the code to make an accurate prediction of internal flow field is sensitive to the expression for heat transfer from gas to the propellant surface. Therefore the mechanism of heat transmission to solid propellant grain is to be accurately modeled. Moreover, the effect of flow unsteadiness on the convective heat transfer is, in general, not well known at least under intensely transient conditions as encountered in the present case.

The heat equation for an unignited propellant grain at a fixed axial location is,

$$\frac{\partial T_{ps}}{\partial t} = \frac{\partial^2 T_{ps}}{\partial y^2}$$

with the following initial and boundary conditions:

$$T_{pr} (0, y) = T_{pi}$$
$$T_{pr} (t, \infty) = T_{pi}$$

$$\frac{\partial T_{pr} (t, \infty)}{\partial y} = \left[ \frac{h_{in} (t) [T_{ps} (t) - T_{ps}]}{\lambda_{pr}} \right]$$

where,

$$h_{in} (t) = \frac{q_{w}(t)}{T_{ig}(t) - T_{ps}(t)}$$

To determine the propellant surface temperature $T_{ps}$, Eq. 1 must be solved together with the governing equations for the gas phase [2]. Performing the differentiation and solving, the following ordinary differential equation for the propellant surface temperature is obtained.

Where $q_{w}$ can be evaluated from the code.

In this study numerical simulations of the flame-spread over dummy solid rocket motors with different ports have been carried out. A constant igniter gas flow is assumed as the inflow condition. The initial propellant surface temperature is prescribed. At the solid walls no-slip boundary condition is imposed and pressure is calculated from the momentum equations. The ignition criterion, however no mass addition invoked, 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 attains the prescribed ignition temperature. The solution is obtained by solving the Eq. (6) simultaneously with the governing equations for the gas phase to yield the propellant surface temperature at any calculated time and position. Using this model several test runs have been made with different port geometries and inflow conditions. Note that the mass addition is deliberately suppressed in this analysis even after the attainment of the ignition temperature at different propellant surface locations to examine the intrinsic flow physics during the pre-ignition chamber dynamics.

Commonly used Ammonium perchlorate (AP) composite propellant (ignition temperature, $T_{ig} = 700$ K, thermal diffusivity, $\alpha_{pr} = 0.1875 \times 10^{-2}$ cm$^2$/s, thermal conductivity, $\lambda_{pr} = 0.9 \times 10^{-3}$ cal/cm-s-°K$^{-1}$) is considered in this study.

III. RESULTS AND DISCUSSION

It is often the practice in ignition studies to use dummy (unignited) grains to obtain physical insight into the flame-spread pattern in SRMs a priori. Moreover dummy motor test results can be used for model validation. In this paper, parametric studies have been carried out on idealized dummy SRMs having sudden expansion of ports with sonic nozzle. For a solid rocket motor with sudden expansion or divergent port, it is important to have a knowledge of spatial and temporal variations of not only pressure, but also of gas temperature, surface heat flux and surface temperature before embarking on any explanation and remedy for the high pressure and pressure-rise rate. Towards meeting this objective in this paper parametric analytical studies have been carried out to examining the pre-ignition characteristics of the propellant surface and the corresponding environment.

FIGURE 1: IDEALIZED PHYSICAL MODEL OF A SOLID ROCKET MOTOR WITH NON-UNIFORM PORT

An idealized physical model of a typical SRM with non-uniform port is shown in Fig. 1. Parameters that are changed in this numerical study are the inlet velocity ($U_{in}$), step location/upstream port length ($X_s$), upstream port height ($H_p$), step height ($H_s$), and the down stream port length ($X_n$). Grid systems (see Fig.2) in the computational region are selected after a detailed grid refinement exercises (see Fig.3). The grids are clustered near the solid walls using suitable stretching functions. In this paper four different port geometries are considered for analysis, viz., Case - 1 ($H_p = 5$ mm, $H_s = 25$ mm, $X_s = 140$ mm, $X_n = 100$ mm, $V_i = 200$ m/s), Case - 2 ($H_p = 15$ mm, $H_s = 15$ mm, $X_s = 100$ mm, $X_n = 140$ mm), Case - 3 ($H_p = 15$ mm, $H_s = 15$ mm, $X_s = 140$ mm, $X_n = 100$ mm), Case - 4 ($H_p = 18$ mm, $H_s = 12$ mm, $X_s = 80$ mm, $X_n = 120$ mm).

FIGURE 2: TYPICAL GRID SYSTEMS IN THE COMPUTATIONAL DOMAIN

Figure 3 shows the numerical predictions of the propellant surface temperature with different grid systems in the computational domain, corresponding to Case-1, with a motor...
length of \( L \) (\( L = X_s + X_n \)), excluding the nozzle length.

Fig. 3 Numerical predictions of the propellant surface temperature with different grid systems in the computational domain (\( t = 0.1 \text{s} \)).

It is evident from Fig.3 that the grid refinement is very critical for the accurate prediction of the propellant surface heat flux distribution. After considering the computational time and the solution accuracy grid system of 200 x 50 is selected for further parametric analytical studies.

Figure 4 shows the propellant surface temperature distributions at various time (\( t = 0.1 \text{s} \) to \( t = 0.5 \text{s} \)) for the Case-1 with constant igniter velocity of 200 m/s. The ignition time is evaluated after fixing the propellant ignition temperature as 700 K. In this analysis mass addition is deliberately suppressed even after reaching the propellant ignition temperature, which corresponds to the situation of a dummy motor with only igniter gas flow. It is inferred from Fig. 3 that at the given inlet velocity (200 m/s) the possibility of formation of secondary ignition is evident. One can also discern from Fig.4 and Fig. 5 that when time advances, during the igniter action, the peak location of the propellant surface temperature will be altering due to the altered variations of the recirculation region and the reattachment point. In most of the cases the peak temperature zone is found shifting towards the step location. Figure 5 is giving the clear description about the formation of recirculation bubble, while time advances, in the form of velocity vectors. One can also detect the shifting of the reattachment points during the pre-ignition chamber pressurization period. Figure 6 shows the comparison of the propellant surface temperature distribution at different inflow conditions and with the same port geometry. It is evident from Fig.6 that the propellant surface will heat up swiftly in accordance with the increase in igniter jet velocity. As a result, and as seen in Figs. 4 & 5, the location of the reattachment point will be shifting towards the step location leading to an altered variation of the flame spread and starting transient history. Therefore, an error in predicting the igniter flow characteristics can lead to significant errors in the prediction of thrust transient of solid rocket motors with non-uniform port geometry. One can also distinguish that the time to reach the ignition temperature at the vertical face of the step is relatively high owing to the fact that heat flux will be less due to the flow recirculation. It is also very clear that one can anticipate to a certain extent the continuous ignition at the upstream port of the SRM, however in most of the cases discontinuous ignition sequence is observed at the downstream region due to the flow recirculation.

Fig. 5 Comparison of the velocity vectors at different time showing the formation of the recirculation bubble and the shifting of the reattachment points (Corresponding to Fig.4)

Fig.6 Comparison of the propellant surface temperature distribution at different inflow conditions with the same port geometry (Case-1)

Figure 7 shows the comparison of the various contours during the pre-ignition period of a solid rocket motor with non-uniform port. The flow features discerned in Fig.7 are sufficed to conclude that heat flux distribution will not be uniform along the propellant surface of such motors. Figures 8-11 also corroborate that the flame spread will not be
Continuous in SRMs with non-uniform port geometry at high igniter jet velocities. In all the cases the first reattachment point falls between 6.45 to 9.8 times the step height ($H_s$) and time advances the reattachment point and the recirculation bubble are found shifting towards the steps in accordance with the chamber dynamics. From these observations, and as discussed in the previous connected papers, one can therefore conclude that the secondary ignition occurs inside the initial recirculation bubble. It may be recalled that the length of the recirculation zone and the maximum heat flux location move towards the step as time progresses. The cases presented in this paper show that port geometry, propellant properties and inflow conditions are the important parameters for modeling the flame spread mechanism in an SRM essentially with non-uniform ports.

The difference in flame spread pattern with different $X_s$ can be explained with the help of boundary layer theory. Note that owing to the viscous friction, boundary layer will be formed on the walls (before the step location/transition region) and their thickness will increase in the downstream direction to the step location. Since the volume of flow must be the same for every section, the decrease in the rate of flow near the walls which is due to friction must be compensated by a corresponding increase near the axis. Thus the boundary layer growth occurs under the influence of an accelerated external flow. As a result at larger distances from the inlet section ($X_s$) velocity will be high at the transition location. When $X_s$ is small external acceleration of flow will considerably be small, due to relatively small boundary layer thickness, this prevents the separation of the flow. The separated flow characteristics such as size of the separation bubble, flow redevelopment, and heat transfer in the recirculation region are known to be dependent on Reynolds number upstream of the step and step height. During the flame-spreading process, the Reynolds number at the top of the step gradually increases as the main flame front advances, attaining a maximum as the flame covers the entire propellant surface before the step. The flame spread being a transient phenomenon, the heat-transfer coefficient gradually increases with time. Hence, ignition of a larger propellant surface area produces more hot gases, which increase the amount of heat transferred to the unburnt propellant surface by convection. Thus, the rate of spread at a given distance or time is increased by increasing the ignition area. As the flame spread rate increases, preheating increases, and the spread becomes accelerative [3].

Although the series of studies on flame spread mechanism proved conclusively the formation of secondary ignition, it is still difficult to independently separate the effects of geometry and the igniter characteristics on the formation of secondary ignition and multiple flame fronts in a general fashion. Therefore one should model the flame features of SRMs case by case for an accurate prediction of the starting transient.
Thrust oscillations during the starting transient period of uniform ports.

Non-uniform ports are presumably due to the joint effects of inflow conditions, propellant properties, and material properties at a given initial and boundary condition of SRMs. We inferred that when the upstream port is narrow the convective flux to the surface of the propellant will be enhanced, which in turn enhance the local Reynolds number. From these hot flow studies one can conclude that the early ignition, secondary ignition and the multiple flame fronts leading to the undesirable start-up transient often occurred in SRMs with non-uniform ports are presumably due to the joint effects of the inflow conditions, propellant properties, the geometry dependent driving forces and the chamber gas dynamics. We concluded that for a better prediction of the flame spread mechanism more accurate description of gas phase to surface heat transfer process is inevitable. The present numerical study is expected to aid the designer for conceiving the physical insight into problems associated with the prediction and the reduction of the pressure spike, pressurization rate and thrust oscillations during the starting transient period of operation of high-performance solid rocket motors with non-uniform ports.

IV. CONCLUDING REMARKS

We have observed through several comparisons that with the same inflow conditions and propellant properties heat flux histories and ignition time sequences are different for different port geometries. The detailed parametric studies carried out in this paper have revealed that the proposed model will be able to reasonably predict the conditions of the flow separation, reattachment and secondary ignition point, if any, at different environmental conditions, geometry and material properties at a given initial and boundary condition of SRMs. We inferred that when the upstream port is narrow the convective flux to the surface of the propellant will be enhanced, which in turn enhance the local Reynolds number. From these hot flow studies one can conclude that the early ignition, secondary ignition and the multiple flame fronts leading to the undesirable start-up transient often occurred in SRMs with non-uniform ports are presumably due to the joint effects of the inflow conditions, propellant properties, the geometry dependent driving forces and the chamber gas dynamics. We concluded that for a better prediction of the flame spread mechanism more accurate description of gas phase to surface heat transfer process is inevitable. The present numerical study is expected to aid the designer for conceiving the physical insight into problems associated with the prediction and the reduction of the pressure spike, pressurization rate and thrust oscillations during the starting transient period of operation of high-performance solid rocket motors with non-uniform ports.

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