Influence of Port Geometry on Thrust Transient of Solid Propellant Rockets at Liftoff

Karuppasamy Pandian. M, Krishna Raj. K, Sabarinath. K, Sandeep. G, and Sanal Kumar. V.R.

Abstract**—**Numerical studies have been carried out using a two dimensional code to examine the influence of pressure / thrust transient of solid propellant rockets at liftoff. This code solves unsteady Reynolds-averaged thin-layer Navier–Stokes equations by an implicit LU-factorization time-integration method. The results from the parametric study indicate that when the port is narrow there is a possibility of increase in pressure / thrust-rise rate due to relatively high flame spread rate. Parametric studies further reveal that flame spread rate can be altered by altering the propellant properties, igniter jet characteristics and nozzle closure burst pressure without altering the grain configuration and/or the mission demanding thrust transient. We observed that when the igniter turbulent intensity is relatively low the vehicle could liftoff early due to the early flow choking of the rocket nozzle. We concluded that the high pressurization-rate has structural implications at liftoff in addition to transient burning effect. Therefore prudent selection of the port geometry and the igniter, for meeting the mission requirements, within the given envelop are meaningful objectives for any designer for the smooth liftoff of solid propellant rockets.

Keywords**—**Igniter Characteristics, Solid Propellant Rocket, SRM Liftoff, Starting Thrust Transient.

I. Introduction

THE basic idea behind a solid rocket motor (SRM) is simple but its design is a complex technological problem requiring expertise in diverse sub disciplines to address all of the physics involved [1-19]. The primary concerns during the thrust transient are the overall time of the transient and the extent of the pressure rise (ignition peak). The overall time, that is, the delay in the development of full thrust must be kept within some limit and must be reproducible. Most of the sophisticated solid propellant rocket motors require greater accuracy in the prediction and control of the thrust and ignition transient i.e., more precise prediction of the pressure time history of the motor. This is also because a detailed knowledge of thrust during the ignition transient may be required for the critical guidance and control especially during the initial phase of motor operation. In certain design, the rate of pressure rise rate may adversely affect the steadiness and stability of burning, the viscoelastic response of the grain and inhibitors and the dynamic response of the hardware parts. An excessive pressurization rate (ignition shock) can cause a failure even when the pressure is below the design limit. This is particularly critical at low ambient temperatures. Often even more stringent requirements are placed on the pressurization rate by the need to protect delicate payloads and guidance systems. The quantitative prediction and the knowledge of the maximum thrust and the thrust-rise rate during the liftoff allow and justify the use of small margin of safety for the engine parts, thus result in high motor mass ratios, in addition to the control and guidance requirement of the vehicle.

The ability to predict and control the SRMs thrust transient enables the following important design and analysis objectives:- (i) prediction and control of over pressure and pressure-rise rate, (ii) predicting how a design modification will alter performance (propellant substitution, changes in throat and motor dimensions, propellant surface treatment). Keeping the above objectives in mind in this paper more attention has been focused on the prediction and control of pressure / thrust-rise rate at liftoff.

The flame-spreading process in SRMs is known to influence the initial part of the thrust or pressure transient. 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, igniter jet characteristics and propellant geometry. Normally, flame spread mechanism is assumed to be smooth or continuous. But this is not true in many practical rocket motors with non uniform port geometry. Note that the design optimization of high-performance rockets is more complex when the mission demands dual thrust. Dual-thrust motors (DTMs) with single chamber necessarily have non-uniform port geometry and its design optimization is a daunting task [1, 2].

II. Literature Review

Solid propellant rocket motor ignition is a transient phenomenon wherein a series of events occurs in a tightly timed sequence starting with application of an electrical impulse. Electrical energy supplied initiates a fire element, called squib, to generate a flash that builds up to a strong flame in the igniter. As the igniter begins to operate, the propellant grain begins to receive an ignition stimulus. The ignition stimulus may take many forms: convection from hot igniter gases, conduction from impinging hot condensed phase particles, radiation from hot gases and particles and/or chemical attack by hypergolic materials. If any mode or combination of modes supplies sufficient energy, any chemical system capable of exothermic reaction will reach a

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thermally unstable state, and subsequent chemical reaction will lead to ignition or explosion [2].

In most of the analyses, during an ignition transient simulation, the internal SRM flow field geometry is held fixed. Since grain deformation can significantly alter the internal geometry, and since there is a rapid increase in the pressure load on the propellant at this time, certain SRMs may exhibit strongly time-dependent internal flow field geometry due to the viscoelastic properties of propellant, during the ignition transient. Sanal Kumar, [3] one of the authors of this paper, reported that one possible cause of ignition peak in high velocity transient (HVT) motor is grain deformation. It may be important to note that in practical situations, if the structural response time of the propellant (time required to deform the grain) is higher than the starting / thrust transient time, then one can rule out the possibility of internal grain deformation being a cause for high transient pressure / thrust peak at liftoff.

The literature review reveals that most of the previous studies, whether theoretical or experimental, constant port area configurations are considered. While constant port area geometry is a good approximation to a large number of solid rockets, there are some which are quite distinct such as DTMs, ISRO SRMs, Titan and Space shuttle solid rocket motors. Sanal Kumar et al. [1-3, 8-11], carried out extensive studies on the internal ballistics of DTMs and highlighted the importance of the prediction and reduction of pressurization rate. However, in the previous work, the authors mainly focused on the cause and effects of transient pressure peak during the starting transient period of operation. In this paper we are focusing on the importance of prediction and control of pressure-rise / thrust-rise rate at liftoff.

Ikawa and Laspesa [4] reported that, during the first launching of the space shuttle from the eastern test range, the launch vehicle experienced the propagations of a strongly impulsive compression wave. This wave was induced by the SRM ignition and was emanating from the large SRM duct openings. The analysis further showed that the compression wave created by ignition of the main grain was the cause of the ignition overpressure on the launch pad [5]. Alestra et al. [6] reported that the ARIENE 5 launcher experienced an overpressure load during the liftoff phase. The overpressure is composed of the ignition overpressure, which emanates from the launch pad, and the duct overpressure, which emanates from the launch ducts. It was reported that, in the Indian industry, a certain class of SRMs with divergent ports experienced ignition overpressure and a pressure-rise rate [1].

The Challenger Accident created a serious concern to the propulsion community to pin point all aspects of problems at liftoff. The photographic data of Challenger revealed that the first indication of a problem occurred at 0.678 seconds into the flight, when a strong puff of gray smoke spurted from the vicinity of the aft field joint on the right solid rocket booster. The vaporized material streaming from the joint indicated the absence of complete sealing action within the joint. Quickly, observers saw eight distinctive puffs of increasingly blacker smoke. At just under a minute into the flight, the first flickering flame would be detected on image-enhanced film on the right solid rocket booster, and one film frame later, the flame was visible without image enhancement. It rapidly grew into a continuous, well-defined plume that was directed onto the surface of the massive external tank, which held the fuel for the main engines. At 64 seconds came the first visual indication that the swirling flames from the right solid rocket booster had breached the external tank. Within 45 milliseconds of the breach, a bright, sustained glow developed on the black-tiled underside of the Challenger between it and the external tank. Less than 10 seconds later, at an altitude of 46,000 feet (14,325 meters), the Challenger was totally engulfed in an explosive burn. At 73 seconds after liftoff, it exploded.

The presidential commission investigated the Challenger accident and released its report and findings on the cause of the accident on June 9, 1986 [20]. The consensus of the commission and participating investigative agencies was that the loss of Challenger was caused by a failure in the joint between the two lower segments of the right solid rocket motor. The specific failure was the destruction of the O-ring seals that were intended to prevent hot gases from leaking through the joint during the propellant burn of the rocket motor. The evidence assembled by the commission indicated that no other element of the Space Shuttle system contributed to this failure. In addition to this primary cause, the commission identified a contributing cause of the accident relating to the decision to launch. It is reported that neither concerns regarding the low temperature and its effect on the O-ring nor the ice that formed on the launch pad had been communicated adequately to senior management or been given sufficient weight by those who made the decision to launch. These are succinctly reported in the commission report [20].

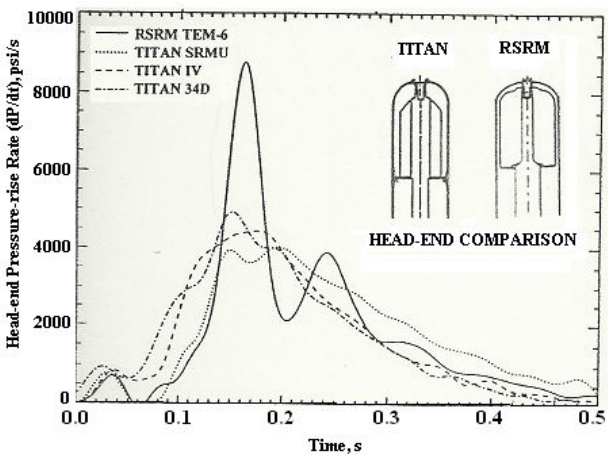

Fig. 1 Comparison of head-end pressure-rise rates of Space Shuttle's redesigned solid rocket motors and various Titan solid rocket motors. (Adopted from Ref. 5)

It has been reported in the open literature that Space shuttle's redesigned solid rocket motor (RSRM) head-end pressure-rise rate is almost twice as high as any of the Titan solid propellant rocket motors (see Fig. 1). Literature review further reveals that the results from the existing models were inconclusive as to the cause of this higher-pressure rise rate encountered on the Space Shuttle's RSRM [5]. During the development phase, at the Indian industry, many solid propellant rocket motors with non-uniform ports are known to have experienced abnormal high ignition peak often in the order of five times the steady state value. Various measures were taken to eliminate the ignition peak, but none of the conventional remedies seemed to help. This review leads to say that the influence of the port geometry on thrust transient of solid propellant rockets at liftoff is of notable topical interest. Therefore, in this paper parametric analytical studies have been carried out in SRMs with uniform and non-uniform port geometries for examining the intrinsic flow physics at liftoff.

III. Numerical Method of Solution

A detailed numerical simulation of the flame spread and corresponding flow field in a sudden expansion combustor has been carried out with the help of a two-dimensional code. This code solves unsteady Reynolds-averaged thin-layer Navier–Stokes equations by an implicit LU-factorization 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.

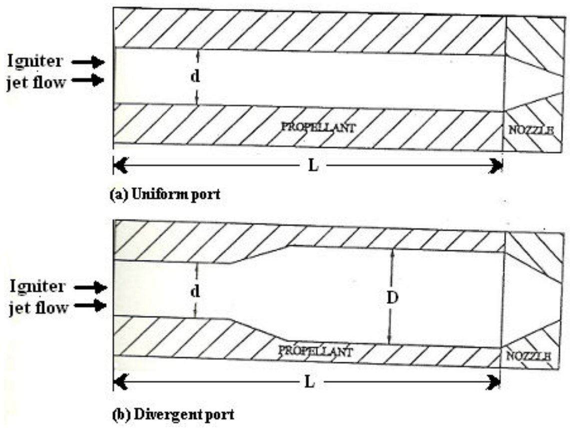

Fig. 2 (a-b) Idealized physical models of SRMs

The idealized physical models are shown in Fig. 2(a-b). These models are good representations of SRMs with uniform and non uniform port geometries respectively. The geometric variable like L/d, A_t/A_{pn} and A_b/A_t are selected based on typical SRMs data. Propellant properties are taken from a ballistic evaluation motor. The system of governing differential equations with boundary conditions is solved using the finite volume method. The viscosity is determined from the Sutherland formula. An algebraic grid generation technique is employed to discretize the computational domain. A typical grid system (baseline) in the computational region is selected after the detailed grid refinement exercises (see Fig. 3). The grids are clustered near the solid walls using suitable stretching functions. The motor parameters and propellant properties including the burning-rate constants are known *a priori*. Especially for internal transient problems boundary conditions are very crucial. Treatment of boundary conditions depends up on the problem to be solved. In this analysis initial

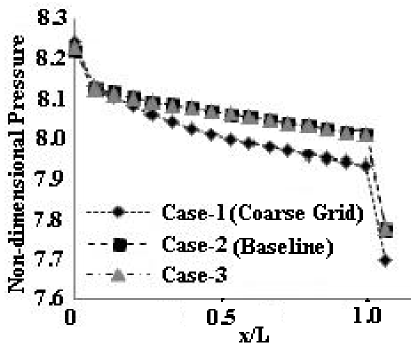

Fig. 3 Axial pressure variations in a dummy SRM with uniform port at three different grid systems

propellant surface temperature is prescribed, and solid-wall (non propellant) temperature is specified as the propellant auto ignition temperature. At the solid walls a no-slip boundary condition is imposed. The propellant surface temperature is determined using Zien's equation [21]. Burn rate ($r = aP^n$) is computed based on the local pressure of the cell. For the initial state of low velocities and low pressure rise, one can ignore erosive and transient burn rates. Using the burn rate, propellant density and gas density, the normal velocity caused by propellant burning is evaluated. The tangential velocities are specified as zero.

IV. Results and Discussion

Fig. 4 shows the variation of the flame-spread mechanism in an SRM with uniform port for the reference case. A typical igniter jet velocity (400 m/s) has been chosen for the parametric study, which corresponds to a Mach number 0.44, for treating it as a High Velocity Transient (HVT) motor. In all the test cases the first ignition takes place within a fraction of millisecond time at the head end. This appears reasonable considering high temperature (2300 K) and velocity (> 400 m/s) of the igniter gases. After the first element has been ignited, its contribution to the heat transfer to all other surface elements is taken into account by the code.

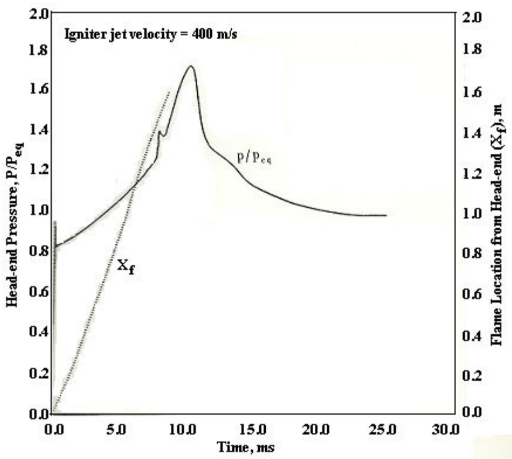

Fig. 4 Numerical prediction of the location of flame front and head end pressure transient in an SRM with uniform port

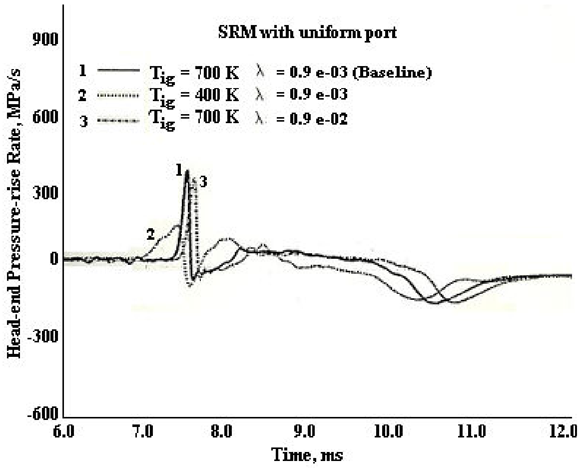

Fig. 5 Demonstrating the effect of altered variations of propellant properties on head-end pressure-rise rate and showing that $(dP/dt)_{max}$ is nearly at the end of flame spreading period in an SRM with uniform port (Corresponding to Fig. 4)

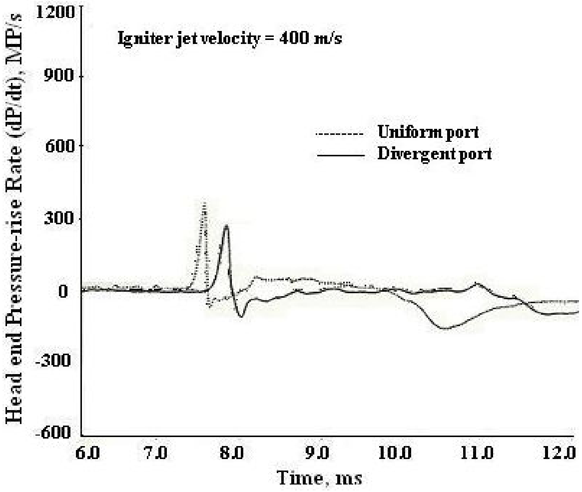

Fig. 7 Comparison of the head-end pressure-rise rate of SRMs with divergent and uniform port cases showing that in all the cases $(dP/dt)_{max}$ is nearly at the end of flame spreading period (Corresponding to Fig. 6)

Following a small pressure peak caused by the prescribed igniter flow, the first ignition and further continuous flame spread towards the aft-end of the rocket motor take place. The chamber pressure begins to rise due to mass addition. Fig. 4 also shows the starting pressure transient of the motor. It can be seen from this figure that during the initial period of flame spread, chamber pressure builds up gradually but nearly at the end of flame spread a sudden increase in chamber pressure rise is observed, ending the second phase of starting transient with a small and sharp pressure spike. Again chamber pressure increases gradually up to the ignition peak before declining to the equilibrium condition. Fig. 5 is demonstrating the effect of altered variation of propellant properties on pressure-rise rate on a magnified time scale, which shows that $(dP/dt)_{max}$ is almost at the end of flame spreading period in an SRM with uniform port. It can also be seen from Fig. 5 that while decreasing ignition temperature from 700 K to 400 K $(dP/dt)_{max}$ is decreased by 50 **%** and relatively high increase of thermal conductivity (λ_{pr} = 0.9 x 10-2 cal/cm-s K) causes a decrease in $(dP/dt)_{max}$ value by 12 %. From these parametric studies it can be concluded that flame spread rate is having a bearing on SRMs pressurization-rate (dP/dt) and thereby the thrust-rise rate at liftoff.

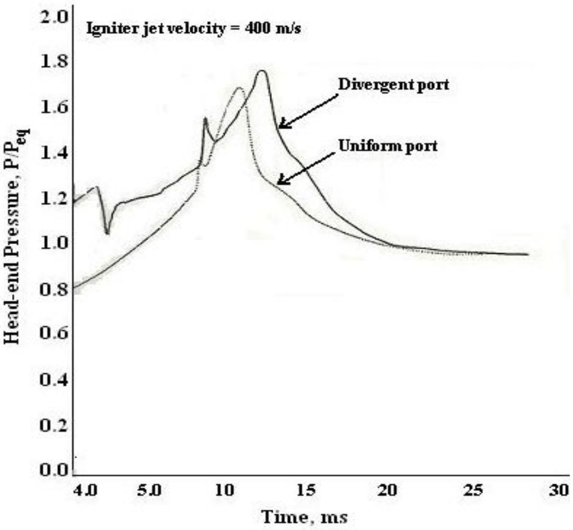

Fig. 6 Comparison of pressure peak and overall pressure transient history at the head-end of SRMs with two different port geometries but with same inflow condition, propellant properties, A_t/A_{pn} and L/d ratios

The uniform port case shown in Fig. 4 is considered as the base for comparing the non-uniform port cases. Inflow conditions, propellant properties, throat-to-port area ratio (for the divergent case the port area at the nozzle end is considered, A_{pn}) and L/d ratio are same in both the cases. In relation to uniform port cases, this case with higher K (burning surface area to throat area ratio, $A_b/A_t \sim L/d$ at constant A_p/A_t) would lead to lower equilibrium chamber pressure, but the discussion below will be based on the ratio (P/P_{eq}). Note that in both cases initial spread rate found almost constant. The effect of mass addition is more pronounced in narrower ports (as $A_p \sim d^2$ and hence $\Delta U \sim L/d$) and hence uniform port cases exhibits the higher flame spread rate. Among the two, a case with divergent port took more time for flame spread. This is anticipated in a divergent case as explained above, but in addition flow separation and recirculation persist. Fig. 6 shows the comparison of the starting pressure transient history of the above two cases, viz., uniform and divergent port cases. Fig. 7 shows the comparison of the corresponding head-end pressure-rise rate. With the same propellant properties and inlet velocity, significant variations in ignition peak and pressurization rate are observed in these motors. Although magnitude of the ignition peak is found high in the case of uniform port, but variation from the steady state value is observed relatively low. Ignition peak is observed 1.8 times

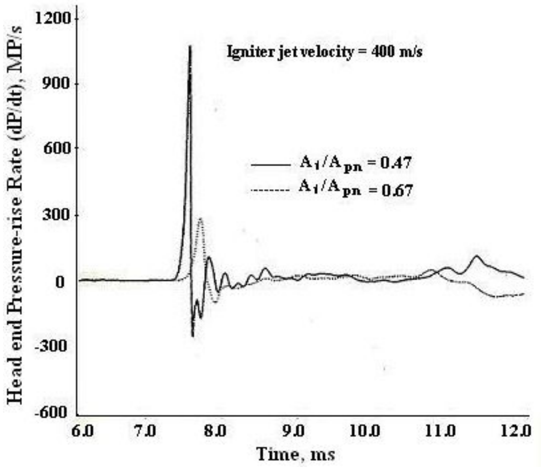

Fig. 8 Comparison of the head-end pressure-rise rate of SRMs with divergent port geometry and with two different throat-to port area ratios (At/A_{pn}) and showing that in all the cases $(dP/dt)_{max}$ is nearly at the end of flame spreading period

the equilibrium pressure for the case with divergent port. Under similar condition ignition peak observed for uniform port is 1.7 times the corresponding steady state pressure values. Again, at the aforesaid conditions, high pressure-rise rate at the head-end is observed in uniform port case than the non-uniform (divergent) port case. The results from the parametric study indicate that when the port is narrow there is a possibility of increase in pressure rise rate due to relatively high spread rate. Hence it appears that high pressure-rise rate at the head end of practical port configurations correlate with flame spread rate, as a result of the SRMs port configuration. The results on the flame spread rate vis-à-vis $(dP/dt)_{max}$ should be viewed in the right perspective. Here the pressure-rise rate (dP/dt) discussion has come in because of the observations made in Fig.1 with regard to RSRM and Titan configurations. This factor $(dP/dt)_{max}$ has structural implications at liftoff in addition to the possibility of giving rising to transient burn rate effects, which however is not considered in the present model. It may be noted that trend of dP/dt rather than $d(P/P_{eq})/dt$ that causes the effect stated above.

Fig. 8 compares head-end pressure-rise rate of SRMs with divergent port geometry and with two different throat-to port area ratios (A_t/A_{pn}) and showing that in all the cases $(dP/dt)_{max}$ is nearly at the end of flame spreading period. We inferred that $(dP/dt)_{max}$ is relatively high (around 3.5 times) for the case with low throat-to-port area ratio (At/A_{pn}), which had shown low ignition peak pressure (P/P_{eq}). In another attempt using k-omega turbulence model it has been found out through the parametric analytical studies that when the igniter turbulent intensity is relatively low the vehicle could liftoff early due to the early flow choking of the rocket nozzle owing to the fact that the internal flow will get accelerated due to the relatively high boundary layer thickness.

V. Concluding Remarks

Successful theoretical studies have been carried out using a two dimensional Navier Stokes solver to explain the effect of port geometry and the flame spread rate on thrust transient of SRMs at liftoff. It has been observed through parametric studies that *a prior* knowledge of the igniter jet characteristics, propellant properties, nozzle closure burst pressure, is crucial for the prediction of the flame spread and the thrust transient. We concluded that in all SRMs high thrust-rise rate will occur nearly at the end of the flame spread during the starting transient period of operation. A minor error in predicting the flame spread rate can significantly alter the chamber dynamics, ignition chain, nozzle closure burst pressure and burst time, prediction leading to an unfavorable liftoff. We concluded that for a smooth liftoff at a desired launch window *a prior* knowledge about the cause and effects of fluid-structural interaction must also be known with respect to the chamber flow physics, igniter jet characteristics, combustion chemistry, viscoelastic response of the hardware, nozzle closure, launch pad characteristics and atmospheric properties. This study leads to say that the prudent selection of the port geometry and the igniter, for meeting the mission requirements, within the given envelop are meaningful objectives for any designer for the smooth liftoff of SRMs.

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