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Studies on Pre-Ignition Chamber Dynamics of Solid Rockets with Different Port Geometries

S. Vivek, Sharad Sharan, R. Arvind, D. V. Praveen, J. Vigneshwar, S. Ajith, V. R. Sanal Kumar

Abstract**—**In this paper numerical studies have been carried out to examine the pre-ignition flow features of high-performance solid propellant rocket motors with two different port geometries but with same propellant loading density. Numerical computations have been carried out using a validated 3D, unsteady, 2nd-order implicit, SST k-ω turbulence model. In the numerical study, a fully implicit finite volume scheme of the compressible, Reynolds-Averaged, Navier-Stokes equations is employed. We have observed from the numerical results that in solid rocket motors with highly loaded propellants having divergent port geometry the hot igniter gases can create pre-ignition pressure oscillations leading to thrust oscillations due to the flow unsteadiness and recirculation. We have also observed that the igniter temperature fluctuations are diminished rapidly thereby reaching the steady state value faster in the case of solid propellant rocket motors with convergent port than the divergent port irrespective of the igniter total pressure. We have concluded that the prudent selection of the port geometry, without altering the propellant loading density, for damping the total temperature fluctuations within the motor is a meaningful objective for the suppression and control of instability and/or thrust oscillations often observed in solid propellant rocket motors with non-uniform port geometry.

Keywords**—**Pre-Ignition chamber dynamics, starting transient, solid rockets, thrust oscillations in SRMs, ignition transient.

I. INTRODUCTION

ALTHOUGH technology in the solid propellant rocket field has advanced significantly over the last several decades, there are still many unresolved problems. In an attempt to resolve some of these problems and in the light of new findings, a substantial revision of the existing ideas may be necessary [1]-[17]. One such problem of urgency is the starting transient / ignition transient prediction prompted by the recent experiences with dual-thrust solid propellant rocket motors [1]. Note that dual-thrust motors (DTMs) with single chamber necessarily have non-uniform port geometry. In such configurations, it is very likely that the flow separation would take place at transition locations. The process of flame-spread through such a port, which is an input to any ignition transient model remains obscure. It may be anticipated that flow separation and reattachment would cause secondary ignition at a downstream point followed by backward spread of the flame in addition to the normal forward spreading. This phenomenon is likely to play an important role in the ignition transient of solid propellant rockets with non-uniform ports. Raghunandan B. N. et al [2], [3] and Sanalkumar V. R., [5]-[8] reported that the implication of the secondary ignition can be quite serious for a practical rocket. One secondary ignition would result in two additional flame fronts, one spreading forward and other backward. This effect will be further accentuated in the case of star grain downstream of sudden expansion where the star points generate multiple flame fronts. The effective time required for the complete burning surface area to be ignited comes down drastically giving rise to a high pressurization rate (dp/dt) in the second phase of ignition transient. This in effect could lead to a hard start of the rocket motor. Therefore optimization of SRM port geometry is inevitable for a successful mission.

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. If any mode or combination of modes supplies sufficient energy, any chemical system capable of exothermic reaction will reach a thermally unstable state, and subsequent chemical reaction will lead to ignition or explosion. Note that the art of igniting practical rocket motors as it has evolved over the years may have been meeting the needs of this technology, essentially in the prediction of thrust transient of solid rocket motors (SRMs), but the underlying physical processes remain undefined and poorly understood particularly in the case of high-performance solid propellant rocket motors with non-uniform port geometry. This research topic, although interesting in its own right, has been motivated by several practical problems. The developments of large and more sophisticated ISRO solid propellant rocket motors, Titan and Space shuttle's solid rocket motors of NASA have emphasized the deficiencies on thrust transient prediction [1]. These rocket motors do not lend themselves to the costly trial and error development techniques and the radical differences in the size and design of these rocket motors defy extrapolation of the empirical knowledge gained in the development of previous, more conventional rocket motors.

Literature review reveals that many studies have been carried out on modeling of starting thrust oscillations of high-performance solid propellant rocket motors but the simulation of starting transient flow features of SRMs with non-uniform port configurations are still incomplete [1]-[17]. Sanal Kumar

Vivek S., Sharad Sharan, Arvind R., Praveen D. V. and Vigneshwar J. are Undergraduate Students, Department of Aeronautical Engineering, Kumaraguru College of Technology, Anna University Chennai, Coimbatore–642 049, Tamil Nadu, India, (Phone: +91-8056344999; email: sv95.spry@gmail.com; sn.sharad@gmail.com; arvindramkumar1996@gmail.com; dvp.eee735@gmail.com; vigneshwarjayakumar@gmail.com).

Ajith. S is with the Aeronautical Engineering Department, Kumaraguru College of Technology, Coimbatore – 642 049, Tamil Nadu, India (e-mail: ajith.aj817@gmail.com).

V. R. Sanal Kumar is with the Aeronautical Engineering Department, Kumaraguru College of Technology, Coimbatore – 641 049, affiliated to Anna University, Tamil Nadu, India (Phone: +91-8754200501/9388679565; e-mail: vr_sanalkumar@yahoo.co.in).

V. R. et al. [1] reported the phenomena of internal flow choking in dual-thrust motors (DTMs) during the starting transient phase with different physical origin, which has received considerable attention in the scientific community. The motivation for the present study emanates from the desire to demonstrate the variations of starting transient flow features of high-performance solid propellant rocket motors with non-uniform port geometry due to its difference in grain orientation (i.e., horizontal and flip horizontal position). In this paper SRM with two different port geometries are selected, one with narrow head-end port and the other with wide head-end port but with same propellant loading density and grain configuration, for internal flow simulation.

This paper addresses the preliminary design challenges associated with development of high-performance solid propellant rocket motors because of its large size, high length to diameter ratio, and complex geometry demanding thrust-time trace shape requirements. The SRMs with highly loaded propellants are selected for parametric analytical studies to examine the starting thrust oscillations due to high temperature igniter mass flow from both narrow and wide upstream port geometry. In this paper an attempt has been made to predict the pre-ignition chamber dynamics of SRMs with non-uniform ports to examine the starting thrust oscillations during the early phase of liftoff.

II. NUMERICAL METHOD OF SOLUTION

Numerical computations have been carried out using a validated 3D, unsteady, 2nd-order implicit, SST k-ω turbulence model. In the numerical study, a fully implicit finite volume scheme of the compressible, Reynolds-Averaged, Navier-Stokes equations is employed.

The SST *k*–ω model has a similar form to the standard *k*–ω model:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho \kappa u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\Gamma_k\frac{\partial k}{\partial x_j}\right]+\tilde{G}_k-Y_k+S_k \tag{1}$$

$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho w u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\Gamma_w\frac{\partial w}{\partial x_j}\right]+\tilde{G}_w-Y_w+S_w \tag{2}$$

In these equations, $\tilde{G}_k$ represents the generation of turbulence kinetic energy due to mean velocity gradients, calculated from G_k and is given by,

$$\tilde{G}_k=\min(G_k,10\rho\beta^* k\omega) \tag{3}$$

G_ω represents the generation of ω, calculated as described for the standard k-ω and is given by,

$$G_w=\alpha\frac{\omega}{k}G_k \tag{4}$$

Γ_k and Γ_ω represent the effective diffusivity of k and ω, respectively, which are calculated as described below. Y_k and Y_ω represent the dissipation of k and ω due to turbulence. D_ω represents the cross-diffusion term, calculated as described below. S_k and S_ω are user-defined source terms.

The model uses a control volume based technique to convert the governing equations to algebraic equations. The viscosity is computed based on Sutherland formula. The grid system in the computational domain is selected after a detailed grid refinement exercises. The grids are clustered near the solid walls using suitable stretching functions. The geometric variables and material properties are known *a priori*. Initial wall temperature, inlet total pressure and temperature are specified. At the solid walls a no slip boundary condition is imposed. In all the cases CFL was selected as 1.0. Fig. 1 shows the grid system in the computational domain of the SRM with both convergent and divergent port geometries.

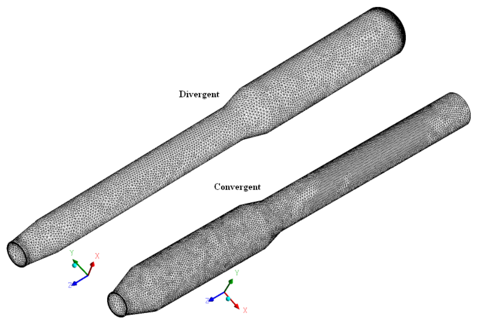


Fig. 1 Grid system in the computational domain of SRMs with convergent and divergent port geometries

III. RESULTS AND DISCUSSION

In most of the starting transient models SRMs with uniform port geometry is 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, PSLV, Titan and Space shuttle solid rocket motors. Therefore, in this paper comparative study of SRMs with both convergent and divergent port geometries have been carried out without altering the inflow conditions and propellant loading density. Figs. 2-12 are demonstrating the flow features during the pre-ignition chamber dynamics of SRMs with convergent and divergent port geometries. It is evident from these figures that SRM with convergent port reached steady state condition early than SRM with divergent port owing to the fact that temperature fluctuations are more in SRMs with divergent port due to flow reattachment and formation of recirculation bubbles, as seen in 2D analyses too [16]. Note that the total temperature has to be readjusted with the corresponding velocity and the pressure values within the motor, which has altered due to the sudden variation of the port geometry. Therefore, SRM port geometry is an important input to any thrust transient model.

We have conjectured from these studies that the SRM designer can ascertain that there is a possibility of more thrust oscillations in motors with divergent port than with convergent port geometry. Although such oscillations do not peril the launch operation, they induce some penalties to the overall performance. Hence, in the mission point of view, to avoid the unpredictable performance variation one has to recast the intrinsic shape of the grain geometry at the transition region. The suppression or the control of such oscillations is then a meaningful objective for any solid rocket motor designer. We also conjectured that in SRMs with highly loaded propellants with divergent port geometry the mass flux of the hot gases moving past the burning surface is large. Under these conditions, the convective flux to the surface of the propellant will be enhanced, which in turn enhance the local Reynolds number. From these studies one can deduce that the thrust/pressure oscillations, pressure-rise rate and the unexpected peak pressure often observed in solid rockets with non-uniform ports are presumably contributed due to the joint effects of the geometry dependent driving forces, transient burning and the chamber dynamics.

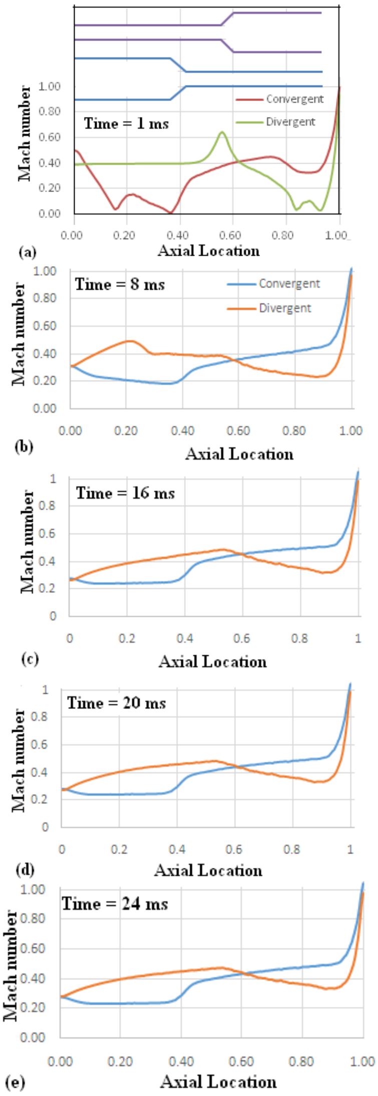


Fig. 2 (a)-(e) Comparing the axial Mach number variations at different intervals of time for SRMs with both convergent and divergent port configurations

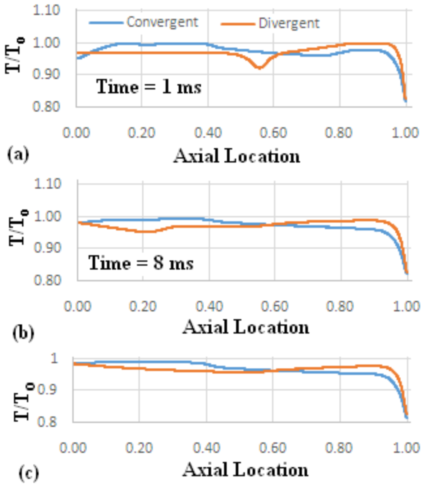


Fig. 3 (a)-(c) Comparing the axial Temperature variations at different intervals of time for SRMs with both convergent and divergent port configurations

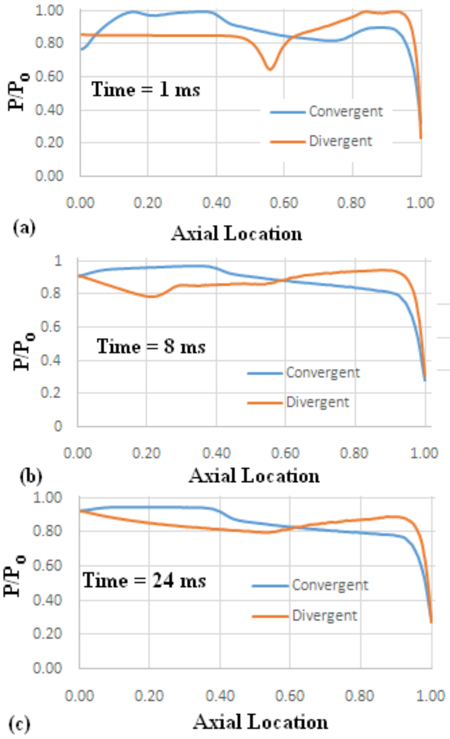


Fig. 4 (a)-(c) Comparing the axial Pressure variations at different intervals of time for SRMs with both convergent and divergent port configurations

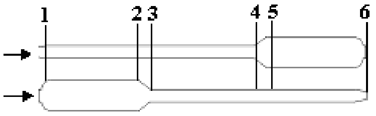
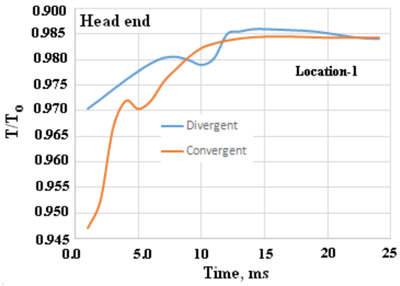
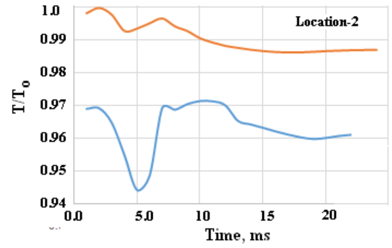


Fig. 5 Physical models showing the axial locations



(a)



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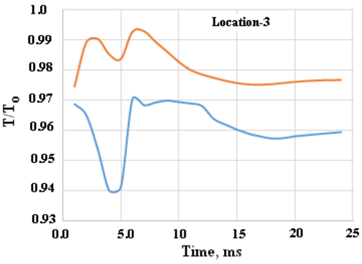

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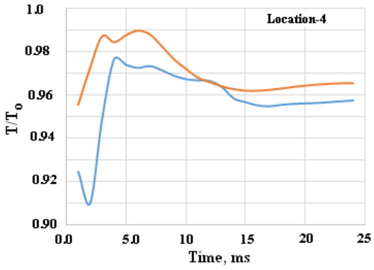

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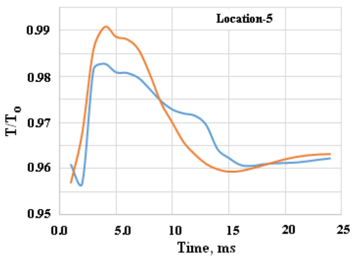

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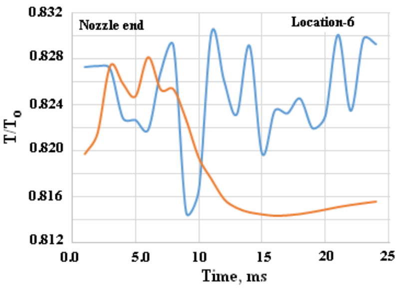
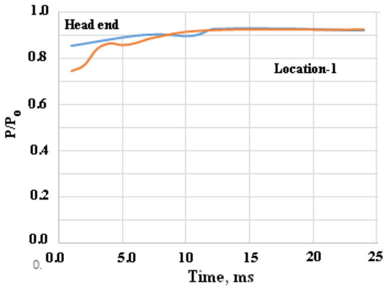
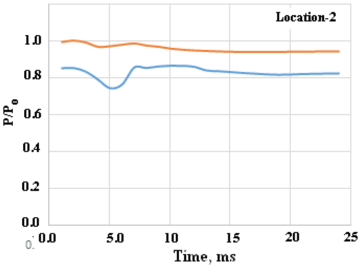


(f)

Fig. 6 (a)-(f) Comparing the axial Temperature transient variations at different axial locations (Fig. 5) from head-end to nozzle end of SRMs with both convergent and divergent port configurations



(a)



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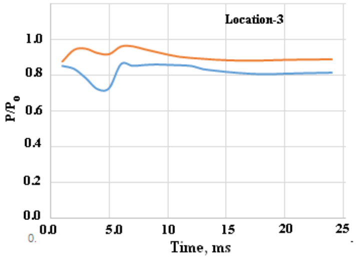

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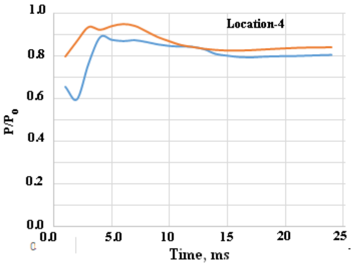

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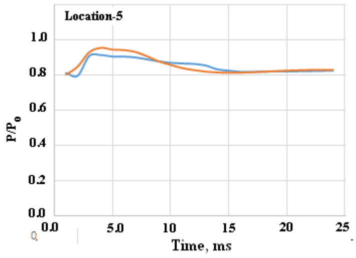

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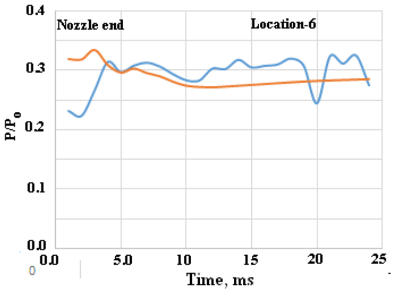

(f)

Fig. 7 (a)-(f) Comparing the axial Pressure transient variations at different axial locations (Fig. 5) from head-end to nozzle end of SRMs with both convergent and divergent port configurations

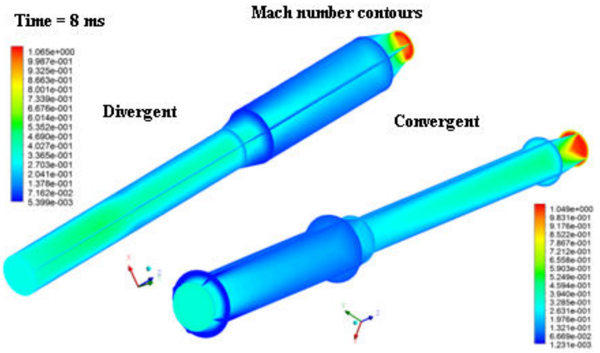

Fig. 8 Comparing the Mach number contours of SRMs with both convergent and divergent port configurations at time 8 ms

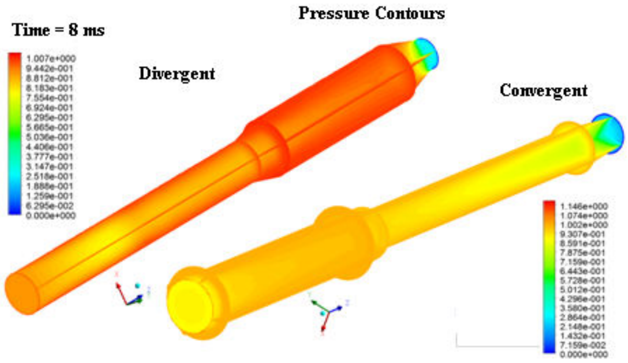

Fig. 9 Comparing the Pressure contours of SRMs with both convergent and divergent port configurations at time 8 ms

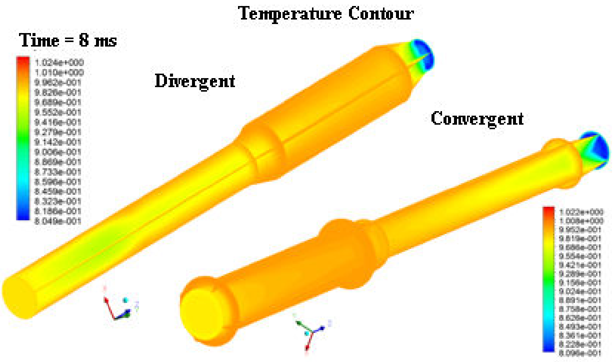

Fig. 10 Comparing the Temperature contours of SRMs with both convergent and divergent port configurations at time 8 ms

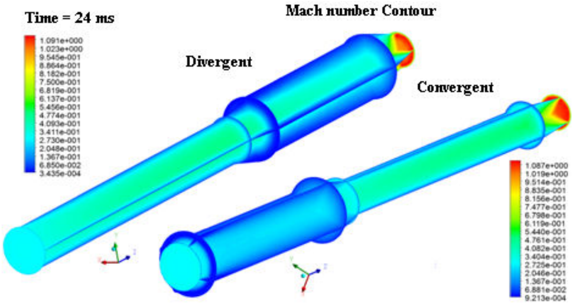

Fig. 11 Comparing the Mach number contours of SRMs with both convergent and divergent port configurations at steady state condition (t=24 ms)

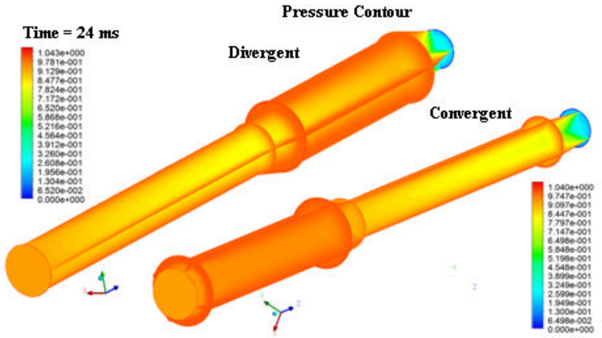

Fig. 12 Comparing the Pressure contours of SRMs with both convergent and divergent port configurations at steady state condition (t=24 ms)

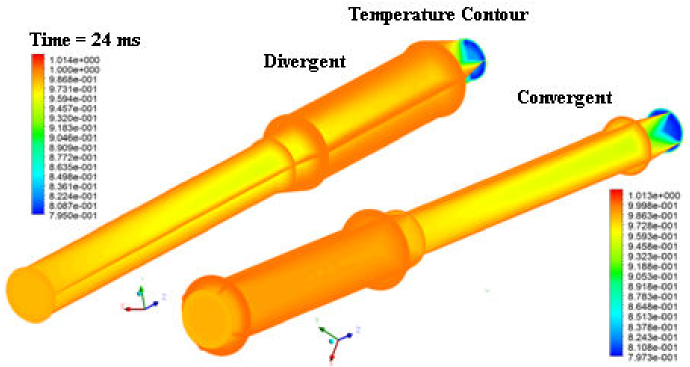

Fig. 13 Comparing the Temperature contours of SRMs with both convergent and divergent ports at steady state condition (t=24 ms)

IV. CONCLUSION

Compressibility effects are encountered in gas flows at high velocity and/or in which there are large pressure variations. We observed that the igniter temperature fluctuations will be diminished rapidly and will reach the steady state value faster in the case of SRMs with convergent port than with the divergent port irrespective of the igniter total pressure. We concluded that the prudent selection of the port geometry, without altering the propellant loading density, for damping the total temperature fluctuation within the motor is a meaningful objective for the suppression and control of instability and/or pressure/thrust oscillations often observed in SRMs with non-uniform port geometry. This paper is a pointer towards meeting the high-performance rocket motors design challenges without altering the mission demanding thrust-time trace shape requirements.

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REFERENCES

[1] Sanal Kumar, V. R., Raghunandan, B.N., Kawakami. T., Kim, H.D., Setoguchi, T., and Raghunathan, S., "Boundary Layer Effects on Internal Flow Choking in Dual-Thrust Solid Rocket Motors," Journal of Propulsion and Power, Vol.14, 2 (2008).

[2] Raghunandan, B. N., Sanal Kumar, V.R., Unnikrishnan, C and Sanjeev, C., "Flame Spread With Sudden Expansions of Ports of Solid Rockets", *Journal of Propulsion and Power*, Vol. 17 (1), 2001.

[3] Raghunandan, B. N., Madhavan, N. S., Sanjeev, C and Sanal Kumar, V. R., "Studies on Flame Spread with Sudden Expansions of Ports of Solid Propellant Rockets under Elevated Pressure," *Defence Science Journal*, Vol. 46, No.5, Nov. 1996, pp 417.

[4] Peretz, A., Kuo, K. K., Caveny, L. H., and Summerfield, M., Starting Transient of Solid Propellant Rocket Motors with High Internal Gas Velocities, AIAA J., Vol. 11, 12 (1973), pp. 1719.

[5] Sanal Kumar, V. R., Raghunandan, B. N., Kim, H.D., Sameen.A., Setoguchi, T., and Raghunathan, S, "Starting Transient Flow Phenomena in Inert Simulators of SRMs with Divergent Ports," AIAA Journal of Propulsion and Power, Vol. 22, 5 (2006), pp. 1138-1141.

[6] Sanal Kumar, V. R., Raghunandan, B.N., Kim, H.D., Sameen, A., Setoguchi, T., and Raghunathan, S., "Studies on Internal Flow Choking in Dual-thrust Motors" *AIAA* Journal of Spacecraft and Rockets, Vol.43, 5 (2006), pp.1139-1143.

[7] Sanal Kumar, V. R., Kim, H.D., Raghunandan, B. N., Sameen.A., Setoguchi, T., and Raghunathan, S, "Fluid-Throat Induced Shock Waves During the Ignition Transient of Solid Rockets," AIAA J. of Spacecraft and Rockets, Vol.43, 1 (2006).

[8] Sanal Kumar, V. R., Kim, H.D., Raghunandan, B. N., Setoguchi, T., and S. Raghunathan, "Internal Flow Simulation of High-Performance Solid Rockets Using a k-ω Turbulence Model," International Journal of Thermal and Fluid Sciences, Vol.14, No.2, June 2005.

[9] Ikawa, Hideo, Laspesa, Fred S. "Ignition/Duct Overpressure Induced by Space Shuttle Solid Rocket Motor Ignition," Journal of Spacecraft and Rockets, Vol. 22, 1985, p. 481.

[10] Salita, M., "Modern SRM Ignition Transient Modeling (Part 1): Introduction and Physical Models", *AIAA Paper*, No. AIAA 2001-3443, 2001.

[11] Alestra, S., Terrasse, I., and Troclet, B., "Identification of Acoustic Sources at Launch Vehicle Lift-Off Using an Inverse Method," AIAA Aerospace Sciences Meeting and Exhibit, 40th, Reno, NV, Jan. 14-17, 2002, AIAA-2002-926.

[12] Kumar, M and Kuo, K.K., "Flame Spreading and Overall Ignition Transient," Prog. Astronaut & Aeronaut, Vol.90, pp. 305-360, 1984.

[13] Sanal Kumar, V.R., "Thermoviscoelastic Characterization of a Composite Solid Propellant Using Tubular Test," *Journal of Propulsion and Power*, Vol.19, No.3, 2003, pp. 397-404.

[14] Sabnis, J.S., Gibeling, H.J. and McDonald, H., "Navier-Stokes Analysis of Solid Propellant Rocket Motor Internal Flows", Journal of Propulsion Power,1989, Vol. 5, pp. 657-664.

[15] Blomshield, F.S. and Mathes, H.B., "Pressure Oscillations in Post-Challenger Space Shuttle Redesigned Solid Rocket Motors", Journal of Propulsion Power, Vol. 9, 1993, pp. 217-221.

[16] Deepthi. S et al., "Studies on Starting Thrust Oscillations in Dual-Thrust Solid Propellant Rocket Motors" Emerging Trends in Science, Engineering and Technology, Springer, 2012, pp 421.

[17] Ajith. S, Sivabalan. M, Tharikaa.R, Hemasai.N.D, and Sanal Kumar. V. R, "Diagnostic Investigation of Flame Spread Mechanism in Dual-thrust Solid Propellant Rocket Motors, 51st AIAA/ASME/SAE/ASEE Joint Propulsion Conference , Florida, U.S.A, 27-29 July, 2015. Paper No: AIAA-2015-4226.