The Ascendancy of Grain Configuration on the Starting Transient of Solid Rockets

V.R. Sanal Kumar,[1] *Heuy-Dong Kim,*[2] *B.N. Raghunandan,*[3] *and Toshiaki Setoguchi*[4]

[1]*Vikram Sarabhai Space Centre, Trivandrum-22, India, email: rsanal@hotmail.com*
(Currently at the Andong National University, Korea, email: rsanal@andong.ac.kr)
[2]*School of Mechanical Engineering, Andong National University, Korea, email: kimhd@andong.ac.kr*
[3]*Aerospace Engineering, Indian Institute of Science, Bangalore-12, India*
[4]*Department of Mechanical Engineering, Saga University, Japan*

Keywords: Solid Rockets, Ignition/Starting Transient, Grain

Abstract

Theoretical studies have been carried out to examine the influence of the grain geometry-dependent driving forces, which control the internal flow pattern of solid rockets. Numerical studies have been executed with the help of a two-dimensional code. This code solves standard k-omega turbulence equations using the coupled second order implicit unsteady formulation. It has been concluded that the grain port divergence angles have significant leverage on the formation of recirculation bubbles leading for pressure oscillations, flow separation and reattachment. In solid rockets flow reattachment will favour secondary ignition and that will add to the complexity of the starting transient prediction.

Introduction

The propellant grain is the shaped mass of viscoelastic materials inside the solid rocket motor. The viscoelastic material possesses a characteristic that can be referred to as a "memory effect," that is, the material response is not only determined by the current state of stress, but is also determined by all of the past stress history. The grain configuration is designed to satisfy several interrelated requirements for a successful mission.[1] The propellant material and geometrical configuration of the grain determine the motor performance characteristics within the given envelope.

Several loadings may act successively or simultaneously on a rocket propellant grain. Among these, the most important are 1) internal pressure, 2) shrinkage-type thermal loading, 3) thermal gradient loading, 4) thermal transient loading, 5) inertia loads (in flight), 6) local difference of pressure inside the grain, 7) vibrations, 8) residual stresses, and 9) body forces (in storage). In this study, the focus is on the altered variation of transient internal pressure load due to the grain configuration effect and the related flow separation.

Many modern high-performance solid rocket motors (SRMs) have grains with sudden expansion/divergence of port combined with high volumetric loading density, high throat to port area ratio and large length-to-diameter ratio. Flow separation and recirculation caused by sudden changes in port geometry plays an important role in the design of these motors.[2] An accurate description of the internal flow could be used to investigate the adequacy of the grain configuration and its companion igniter for a particular mission. Moreover, the knowledge of the transient pressure loads, that a propellant grain experiences, is possible only if one posses a detailed knowledge of the ignition transient/starting transient history[3]. The literature review reveals that, although the pertinent component technologies are apparently well understood, the ascendancy of grain configuration on the prediction of overall starting transient of SRMs needs more attention.

The motivation for this study emanates from the desire to explain the phenomena or mechanism(s) responsible for the high pressure and pressure rise rate often observed during the static tests and the actual flights of certain class of solid rockets with non-uniform ports. For technological reasons, large solid propellant space boosters, such as US Space Shuttle and Titan SRMs or European Ariane 5 P230 are made from segmented propellant grains from three to seven segments with non-uniform ports according to the motor versions. Earlier works in the USA[4, 5] shown that such grain segmentation conducted to low amplitude, but sustained pressure and thrust oscillations, on the first longitudinal acoustic mode frequencies[4,5]. Although such oscillations do not jeopardize the mission, they induce some penalties to the overall performance. The suppression or the control of such oscillations is then a meaningful objective for further study.

In the case of Ariane 5 P230 solid rocket motor, early studies concluded that the risk of instabilities existed and that works had to be carried out to understand the physical mechanisms at the origin of this oscillatory behaviour[6]. These works pointed out the role of the vortex shedding as a source of acoustic energy inside solid rocket motors. Another important conclusion of these works is, in such complex situations as the P230 motor, simplified methods cannot give reliable results. Full numerical approaches must be used, in providing unprecedented insight into oscillatory flow fields especially in geometrically complex situations.

Detailed studies on instabilities and pressure oscillations in solid rocket motors have been carried out by Yves Fabignon et al.[7] at ONERA. In these studies influence of secondary ignition on pressure oscillations in complicated grain geometry essentially with divergent port is not addressed.

Studies of Raghunandan et al.[2,8] at IISc and ISRO reveal that the implication of the secondary ignition can be quite serious for a practical rocket. One secondary ignition gives rise to two additional flame fronts, one spreading forward and the 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 pressure-rise rate in the second phase of starting transient. This in effect could lead to a hard start of the rocket motor. It has been proved conclusively through experimental and numerical studies that when flow separation is likely to occur during the flow of igniter gases, multiple flame fronts may be generated. Sudden expansion regions, steep divergences or protrusions might cause such flow separation over the surface in the port of a rocket motor[2]. Having proved this point, the next step will be to optimize the port geometry without sacrificing the mission requirements.

It has been reported through the earlier connected paper that the location of the divergence/transition region is a design constraint for finalizing the port configuration of solid rockets for achieving high motor mass ratio[3]. Conventionally, within the given envelope solid rocket motor designers will try different combination of radial burning port geometry for a particular launcher operation and finally will arrive at a complicated geometry based on the ballistic considerations, which will not be amenable for conventional flow analysis. As a result internal flow physics of many of the sophisticated solid rocket motors with non-uniform ports are not well understood, essentially during the initial period of motor operation. In an attempt to resolve some of these problems and in the light of new findings, a systematic approach has been envisaged. It has been reported that the narrow port and long flow development ahead of the steep divergence are shown to favour flow separation, which might lead to high pressure-rise rate during the starting transient of SRMs[3, 8].

The accurate and *a prior* knowledge of the internal flow characteristics and the ascendancy of grain configuration on the overall starting transient of SRMs will be helpful for the designer to select the best port configuration, in the thrust transient point of view, without sacrificing the propellant loading density. Moreover, the increased versatility of the analysis will be very useful to the designers for improving the payload capability of the future space vehicles.

Traditionally, the transient analysis of solid propellant grains subjected to internal pressurization loading during the starting transient period was not contemplated, and quasi-elastic–static analysis was widely adopted for structural integrity because the analytical task gets simplified[9]. It does not mean that the dynamic effect is not instrumental and could be deserted peremptorily. It has been reported through the earlier connected and the recent companion papers that the internal pressurization effect usually plays a decisive role for some critical design of solid rockets[10-14], essentially with non-uniform port.

Of late, in order to simulate the dynamic response of solid rocket motors, a transient finite element model, accompanied by concepts of time–temperature shift principle, reduced integration and thermorheologically simple material assumption, was used by Shiang-Woei Chyuan[9]. Results show that the dynamic effect is important for structural integrity of solid propellant grains under ignition pressurization loading.

The port geometry of the SRM is generally held fixed during the starting transient simulation. 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 geometry, during the starting transient period of operation. It has been hypothesized many investigators that one possible cause of ignition peak (pressure peak) in high velocity transient motors is grain deformation. It is true only when the structural response time of the propellant (time required to deform the grain) is smaller than the starting transient time[1]. A comprehensive structural-fluid dynamic interactive model is required for the design optimization.

Solid propellant rocket design is a complex technological problem requiring expertise in diverse sub disciplines to address all of the physics involved, including: ignition and combustion of composite energetic materials, solid mechanics of the propellant, case, insulation, and nozzle; fluid dynamics of the interior flow and exhaust plume; shock physics and quantum chemistry of energetic materials; aging and damage of components; analysis of potential failure modes. These component problems are characterized by very high energy densities, extremely diverse length and time scales, moving interfaces, and reactive, turbulent, and multiphase flows. Accurate simulation of each component is a daunting challenge in its own right; still more challenging is the integration of the component models to simulate overall rocket behavior. Such integrated system simulations are required to assess performance safety and reliability[15-16]. The design optimization is more complex when the mission demands dual thrust. Because dual-thrust motors with single chamber necessarily have non-uniform port geometry. The literature review reveals that existing models are incapable of considering those geometry-dependent driving forces that control the starting transient. Although many hypotheses are available, the magical parameter(s) that caused the high-pressure and pressure-rise rate often observed in SRMs with non-uniform ports are not well understood. An accurate simulation of the unsteady internal flow is required for the grain structural integrity evaluation and also for examining the ascendancy of grain configuration on the starting transient of solid rockets.

In this paper characteristic turbulence flow pattern in dummy (unignited) solid rockets with different port geometries are examined in a judicious manner using a two-dimensional standard k-omega model.

Numerical Method of Solution

The numerical studies have been carried out with the help of a two dimensional code. This code solves standard k-omega turbulence equations using the coupled second order implicit unsteady formulation. It uses a control-volume based technique to convert the governing equations to algebraic equations, which can be solved numerically. The viscosity is determined from the Sutherland formula. An algebraic grid-generation technique is employed to discretize the computational domain. The present solver has been selected for capturing the fine flow features often observed in SRMs with non-uniform port. A typical grid system (325 x 80) in the computational region is selected after the detailed grid refinement exercises. These are succinctly reported in the companion paper[14]. The grids are clustered near the solid walls using suitable stretching functions. In all the cases length of the first grid from the solid surfaces is taken as 0.1 mm.

The motors geometric variables and material properties are known a priori. Initial wall temperature, inlet total pressure and temperature are specified. At the solid walls no-slip boundary condition is imposed. At the nozzle exit a pressure profile is imposed. The Courant-Friedrichs-Lewy number is initially chosen as 3.0 in all of the computations. The specific dissipation rate is chosen as 0.5 and turbulent viscosity ratio is taken as 0.7 in all the cases reported in this paper. Ideal gas is selected as the working fluid. The steady and the unsteady numerical solutions have been judiciously examined and the different characteristic curves are reported in this paper.

Results and Discussion

Choice of the geometry is based on the flight motors configurations discussed in the introduction. In this analysis constant igniter gas flow is assumed as the inflow condition, which is prescribed by the inlet total pressure and temperature. Initial chamber pressure is assumed as the atmospheric pressure. The fine grid system (325 x 80) is chosen for parametric studies after the detailed grid refinement attempts. In this paper, parametric studies have been carried out on dummy (unignited) grains, essentially with divergent ports. For a solid rocket motor with divergent port, it is important to have a knowledge of spatial and temporal variations of not only pressure but also of dynamic pressure, pressure-rise rate, wall shear stress, surface heat flux, surface temperature and turbulence energy level before embarking on any explanation of and remedy for high pressure, pressure-rise rate, flow instabilities and pressure oscillations. These phenomena are often observed in certain class of solid rockets, which are succinctly discussed in the introduction.

It is often the practice in ignition studies to use dummy grains to obtain physical insight into the surface heat flux pattern based on the flow structure. Note that fine data are not available in any open literature for quantitative comparison. In this numerical study unignited grains are chosen to characterize the internal flow field of SRMs. Detailed parametric studies have been carried out with different port geometry of the grain but with the same initial and boundary conditions.

Fig.1 Grid system (325 x 80) in the computational domain (Angle of divergence 26^0).

The grid system of an idealized physical model of a dummy grain with sonic nozzle is shown in Fig.1. In this study total length of the grain is retained as 1.6 meters and all other geometric variables are altered for examining its sensitivity on internal flow characteristics. Figure 2 shows the enlarged view of the velocity distribution highlighting with recirculation bubble at the down stream of the expansion region (angle of divergence 26) of a solid rocket at the steady state condition. It is also observed through parametric studies that at the same initial and boundary conditions, a case with angle of divergence 14, recirculation region was not perceptible at the divergence region.

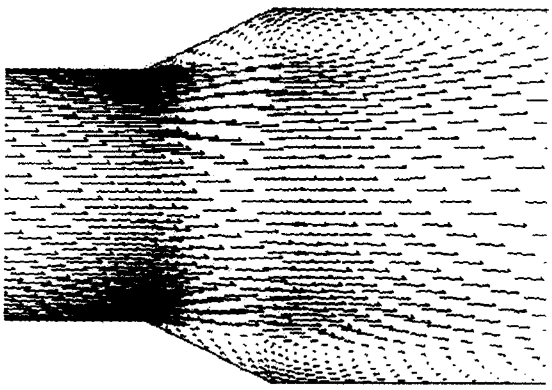

Fig. 2 Velocity vectors at the steady state condition showing the recirculation. (Angle of divergence 26^0).

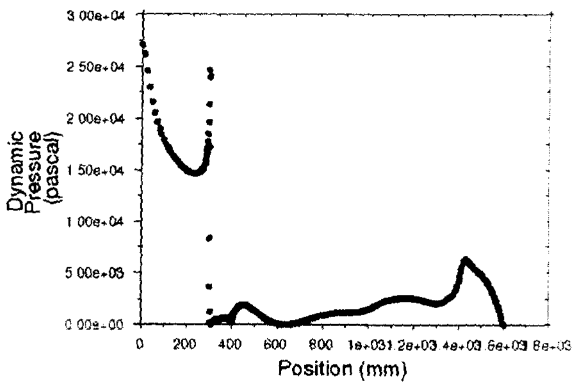

Fig. 4 Dynamic pressure variation along the internal surface of the grain with angle of divergence 26^0.

Figure 3 shows the distribution of the pressure coefficient along the surface of the grain at the steady state condition. Figure 4 shows the dynamic pressure distribution at the internal port surface of the grain. Corresponding variation of the wall shear stress and the turbulent kinetic energy are presented in Fig. 5 & 6 to understand the physics behind it.

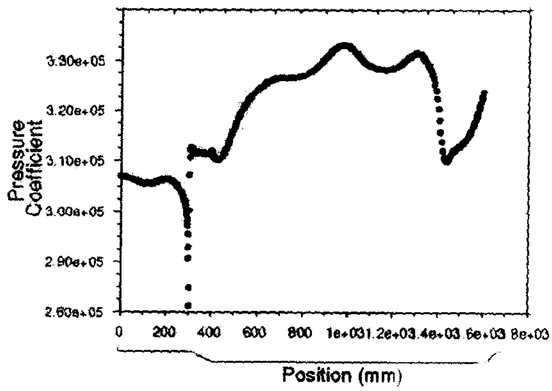

Fig.3 Pressure coefficient along the grain surface. (Grain length 1600mm, Motor length 1700mm, Angle of divergence 26^0, Divergence location 300mm from the head end, Inlet velocity 145 m/s)

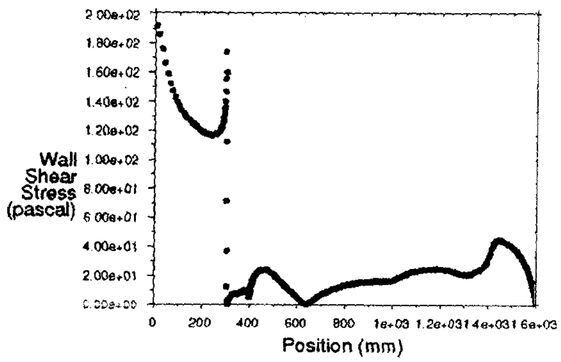

Fig. 5 Wall shear stress variation along the internal surface of the grain with angle of divergence 26^0.

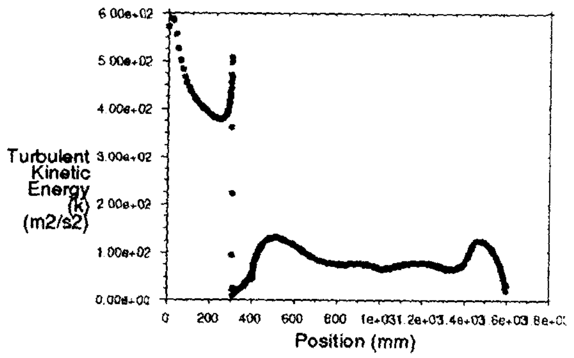

Fig. 6 Turbulent kinetic energy variation along the internal surface of the grain with an angle of divergence 26^0 at a distance of 300mm from the head-end.

Pressure coefficient observed at the divergence region is anticipated, however variation at the grain aft-end is deviated from the conventional solutions due to the shape of the sonic nozzle. This variation has been examined through different nozzle contours, which is however beyond the scope of this study. Dynamic pressure variations presented in Fig. 4 will give a reasonable insight into the differential pressure load acting on the grain surface during the motor operation.

In another attempt a case with an angle of divergence 14^0 is considered for the study. The grid system in the computational domain is shown in Fig. 7.

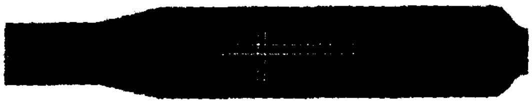

Fig.7 Grid system (325 x 80) in the computational domain (Angle of divergence 14^0).

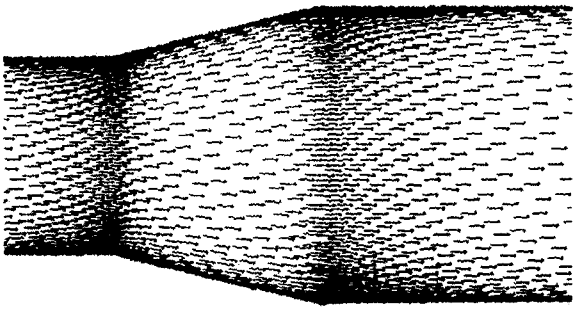

Fig. 8 Velocity vectors at the steady state (A case without recirculation when angle of divergence = 14^0).

The velocity distribution and the characteristic curves at the steady state condition are shown in Fig.8-12. Detailed parametric studies reveal that in certain cases recirculation region got vanished well before the motor equilibrium state and in some cases, at relatively low angle of divergence, recirculation flow was not discernible at all. All these lead to say that the motor port geometry got some bearing on the formation of recirculation bubble and further reattachment of flow.

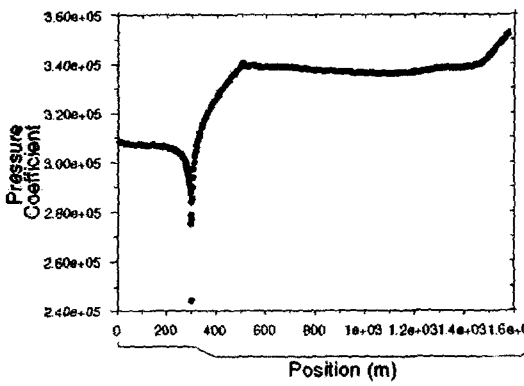

Fig.9 Pressure coefficient along the grain surface. (Angle of divergence = 14^0)

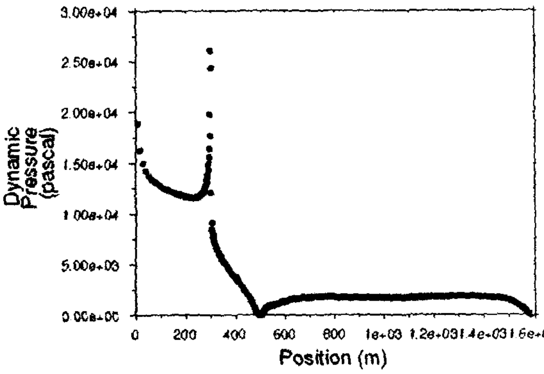

Fig. 10 Dynamic pressure variation along the internal surface of the grain with angle of divergence 14^0.

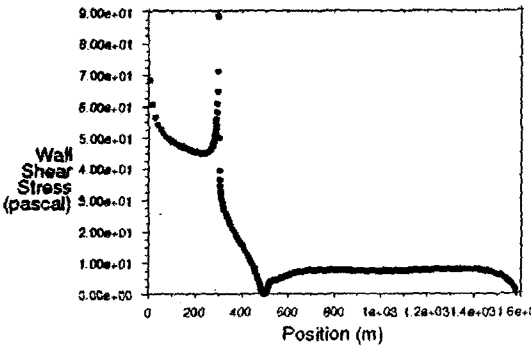

Fig. 11 Wall shear stress variation along the internal surface of the grain with angle of divergence 14^0.

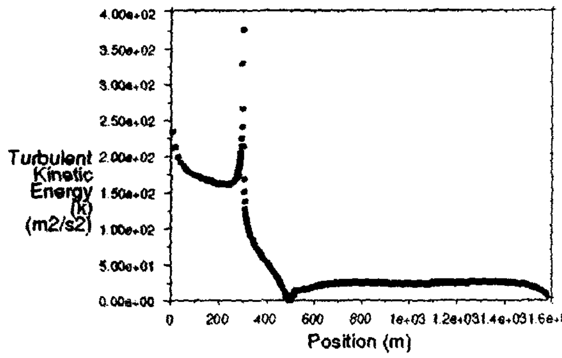

Fig. 12 Turbulent kinetic energy variation along the internal surface of the grain with an angle of divergence 14^0 at a distance of 300mm from the head-end.

Detailed parametric studies have been carried out with dummy grains under unsteady flow conditions. Different characteristic curves at different time intervals are presented in Figs. 13-27 for examining the influence of the grain port geometry dependent driving forces on starting transient of solid rockets.

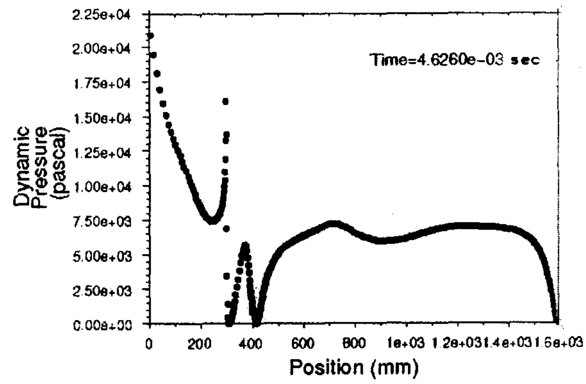

Fig. 13 Dynamic pressure variation along the internal surface of the grain with angle of divergence 26^0 at time, t = 0.0046sec.

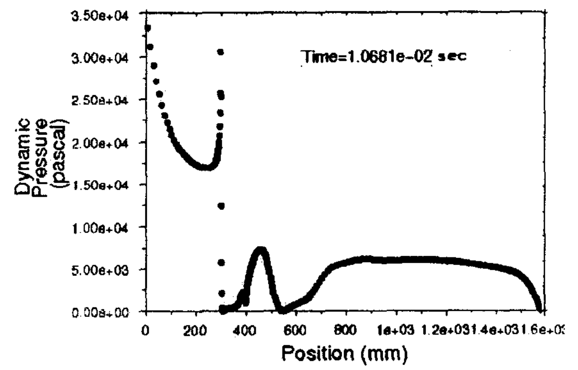

Fig. 14 Dynamic pressure variation along the internal surface of the grain with angle of divergence 26^0 at time, t = 0.01068 sec.

One can easily inferred from Figs13-16 that transient pressure load acting on the port surface of the grain is different at different interval due to the variation of the velocity field. The high pressure-rise rate has structural implications in addition to the possibility of giving rising to transient burn rate effect in the real motor, which however is not attempted in this study. The sequence of pictures showing the velocity distribution pattern at the expansion region of the grain is presented in Fig. 28(a-d). From these figures, one can easily conclude that in the actual case due to transient burning the flow field will be deviated from the present pattern leading to the complexity of the starting transient prediction.

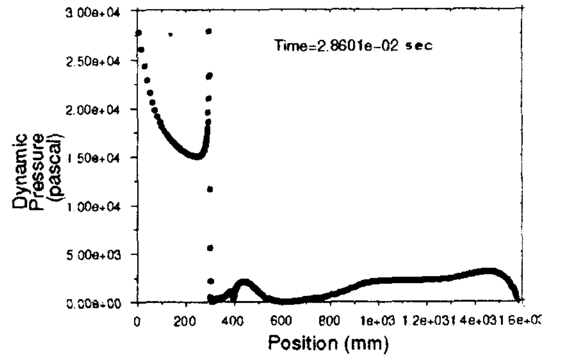

Fig. 15 Dynamic pressure variation along the internal surface of the grain with angle of divergence 26^0 at time. t = 0.0286 sec.

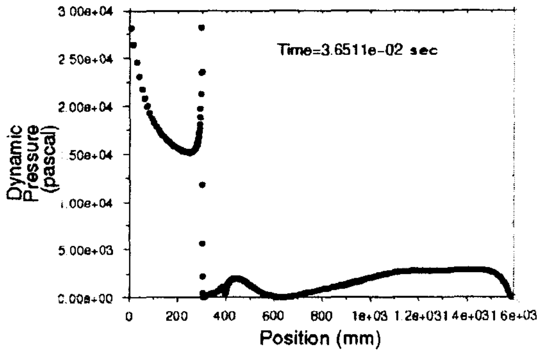

Fig. 16 Dynamic pressure variation along the internal surface of the grain with angle of divergence 26^0 at time. t = 0.0365 sec.

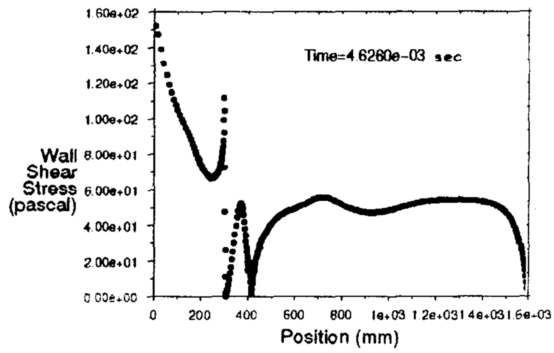

Fig. 17 Wall shear stress variation along the internal surface of the grain with angle of divergence 26^0 at time. t = 0.00463 sec.

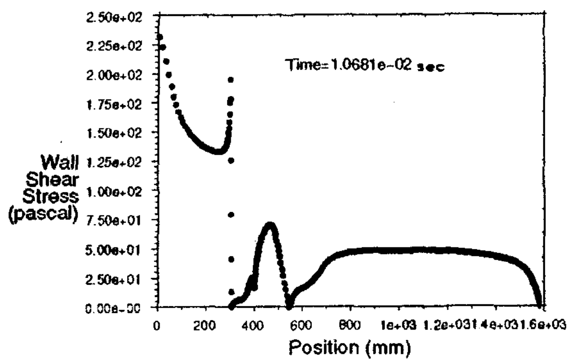

Fig. 18 Wall shear stress variation along the internal surface of the grain with angle of divergence 26^0 at time, t = 0.01068 sec.

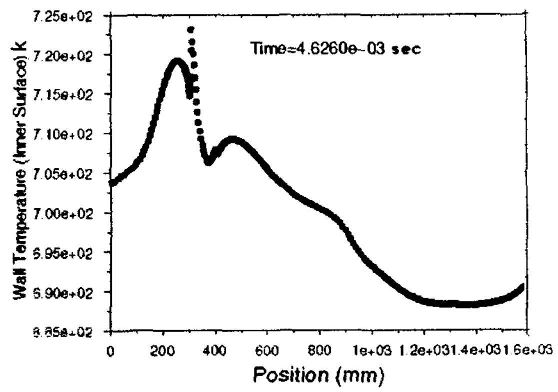

Fig. 21 Wall temperature variation along the internal surface of the grain with angle of divergence 26^0 at time. t = 0.00463 sec.

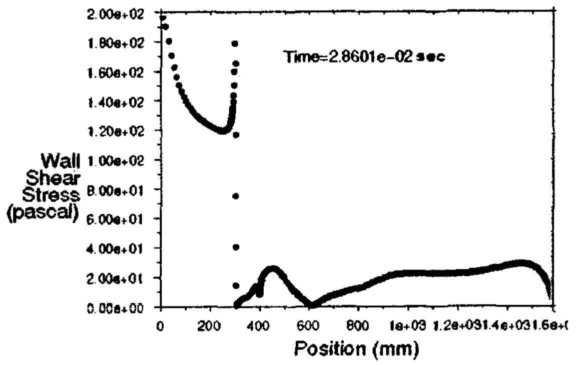

Fig. 19 Wall shear stress variation along the internal surface of the grain with angle of divergence 26^0 at time, t = 0.0286 sec.

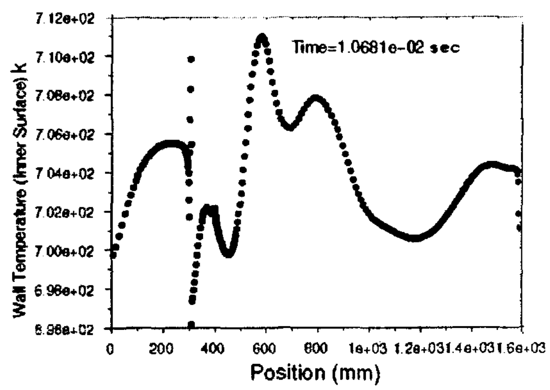

Fig. 22 Wall temperature variation along the internal surface of the grain with angle of divergence 26^0 at time. t = 0.01068 sec.

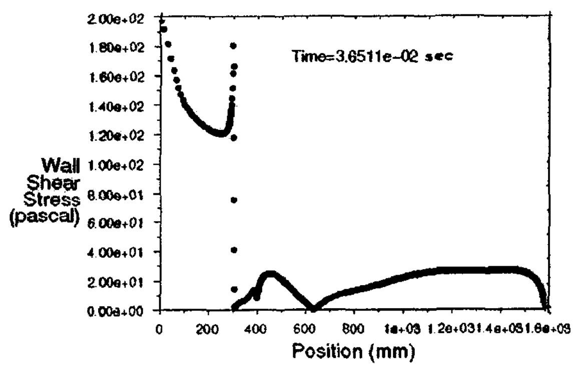

Fig. 20 Wall shear stress variation along the internal surface of the grain with angle of divergence 26^0 at time, t = 0.0365 sec.

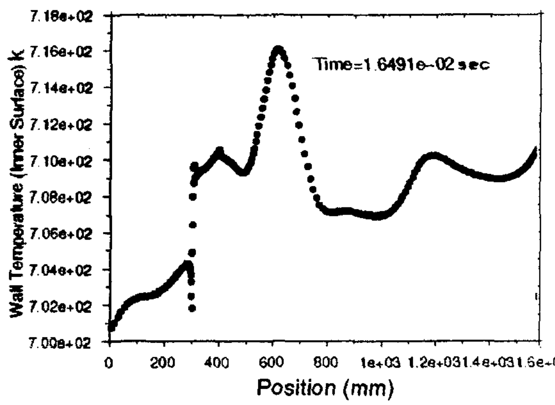

Fig. 23 Wall temperature variation along the internal surface of the grain with angle of divergence 26^0 at time. t = 0.01649 sec.

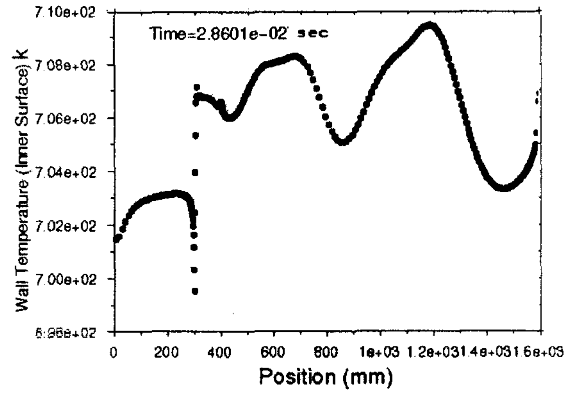

Fig. 24 Wall temperature variation along the internal surface of the grain with angle of divergence 26^0 at time, t = 0.0286 sec.

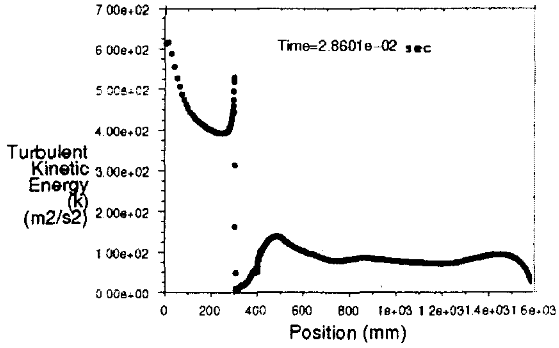

Fig. 27 Turbulent kinetic energy variation along the port surface of the grain with angle of divergence 26^0

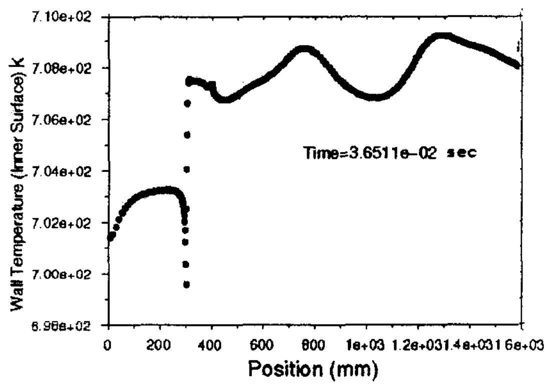

Fig. 25 Wall temperature variation along the internal surface of the grain with angle of divergence 26^0 at time, t = 0.0365 sec.

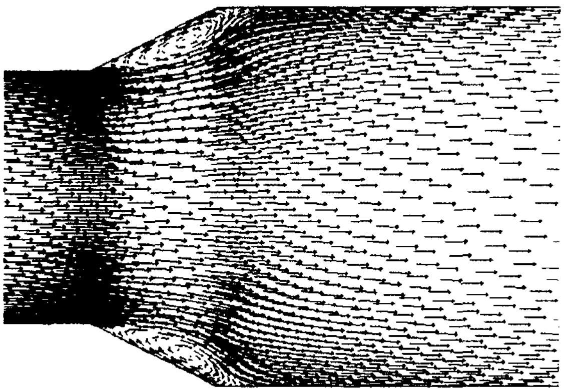

Fig.28 (a) Velocity distribution at time, t = 0.00462 sec.

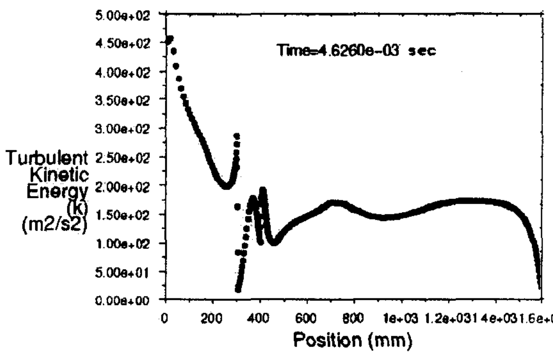

Fig. 26 Turbulent kinetic energy variation along the port surface of the grain with angle of divergence 26^0

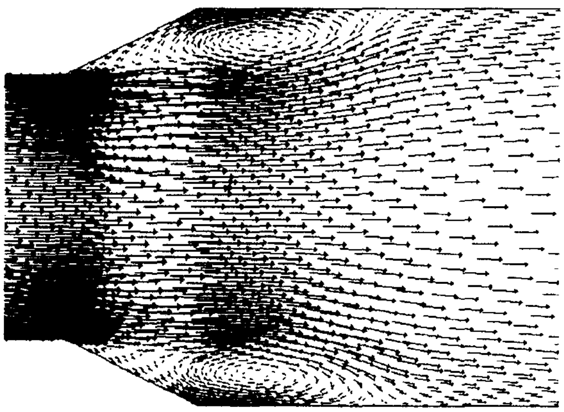

Fig.28 (b) Velocity distribution at time, t = 0.01068 sec.

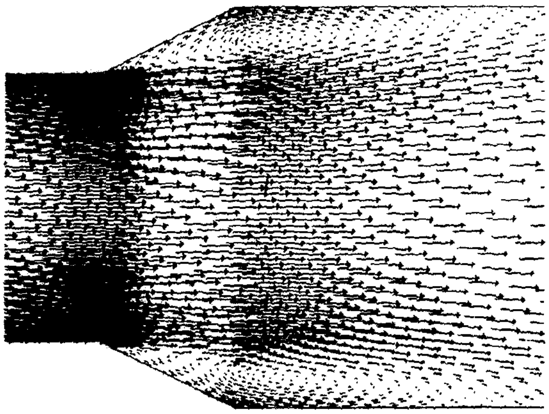

Fig.28 (c) Velocity distribution at time, t = 0.0302 sec

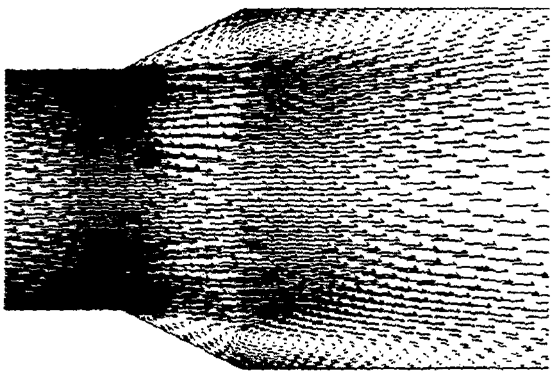

Fig.28 (d) Velocity distribution at time, t = 0.046 sec

The different characteristic curves presented so far in this paper are sufficient enough to understand the complexity of the flow field and the corresponding transient loads acting on the dummy grains with divergent port. Figures 21-25 indicate that the location of the maximum surface temperature is altering when the flow is advancing. Note that location of the maximum surface temperature will be at the reattachment region. In real situation this will cause discontinuous ignition sequence in the solid rocket motors, and that might lead to the formation of secondary ignition and multiple flame fronts. This needs to be examined further with the transient mass addition, which will further add the complexity of the starting transient prediction. An error in predicting the time and the location of the secondary ignition can lead to significant errors in the prediction of the overall starting transient of solid rockets with such port.

Figures 26 & 27 show the variation of the turbulent kinetic energy at two different intervals. Initially oscillatory behaviour is observed due to the movement of the recirculation bubble and later it has diminished at the time of equilibrium condition. The movement of the recirculation bubble is discernable in Fig. 28 (a-d). It can be seen from these sequence of pictures that recirculation bubble is moving from the divergence region to the downstream when the time is advancing. During this period oscillatory pressure behaviour is observed and the wall shear stress and the dynamic pressure load acting on the grain surface is also found altered. This oscillatory behaviour is not benign in any solid rocket motor. This is an area that needs more attention for the accurate performance prediction of solid rockets with non-uniform port geometry. All these lead to pronounce that the ascendancy of grain configuration on the starting transient of solid rockets need to be examined more carefully.

Conclusion

It has been inferred through this study that geometry-dependent driving forces have significant influence on the overall starting transient histories of solid rockets. It has been concluded that the grain port divergence angles have significant influence on the formation of recirculation bubbles leading for pressure oscillations, flow separation and reattachment. In solid rockets reattachment will favour secondary ignition and that will add to the complexity of the starting transient prediction.

Acknowledgement

The Andong National University under the overseas research scheme has supported this work and acknowledged the same by the first author.

References

1) Sanal Kumar, V.R., Thermoviscoelastic characterization of a composite solid propellant using tubular test, *Journal of Propulsion and Power*, **19** (3), 2003, pp. 397-404.

2) Raghunandan, B.N., Sanal Kumar,V.R, Unnikrishnan, C and Sanjeev, C., Flame spread with sudden expansions of ports of solid propellant rockets, *Journal of Propulsion and Power*, **17** (1). 2001, pp. 73-78.

3) Sanal Kumar, V. R., Unnikrishnan, C., and Raghunandan, B. N., Influence of transition region on flowseparation and pressurization rate in solid rockets, *AIAA paper 2002-4170*, July 2002.

4) Brown, R.S., Dunlup, R., Young, S.W., and Waugh, R.C., Vortex shedding as a source of acoustic energy in segmented solid rockets, *Journal of Spacecraft and Rockets* **18** (4), 1981, pp. 312-319.
5) Manson, D.R., Folkman, S.K., Behring, M.A, Thrust oscillations of the space shuttle solid rocket booster motor during static tests, *AIAA paper 79-1138*, June 1979.
6) Vuillot, F., Vortex-shedding phenomena in solid rocket motors, *Journal of Propulsion and power*, **11** (4), 1995, pp. 626-639.
7) Fabignon, Y., Dupays, J., Avalon. G., Vuillot, F., Lupoglazoff, N., Casalis, G and Prevost, M, Instabilities and pressure oscillations in solid rocket motors, *Aerospace Science and Technology*, **7**, 2003, pp. 191-200.
8) Raghunandan,B.N., Madhavan, N.S., Sanjeev, C and Sanal Kumar, V. R., Studies on flame spread with sudden expansions of ports under elevated pressure, *Defence Science Journal*, **46** (5), 1996, pp 417-423.
9) Shiang-Woei Chyuan, Dynamic analysis of solid propellant grains subjected to ignition pressurization loading, Dynamic analysis of solid propellant grains subjected to ignition pressurization loading, *Journal of sound and vibration*, **268** (3), 2003, pp. 465-483.
10) Unnikrishnan, C., Sanal Kumar, V. R., and Raghunandan, B.N., Internal flow simulation of solid rockets using an unsteady Navier Stokes solver, AIAA Paper 2001-3450, *37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, UT, USA, 8-11 July 2001.
11) Sanal Kumar, V. R., and Unnikrishnan, C., Raghunandan, B.N., Effect of flame spread mechanism on starting transients of solid rocket motors, AIAA Paper 2001-3854, *37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, UT, USA, 8-11 July, 2001.
12) Sanal Kumar, V. R., and Unnikrishnan, C., Raghunandan, B.N., Studies on ignition transients of solid rocket motors with non-uniform ports, Paper AIAA 2000-3701, *36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, AL, USA, 17-19 July 2000. *(Also abstracted in International Aerospace Abstract – 2001).*
13) Sanal Kumar, V.R., Unnikrishnan, C Raghunandan, B. N and Kim, H.D., Studies on heat flux distribution in solid rocket motors with non-uniform port, AIAA 2003-4959, July 2003.
14) Sanal Kumar, V. R., Heuy-Dong Kim, Raghunandan, B. N., and Toshiaki Setoguchi, Studies on turbulent separated and reattaching flows in solid rockets, *The 15th International Symposium on Transport Phenomena, Bangkok. Thailand, 9-13 may 2004 (To Appear).*
15) Heath, M. T., and Dick, W. A., Virtual Rocketry: Rocket Science Meets Computer Science, *IEEE Computational Science & Engineering*, **5** (1), 1998. pp. 16-26.
16) Heath, M. T., and Dick, W. A., Virtual Prototyping of Solid Propellant Rockets, *Computing in Science and Engineering*, **2** (2), 2000, pp. 21-32.