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Engineering Notes

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Studies on Internal Flow Choking in Dual-Thrust Motors

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Introduction

A detailed picture of the internal flow during the starting transient of high-performance solid rocket motors (SRMs) is of topical interest for several reasons in addition to the motor performance itself [1–12]. Despite the fact that many of the existing models could predict the internal flow features of certain classes of SRMs, none of these models could capture the unusual starting transient flow features such as pressure overshoot and pressure-rise rate often observed during the initial phase of operation of the dual-thrust motors (DTMs) [1]. Ikawa and Laspesa [8] 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 [9]. Alestra et al. [10] reported that Ariene 5 launcher experienced 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. Of late, Sanal Kumar et al. [1,2] reported that abnormal high-pressure overshoot in certain class of DTMs during the startup transient is due to the formation of shock waves because of the *fluid-throat* effect, which has received considerable attention in the scientific community. This manuscript is the continuation of the previous connected note for establishing the intrinsic flow physics pertinent to internal flow choking in inert simulators of dual-thrust motors [1]. Note that the illustration of ignition pressure spike is deliberately set aside in this note for explaining the intrinsic flow physics pertinent to internal flow choking without complications arising from the propellant combustion.

This paper addresses the design challenges associated with development of high-performance dual-thrust motors because of their large size, high length to diameter ratio, and demanding thrust-time trace shape requirements. This note promises to produce an optimum and also a profitable flight motor design that meets all high-performance objectives while accommodating program development uncertainties.

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Numerical Methodology

Numerical simulations have been carried out in inert simulators of DTM with the help of a two-dimensional standard k–ω turbulence model. This code solves standard k–ω turbulence equations with shear flow corrections using a coupled second order implicit unsteady formulation. In the numerical study, a fully implicit finite volume scheme of the compressible, Reynolds-averaged, Navier–Stokes equations is employed. Compared with other models, this model could well predict the turbulence transition in duct flows and has been validated through benchmark solutions [3–5,13]. Initial wall temperature, inlet total pressure, and temperature are specified. At the solid walls, a no-slip boundary condition is imposed. At the nozzle exit, a pressure profile is imposed. Note that the motor exit geometry (nozzle) considered in this study is a short, straight duct followed by the convergent duct. Therefore, a radial axisymmetric pressure distribution at the exit was approximated analytically. Note that this is more realistic than the conventional exit boundary conditions. The Courant–Friedrichs–Lewy number is initially chosen as 3.0 in all of the computations. An algebraic grid-generation technique is employed to discretize the computational domain. The grids are clustered near the solid walls using suitable stretching functions. Ideal gas is selected as the working fluid.

Evaluation of Boundary Layer Blockage

It is assumed that the developing flow can be represented by boundary layer thickness together with a core in which the velocity is uniform. The approach applies equally to smooth or rough grain surfaces. In a two-dimensional flow model, boundary layer blockage is given by

$$\frac{\delta^*}{d/2} = 1 - \frac{U}{U_{\max}} \tag{1}$$

where δ^* is displacement thickness, $U_{\max}$ is the velocity on the axis, and d is the diameter of the upstream port of the DTM. Although many empirical methods are available, an acceptable method of calculating the mean flow velocity U is by numerical solution of the flow equations, which is applied here in toto.

Results and Discussion

Static tests conducted at the Indian industry show unusual and unacceptable ignition pressure spike during the startup transient of a DTM with high L/d ratio (=44.4). Through empirical design techniques, it was reported that at low L/d (=28.6) ratio this unusual pressure spike could negate the cost of the high-performance nature of the motor [1]. Therefore, these two specific cases are selected for further parametric analytical studies with reference to the boundary layer blockage factor. In case 1, attention is focused on a dual-thrust motor with narrow upstream port and with steep divergence. The port geometry ($d_t/D = 0.58$, $L/D = 17.85$, $L/d = 44.4$) is selected based on a typical DTM. Igniter geometry is deliberately avoided in this study to examine the intrinsic flow physics pertinent to the fluid-throat induced shock waves in DTMs at subsonic inflow conditions. The initial total pressure and temperature are specified as input to the code and a pressure profile is imposed at the exit. Except for the geometric variables, all other parameters are kept constant in the parametric studies. Figure 1 is demonstrating the axial (centerline) Mach number variations of the DTM at different time intervals. It shows that the magnitude of Mach number at the transition location ($x/X_s = 1$) is high due to the boundary layer effect [1,2]. It is evident from Fig. 1 that at the given subsonic inflow conditions and without any igniter nozzle or geometrical throat inside the port of the motor, the flow gets accelerated to a higher Mach number ($M > 1$) near the transition region at $t = 10$ ms, and suddenly drops to a lower Mach number ($M < 1$). It is presumed that the flow must have accelerated through a throat, which is sonic. The way in which the flow adjusts itself to maintain sonic velocity at the throat depends on the conditions downstream of the throat. Figure 1clearly shows that the entire flow is subsonic inside the DTM except at the transition region. It has been noticed that the DTM nozzle remains unchoked. The enlarged views of the static pressure contours at the transition region of the corresponding DTM (case 1) before ($t = 0.7$ ms) and after ($t = 10$ ms) choking are shown in the inset of Fig. 1. Formation of shock wave is evident at $t = 10$ ms.

In case 2, it has been observed that when the upstream port area of the DTM was increased by 55% (i.e., L/d ratio reduced to 28.6) the formation of the *sonic fluid-throat* was not discerned with the same initial and boundary conditions. This has been done without altering the other geometric variables ($d_t/D = 0.58$, $L/D = 17.85$) of the DTM. Figure 2 shows the axial (centerline) velocity variations, at different time intervals, of the aforesaid DTM. The physical model of the DTM is shown in inset of Fig. 2. It has been observed that after the flow gets choked at the nozzle throat ($t = 1.5$ ms), the velocity at the transition region marginally decreased and there was no evidence of choking condition at the transition location. Note that the maximum Mach number observed within the motor was only 0.48. This reveals that with the same inflow conditions, but with a relatively large upstream port area, the flow will not accelerate to a higher Mach number ($M \geq 1$) leading to the formation of shock waves inside the rocket motor. The shock wave pattern is merely the mechanism the flow adopts to adjust the pressure distribution between the sonic point and the condition on the flow downstream. In comparison with case 1, a substantial reduction in blockage factor is noticed in case 2. Figure 3 shows the comparison of the blockage at the different upstream axial locations of the DTMs, evaluated from the displacement thickness, up to the transition region ($x/X_s = 1$) at two different time intervals. It is presumed that the maximum in this figure is associated with the coalescence of the boundary layer on the axis of the motor port. A sudden increase in blockage was noticed at different axial locations during the flow transition period, which, however, is not reported here. These results are supported with the available experimental findings [14]. Figure 3 is corroborative evidence of the area blockage at the transition region, which amounts to the internal flow choking at the transition region of the DTM with a narrow upstream port (case 1). Note that for case 1, around 30% area blockage is observed at the transition region at $t = 1–10$ ms. Also note that solution is converged at $t = 10$ ms. This is sufficient to propose the temporary formation of a *fluid-solid convergent–divergent nozzle* at the transition region during the startup transient of the aforesaid DTM. As a result, the upstream narrow port of the DTM will act like a second igniter to the downstream port leading to the formation of possible shock waves inside the DTM.

Normal shock waves, which we normally assume to be simple discontinuities in the flow, occurring at a discrete cross section, in practice have more complicated geometries, in part simply due to the nonuniformity of the velocity profile, but also due to the complex interaction of the shock wave with the viscous flow in the vicinity of the duct walls. Note that large adverse pressure gradients are imposed on a moving stream by the presence of a shock. The slow-moving fluid close to the wall of duct has insufficient momentum to negotiate this pressure gradient. As a consequence, depending upon the original thickness of the boundary layer and strength of the shock wave, boundary layer or even flow separation occurs near the wall, and in the central portion of the flow a complex oblique shock pattern may be established. The presence of a shock implies that the flow is choked.

Numerical computations are continued until the solutions converge. In case 2 (see Fig. 2), solution is converged at $t = 8$ ms.

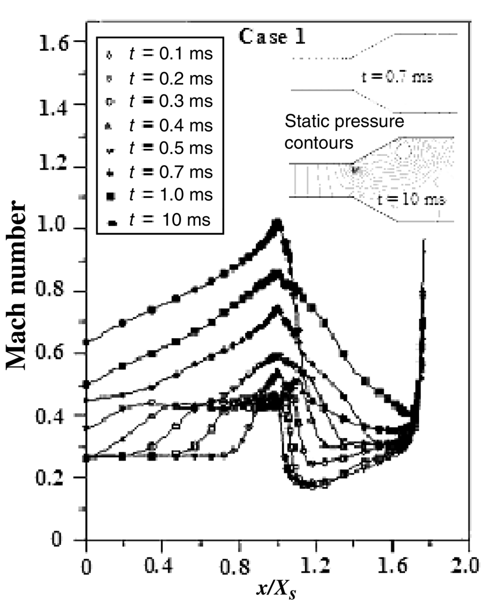

Fig. 1 Mach number variations along the axis of a DTM with narrow upstream port.

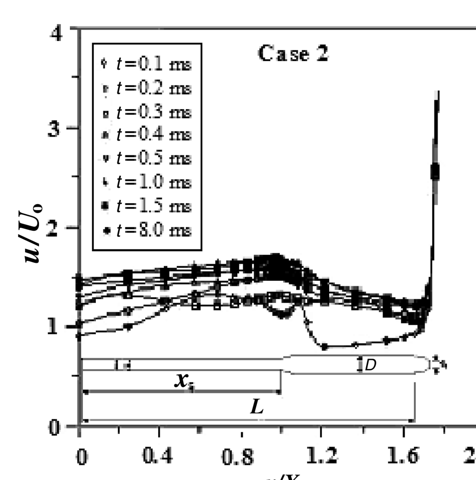

Fig. 2 Velocity variations along the axis of a DTM with enlarged upstream port ($L/d = 28.6$).

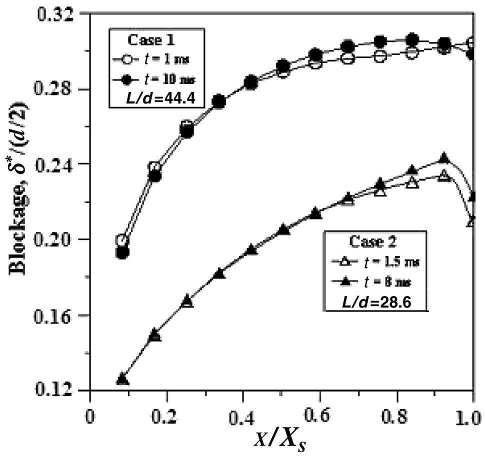

Fig. 3 Blockage factors along upstream ports of DTMs with different L/d ratios at different time intervals.

Note that by that time the flow is choked at the nozzle end and not at the transition location. At the transition location ($x/X_s = 1$) Mach number observed was 0.48. But in case 1, solution was converged at $t = 10$ ms and a choked flow condition was observed at the transition location (See Fig. 1 at $x/X_s = 1$) before the nozzle choking. Note that these time scales can be altered by altering the igniter gas temperature. In real motors, time scale of ignition pressure spike depends on many factors including the igniter jet characteristics, ignition delay, propellant properties, and motor geometry [4]. It was observed through static tests that ignition delay (45–200 ms), time at motor peak (100–500 ms), and time at igniter peak (20–50 ms) altered at identical test conditions, too. It was reported previously through different parametric analytical studies that altered variations of igniter characteristics, propellant properties, grain surface effects, ignition delay, and motor configuration effects could alter the time scale of the igniter/motor peak pressure [4]. In a nutshell, with reference to the present CFD results, it may be noted that the small time scale (10 ms) adopted in this analysis will not dilute the proposed postulation on internal flow choking due to the *fluid-throat* effect.

Figure 4 shows the dissection of the velocity up to the divergent location, X_s, at two different axial locations of the DTMs at different time intervals, up to the time of convergence ($t = t_{eq}$), to facilitate the comparison of the sequence of the flow transition at the upstream region of case 1 and case 2. In both cases, at the head-end region of the DTM, a boundary layer grows from the port wall and the core of the motor port is filled by fluid which has nearly uniform velocity. Note that the turbulent boundary layer grows to fill the entire cross section and the core disappears. Following the elimination of the core, further changes in the velocity profile and in the turbulent structure continue to occur within the flow. At the stage when the core is just eliminated, the velocity distribution is such that there is a well-defined peak velocity on the motor axis before the transition region, and appreciable variations in velocity occur over the whole cross section. As the flow further develops, the peak in the velocity profile gradually disappears until a much flatter distribution is established in the center of the motor port, the largest changes in velocity being confined to a narrow region near the port walls. Eventually, the fully developed state is attained. These flow features can be discerned in Fig. 4. Figure 4b shows the deviation of the maximum velocity from the DTM axis (centerline) at $t = 10$ ms. Evidently, this is because of the flow distortion (see inset of Fig. 1 at $t = 10$ ms) due to the shock wave. It is also observed that a case with narrow upstream port shows high mean velocity.

The apparently obvious inference that can be drawn from this study is that the possibility of the occurrence of a choked flow condition at the transition region of the DTM with a narrow upstream port is very high. This will lead to the formation of shock waves inside the rocket motor. It has been observed that when the upstream port area was large the formation of the *sonic fluid-throat* was not discerned with the same igniter jet flow. Note that when the upstream port area of the DTM was narrow, the ignition pressure spike observed during the full scale static test was on the order of five times that of the steady-state value. But this pressure spike was not observed during the full scale static tests of DTMs with the enlarged upstream port area and with the same igniter. This technique was also

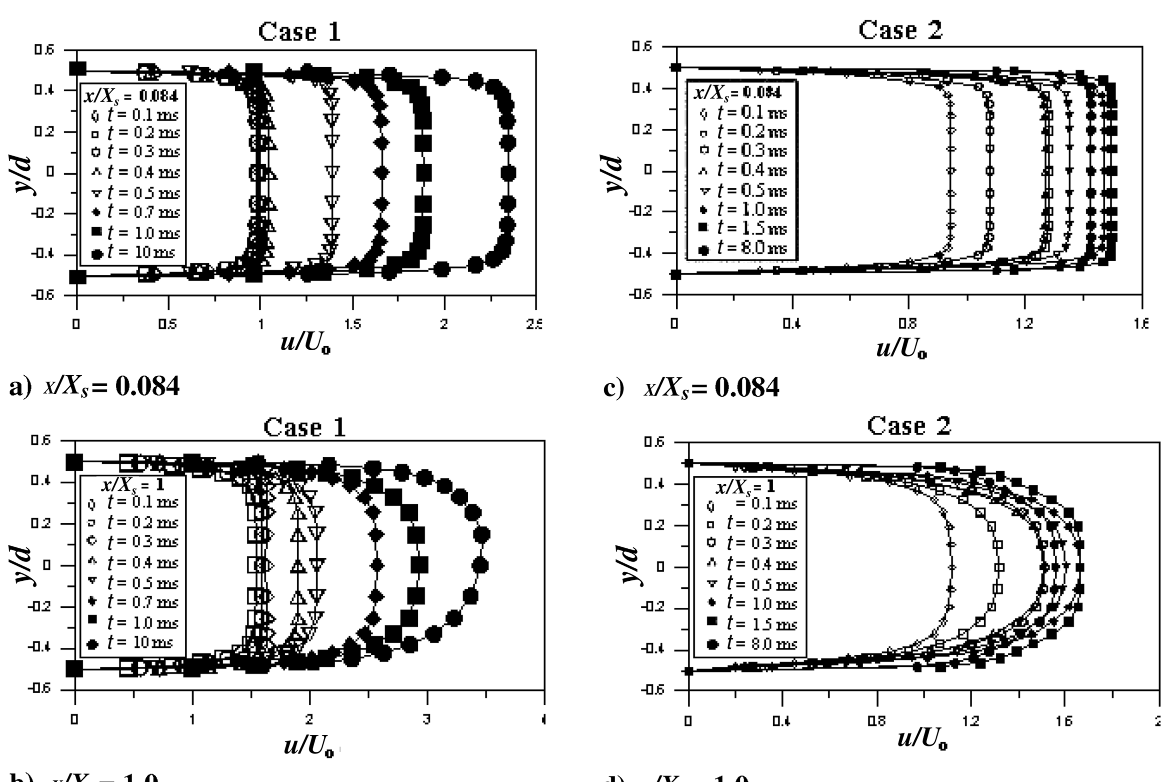

Fig. 4 Comparison of the velocity dissections in the upstream ports of case 1 & 2.

successfully applied to certain class of flight motors of Indian origin for reducing the magnitude of the ignition pressure spike. As stated in the companion note [1], this remedy (i.e., enlarging the upstream port area) has affected the high-performance nature of the rocket motor. In the process of identifying which phenomenon or a combination of phenomena was causing the pressure spike, pressure-rise rate, and pressure oscillations in dual-thrust motors, the importance of hitherto unexpected flow features of the rocket motors have come to the foreground. Through these findings, ballisticians can explore possible remedies (like boundary layer trips) for eliminating the unacceptable pressure spikes and the pressure oscillations often experienced in DTMs without diluting their high-performance.

Concluding Remarks

Theoretical studies have been carried out to examine the aerodynamic choking and the existence of a fluid-throat, at the transition region, during the startup transient of DTMs. It was observed that at the subsonic inflow conditions there is a possibility of the occurrence of internal flow choking in DTMs due to the formation of a *fluid-throat* at the beginning of the port divergence location induced by area blockage caused by boundary layer displacement thickness. It has been observed that a 55% increase in the upstream port area of the DTM contributes a 25% reduction in blockage factor at the transition region, which could negate the internal flow choking and supplement with an early choking of the DTM nozzle. Note that in developing turbulent flows at the point when the potential core is just eliminated, the velocity on the duct axis, the displacement thickness, and the momentum thickness parameters all attain their maximum values. Downstream of this point, further adjustments to the velocity profile occur, resulting in a reduction in the magnitude of the above parameters, before fully developed flow is established. Hence, equal values of the integral parameters can occur at different entry length, although the velocity profiles and turbulence structures for these conditions are quite different. These parameters have been found to have a significant effect on motor performance. The seemingly obvious conclusion that can be drawn from this study is that the possibility of the occurrence of a choked flow condition at the port divergence region of the DTM with a narrow upstream port is very high and that might lead to the formation of shock waves. Shock waves, both normal and oblique, are events which occur over a very short distance. From the point of view of the continuum theory, they can be treated as localized discontinuities within the flow, which everywhere else satisfies the continuum hypothesis. The authors have conjectured that the shock waves in DTMs can generate additional turbulence. The fact is that the reference velocity will be less after shocks, which could increase the turbulence intensity. In real motors, shock waves and the new turbulence level will alter the location of the reattachment/secondary ignition point and also enhance the heat flux to the propellant surface, which in turn will enhance the flame spread rate and the transient burning [2]. The cumulative affects of this entire phenomenon would result to amplify the pressure spike, the pressure-rise rate, and the thrust oscillations during the mission of dual-thrust motors. 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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