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Flow Investigation in a Convergent-Divergent Nozzle with Spike Injection System

M Vadivelshakthi[1], S Prakash[2], S Kiran Kumar[3]

[1]*Assistant Professor, Department of Mechanical, Meenakshi Sundararajan Engineering College, India*

[2, 3]*III Year, Department of Mechanical Engineering, Meenakshi Sundararajan Engineering College, India*

Corresponding Author: M Vadivelshakthi

ABSTRACT : *All space launch vehicles and missiles require thrust vector control (TVC) to fly along programmed flight path. In the Convergent-Divergent nozzle thrust vector control was introduced by heat resistant movable bodies which are one of the passive control methods. Vortex generators, riblets, large-eddy break-up devices, castellation and passive cavities belong to passive control system. Passive control of the jet can be achieved by adding geometrical modifications in the Convergent-Divergent nozzle. Spike Injection Thrust Vector Control-SPITVC is one of the passive control methods. A convergent-divergent nozzle is designed using CATIA V5R21 in which spike has to introduced. Square and rectangular spikes are introduced through the supersonic jet stream through the wall of the diverging cone of the rocket nozzle. It is introduced through the wall of the diverging cone of the nozzle into the flow stream from 35% of the nozzle length i.e. from throat to exit. It is also injected to centerline of the nozzle in the diverging section at 2/3 positions of the diverging length of the nozzle. A parametric study on Spike Injection Thrust Vector Control has been accomplished numerically with the help of a Computational Fluid Dynamics (CFD) code called ANSYS FLUENT® for various Mach number (M_e) 1.82 with and without spike. The simulation of three dimensional flow fields inside a test case nozzle for the selection of parameters associated with both computational grid and the CFD solver such as mesh size, turbulence model approaches, and solver type. This part revealed that simulation of internal flow field by a segregated solver with realizable k-ε turbulence model accompanied by enhanced wall treatment approach is accurate enough to resolve this kind of complex three dimensional fluid flow problems. Spike injection resulted in faster decay of the jet as well as reduction in potential core length. It induces the stream wise vortices into the mixing layer of the jet. These vortices can then interact with the flow structures in the mixing layer and could potentially enhance the mixing of the main jet with the ambient air. These results were also compared with uncontrolled jet and jet with solid spike. Observation of Mach number, total pressure, velocity, pressure and density contour plots are simulated. Data on the relationships of side force created by the spike injection, the effect of axial location of the spike are presented and discussed.*

Keywords: *Convergent-Divergent Nozzle, Passive Control, Potential Core Length, Spike, Thrust Vector*

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I. INTRODUCTION

Most vehicles used for launching spacecraft require some guidance (or) steering to ensure that required flight trajectory will be achieved. In addition, steering is needed to compensate for flight disturbance (e.g. winds) and for vehicle imperfections (e.g. misalignment of thrust and center of gravity). To provide this steering, nozzles are equipped with thrust vector control system. The primary control is provided by the fin tip control surfaces, while secondary injection thrust vector control-SITVC system operates in a proportional mode, whenever the control force demand is in excess of the fin tip control capability. The SITVC system is inherently heavy, as it has to carry the injectant and the pressurization system. Extra mass gets added on account of additional thermal protection at the injection point and the quantity of injectant to be carried to cater to flight contingency demands. A TVC scheme, which eliminates or minimizes these negative features, therefore will add to the value and performance of the vehicle. In the Convergent-Divergent nozzle thrust vector control was introduced by heat resistant movable bodies i.e. Spike Injection Thrust Vector Control-SPITVC in the supersonic jet stream through the wall of the diverging cone of the rocket nozzle. The solid probe thrust vector control provides an attractive alternative to secondary injection thrust vector control concept. In this scheme, a solid wedge or strut is inserted in the gas stream to provide an obstruction to the flow, similar to the effect provided by the SITVC. In the classical case of secondary injection, we have a boundary layer separation slightly upstream of the injection accompanied by a conical weak shock. At the point of injection is the strong bow shock resulting from the impingement of the primary stream on the obstruction caused by injectant. The solid wedge will provide a similar effect and can be effectively used as a thrust vector device. The concept has been studied in the laboratories through Computational Fluid Dynamics simulation. Cold flow studies have shown that the system response time is in the order of 20 m-secs.

II. SPIKE INJECTION THRUST VECTOR CONTROL FOR S9 ROCKET MOTOR

The S9 rocket motor presently employs secondary injection thrust vector control (SITVC) system for vehicle steering during the initial 16 seconds of flight. After this phase of flight, the primary control is provided by the fin tip control surfaces, while the secondary injection thrust vector control (SITVC) system operates in a proportional mode, whenever the control force demand is in excess of the fin tip control capability. The SITVC system is inherently heavy, as it has to carry the injectant and the pressurization system. Extra mass gets added on account of additional thermal protection at the injection points and the quantity of injectant to be carried to cater to flight contingency demands. A thrust vector control scheme which eliminates or minimizes these negative features therefore, will add to the value and performance of the vehicle. It is therefore thought that an alternative TVC system lie Spike Injection Thrust Vector Control (SPITVC) is more suitable for a rocket motor especially like S9 (which is used for missiles). It is also due to the fact that the hardware and tooling systems of S9 are all frozen and any change in the TVC system should have no impact on existing nozzle design. Hence, a flexible nozzle control system is ruled out. For the S9 motor, SPITVC is an ideal replacement for the existing SITVC system as no major hardware changes are needed. Based on the theoretical and experimental modeling, hardware changes are expected only in TVC plane. No changes in the nozzle liners or interfaces with the motor are required. Also the extra mass on account of the secondary injectant and its pressurization system can be dispensed with, with a resultant increases in payload/performance.

III. CONVERGENT-DIVERGENT NOZZLE AND SPIKE

In the CD nozzle spike injection thrust vector control (SPITVC) is designed and the cold flow studies CFD modelling will be taken up and meshing is done in hyper mesh. Parameters, which influence the side thrust, are the dimensions and shape of the spike and the depth of penetration in the flow. These will be investigated. For SITVC, injection location is found optimum around 35% of the nozzle length from throat to exit. It is also injected to centreline of the nozzle at various locations in the diverging section at 2/3 positions of the diverging length of the nozzle. A point of investigation will be to verify, if this is true for the SPITVC system and if different, to experimentally determine the optimum effective location. Test will be carried out in the Mach number range of 1.8 which corresponds approximately to the Mach numbers at the injection plane (35% of the nozzle length i.e. from throat to exit) for booster rocket nozzles. For nozzles inlet area, throat area, convergent length and divergent length are kept constant for both with and without spike. The nozzles have been designed for the pressure ratio 6 therefore desired Mach number 1.8282, area ratio 1.498 and maximum mass flow rate 0.1259 Kg/s. The nozzles have been modeled by using CATIA V521. The following are the parameters of the nozzle that have been maintained constant in both with and without spike.

Dimension of C-D Nozzle

Parameters	Dimensions
Inlet Diameter	19.40 mm
Inlet Area	295.59 mm^2
Throat Diameter	10.70 mm
Throat Area	89.92 mm^2
Exit Diameter	12.93 mm
Exit Area	262.735 mm^2
Length of the Nozzle	75 mm
Convergent Length	30 mm
Divergent Length	45 mm
Divergent Angle	1.42°

Dimension of Square Spike TVC - SPITVC

Parameters	**Dimensions**
Spike Configuration	Square
Length of the spike	10 mm
Length of the spike penetration @ 2/3 from throat	6.09 mm
Cross Sectional area	1.5 * 1.5 mm
Penetration Depth	Up to the nozzle centreline

IV. COMPUTATIONAL ANALYSIS

Computational Fluid Dynamics (CFD) uses various numerical methods and approximations to solve the fluid flow problem. A fluid flow problem is governed by three fundamental principles: 1) Conservation of mass, 2) Conservation of momentum, and 3) Conservation of energy. These principles can be expressed in the form of mathematical equations, usually as partial differential equations (PDEs). These equations are together represented as a Nervier Stokes Equation which can effectively be used to depict any single phase fluid flow problem. For simulation of nozzles, the geometry has to be generated and discretized and then solved with CFX. The three steps involved in CFX are pre-processing, processing and post-processing. Ansys CFX is used for the simulation of the nozzle. The modeled flow domain is then taken for meshing where the domain is divided into cells for solving the discretized problem. HYPER MESH meshing is used to mesh the geometry. Shown below is the typical meshed geometry which shall be processed using CFX solver. For an accurate representation of the flow field, sufficient grid density mesh must be provided in the mixing region. Because the position of the shear layer is not known in advance, a large number of predetermined grid points are required to provide high density coverage of the three-dimensional space if a fixed grid is used for the computations. An alternative is to provide high grid density in the appropriate locations. Patch confirming hexahedron method is used for meshing.

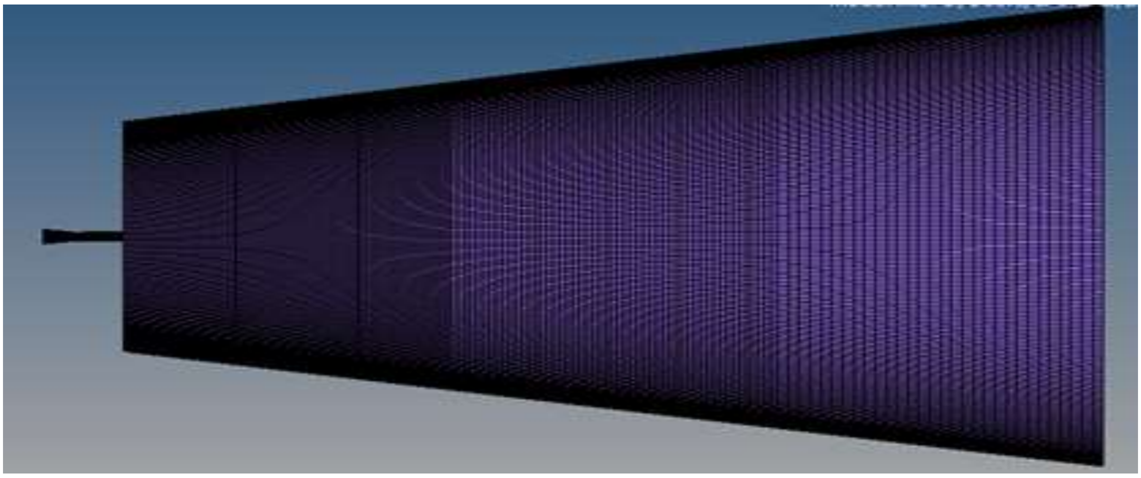

Figure 1: Structured Mesh of C-D Nozzle

V. RESULT AND DISCUSSION

The computational study for uncontrolled Jet in the convergent-divergent nozzle without spike has been completed for the flow through the nozzle. All simulations were done for the same boundary conditions and same length of the domain length. The nozzle jet Mach number studied is 1.8. The Mach number contour along the jet axis from the throat of nozzle is obtained after simulation for the 6 bar inlet pressure conditions.

Centreline pressure decay or Mach decay or Mach number decay can be taken as an authentic measure of mixing enhancement in high speed jets. Centreline Mach Decay (CMD) for free jet at Mach number 1.8. The measured Pitot pressure along the centreline with the assumption that the static pressure in the jet field is the atmospheric pressure, were converted to Mach using the isentropic relations. This assumption on the static pressure is valid for all subsonic Mach numbers, because they are always correctly expanded. For Sonic jet this assumption is valid for correctly expanded jets. X-axis is nondimensionalized by the exit diameter of the nozzle and Y-axis is normalized with normal exit Mach. The free jet results clearly revealed the important regimes of the jet flow field namely the potential core region, characteristic decay and the self-similar region. Beyond the potential core region there had been decay in the Mach ratio which clearly indicates the entrainment of the ambient air into the jet core.

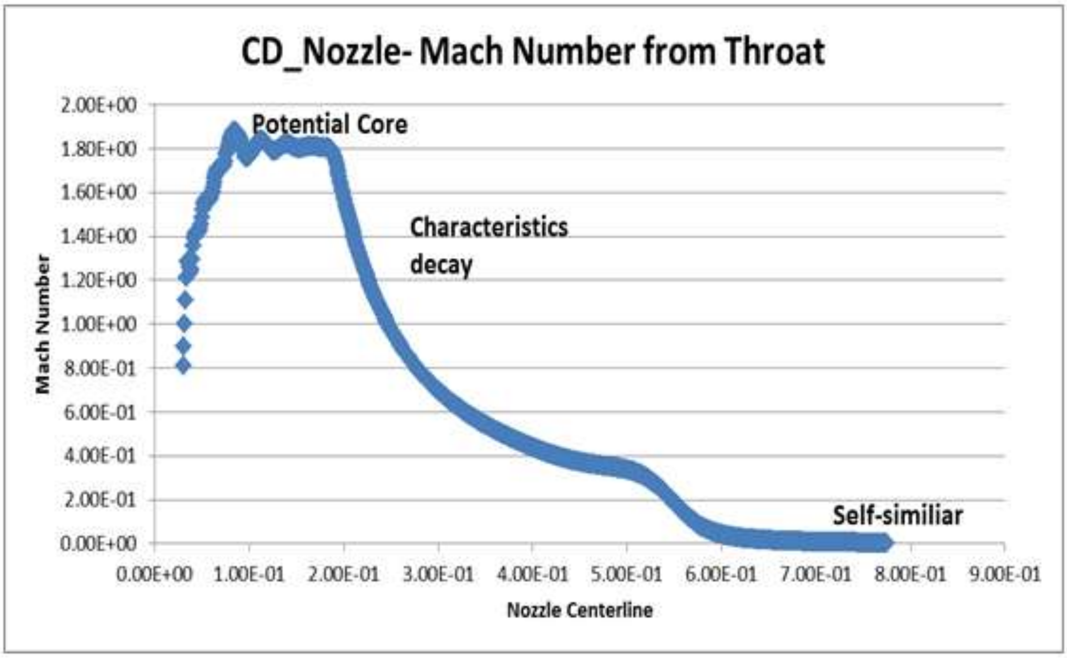

Figure 2: Mach number plot of C-D Nozzle

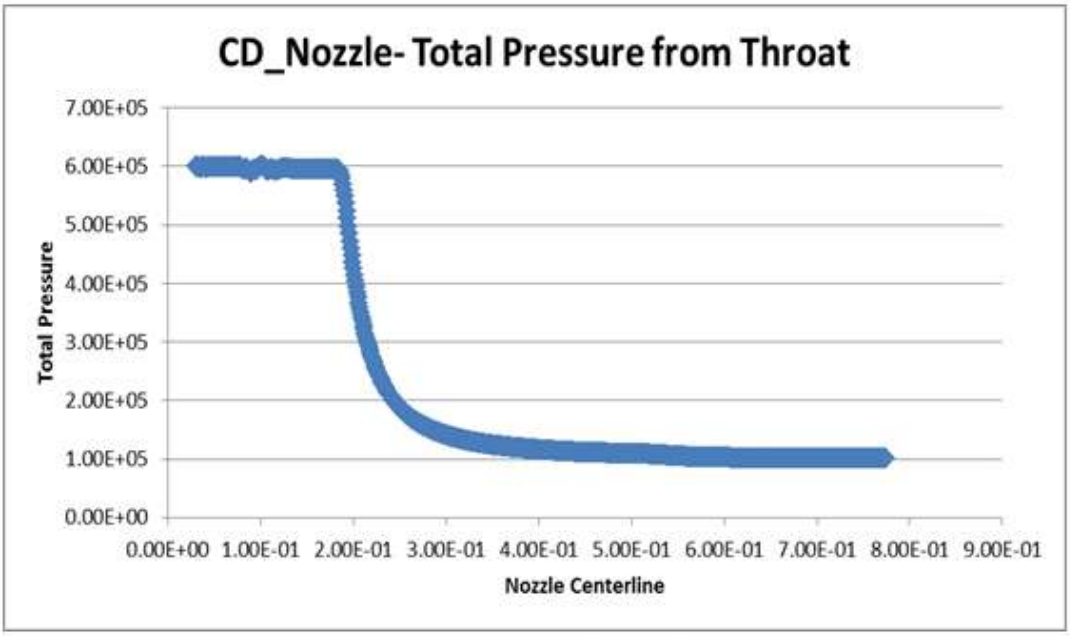

Figure 3: Total Pressure Plot of C-D Nozzle

Spike is introduced through the wall of the diverging cone of the nozzle into the flow stream by active control method. It induces the stream wise vortices into the mixing layer of the jet. These vortices can then interact with the flow structures in the mixing layer and could potentially enhance the mixing of the main jet with the ambient air. Square spike are injected in supersonic jet stream of the divergent cone at 30 mm from the throat of the rocket nozzle, CFD flow analysis carried out for Mach number (M_e) 1.8. At the point of injection the strong bow shock resulting from the impingement of the primary stream on the obstruction caused by injectant. From the below contours and graphs it is observed that the velocity decay is higher and shock cell is weaker for nozzle with spike as compared to without spike

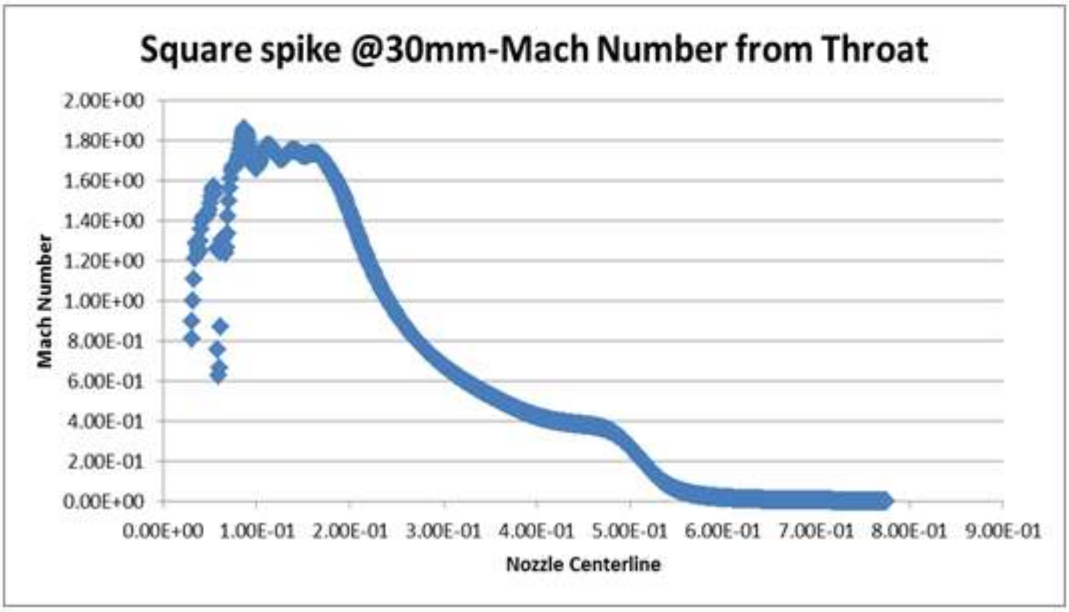

Figure 4: Mach number plot of C-D Nozzle with Square Spike at 30mm

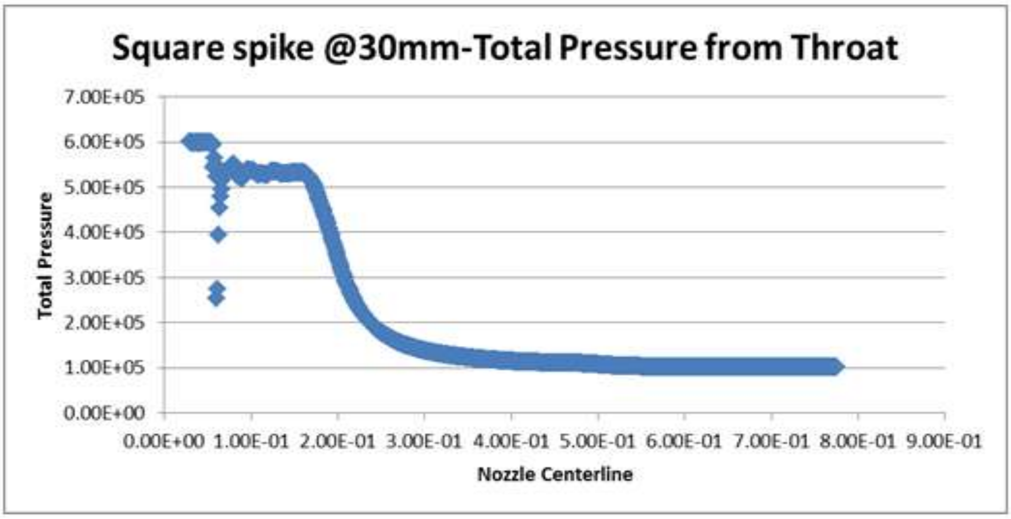

Figure 5: Total Pressure Plot of C-D Nozzle with Square Spike at 30mm

There is the sudden drop in both Mach number and pressure at the point where the spike is introduced. One pair of stream wise vortices is generated when spike were introduced at the 30mm of the diverging section of the nozzle exit of the nozzle. These vortices are small and have a long life span. Therefore they act as effective mixing promoters and enhance mixing. This faster mixing result in rapid jet decay of the jet with spike compared to a jet from a plain nozzle. According to past research smaller the size of vortex, the better is the mixing because small size vortices travel longer distance and are stable.

VI. CONCLUSION

It has been proved that jet control with spike at the nozzle wall of the diverging cone shows that the Mach decay is faster drastically as compared to uncontrolled jets. Mach Variation measured in the jet flow field clearly demonstrates the increased spreading of the jet under the influence of spike. The possible reason is due to the acceleration of flow because of spike introduction. The increased mixing is due to the impinging action of the flow in the spike due to that the major flow is disturbed in the area of mixing layer *i.e., wake* exposed to mixing. This increase had caused an increase in the entrainment of the flow in the diverging portion to the jet core. Thus the centreline Mach decay is more at 30mm spike location when comparing to the other spike location. This leads to noise reduction and thrust loss during thrust vectoring. When comparing to square spike, rectangular spike reduction in potential core length is more. Rectangular spike tends to reduce pressure oscillations more in core region of jet compared to the uncontrolled jet. Also, the rectangular spike could able to weaken the waves in the jet core. The flow analysis also showed that rectangular spike thrust vector control SPITVC is efficient than the C-D nozzle without spike in terms of better entrainment and minimize thrust loss during thrust vectoring.

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