World Academy of Science, Engineering and Technology
International Journal of Aerospace and Mechanical Engineering
Vol:7, No:8, 2013

Numerical Studies on Thrust Vectoring Using Shock Induced Supersonic Secondary Jet

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Abstract**—**Numerical studies have been carried out using a validated two-dimensional RNG k-epsilon turbulence model for the design optimization of a thrust vector control system using shock induced supersonic secondary jet. Parametric analytical studies have been carried out with various secondary jets at different divergent locations, jet interaction angles, jet pressures. The results from the parametric studies of the case on hand reveal that the primary nozzle with a small divergence angle, downstream injections with a distance of 2.5 times the primary nozzle throat diameter from the primary nozzle throat location warrant higher efficiency over a certain range of jet pressures and jet angles. We observed that the supersonic secondary jet opposing the core flow with jets interaction angle of 40° to the axis far downstream of the nozzle throat facilitates better thrust vectoring than the secondary jet with same direction as that of core flow with various interaction angles. We concluded that fixing of the supersonic secondary jet nozzle pointing towards the throat direction with suitable angle at a distance 2 to 4 times of the primary nozzle throat diameter, as the case may be, from the primary nozzle throat location could facilitate better thrust vectoring for the supersonic aerospace vehicles.

Keywords**—** Fluidic thrust vectoring, rocket steering, supersonic secondary jet location, TVC in spacecraft.

I. INTRODUCTION

THRUST vectoring technique can deflects the mean flow of an engine jet from the centerline in order to transfer some force to the aimed axis. Although many studies have been carried out in fluidic thrust vector nozzles the design optimization of thrust vector control (TVC) is still a daunting task in aerospace industry [1]-[18]. One such problem of urgency is the vectoring of launch vehicles. Note that the desirable goal of a fighter aircraft designer is to increase the agility, maneuverability, and survivability of the jet aircraft. But in the case of a rocket, it is well known that in addition to providing a propulsive force to a flying vehicle, a rocket propulsion system can provide moments to rotate the flying vehicle and thus provide control of the vehicle's attitude and flight path. And it is possible to control a vehicle's pitch, yaw, and roll motions using appropriate TVC mechanisms. All chemical propulsion systems can provide with one of several types of TVC mechanisms. Most of the TVC mechanisms are specific to certain propulsion categories such as, solid, hybrid or liquid propulsion systems. There are two types of popular TVC concept viz., for an engine or a motor with a single nozzle; and those that have two or more nozzles. Note that the thrust vector control is effective only while the propulsion system is operating and creating an exhaust jet. Therefore during the coasting time a separate mechanism needs to be provided to the flying vehicle for achieving control over its attitude or flight path.

Usually, the thrust vector of the main rocket nozzle is in the direction of the vehicle axis and goes through the vehicle's center of gravity. Thus it is possible to obtain pitch and yaw control moments by the simple deflection of the main rocket thrust vector; however, roll control usually requires the use of two or more rotary vanes or two or more separately hinged propulsion system nozzles. Thrust vectoring is the ability of an aircraft, rocket or other vehicle to deflect the angle of its thrust away from the vehicles longitudinal axis. The criteria governing the selection and design of a TVC system stem from vehicle needs and include the steering-force moments, force rates of change, flight accelerations, duration, performance losses, dimensional and weight limitations, available vehicle power, reliability, delivery schedules, and cost. These are succinctly reported by Sutton, G.P., and Biblarz O. [1].

With the advent of computational fluid dynamics (CFD) and available computer power, several numerical studies have been reported on the TVC of aerospace launch vehicles using different techniques. Even though all these studies have been helpful in interpreting many fundamental processes on thrust vectoring, the understanding of an efficient and lucrative TVC system has been elusive [18]. This calls for a reexamination of all the available information before embarking on the formulation of a new TVC system and its code of solution. Towards this objective, in this connected paper, with the help of a theoretical model, parametric analytical studies have been carried out to determining the secondary jet location and its angle for inducing desirable shock and its characteristics for an efficient and lucrative TVC system using a conventional

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CD nozzle. The studies are directed toward the diagnostic investigation; so that readers can connect the coupling of many complex processes for the possible improvements and modifications on overall thrust vectoring of aerospace vehicles on their hand. The secondary injection thrust vector control is particularly attractive for thrust vectoring in large boosters (especially solid propellant rocket) where large side thrust can be generated. Injection ports are provided at a particular axial station around the periferi in the divergent cone. The injectant can be liquids (Ferons, Strontium perchlorate solution) or gases (e.g. Bleed from combustion chamber) and these can be inert or reactive. The secondary fluid injected, creates an unsteady complex three-dimensional flow field inside the nozzle. This complex flow field includes not only a strong bow-shock creating asymmetry and a weak separation shock due to boundary layer separation upstream of the injection location but also a Mach disc and reattachment region accompanied by recompression downstream of the injection location as shown in Fig. 1. Though the complex flow structure, as seen in Fig. 1, associated with the secondary injection thrust vector control (SITVC) is reported in open literature its modeling effort is still a daunting task.

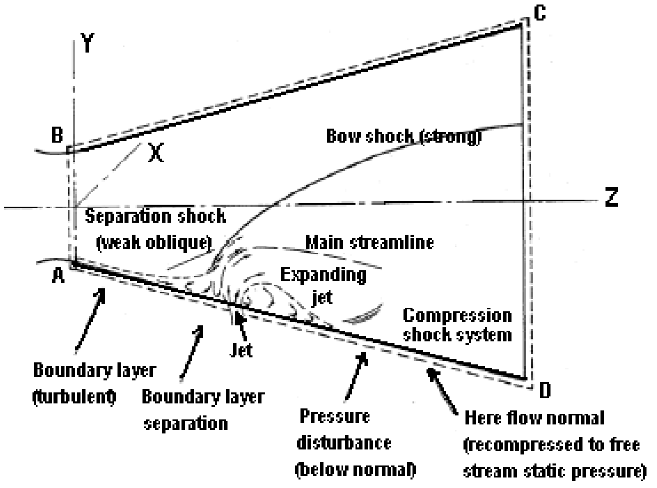

Fig. 1 Complex flow structure associated with SITVC

The concept of TVC by *secondary fluid injection* into the exhaust stream dates back to 1949 and can be credited to A. E. Wetherbee, Jr [2]. Application of *liquid injection thrust vector control* (LITVC) to production vehicles began in the early 1960s. Both inert (water) and reactive fluids (such as hydrazine or nitrogen tetroxide) have been used. Although side injection of reactive liquids is still used in some of the older vehicles, it requires a pressurized propellant tank and a feed system. Fluid injection induces a bow shock in the supersonic stream followed by a deflection of the flow and high pressure on the downstream side of the shock. This produces necessary vectoring in the desired direction.

Literature review reveals that the maximum vector deflection angle occurs at mass flow rate ratios (m_{inj}/m_{nozzle}) in the range of 0.05 - 0.08. The deflection angles can be as high as 7^o with liquid injection and up to 12^o with hot gas injection. In this paper we focus on three critical elements of the thrust vector control system with non-reacting gases for both primary and secondary jets before embarking on the formulation of a new TVC system with supersonic secondary injection. The first one pertains to the location of the secondary injection nozzle, second one refers to jets interaction angle and the third one refers to the desired flow features of the secondary jet.

II. NUMERIAL METHOD OF SOLUTION

Numerical simulations have been carried out with the help of a two-dimensional steady RNG k-epsilon turbulence model. Ideal gas is considered for analysis. The model uses a control-volume based technique to convert the governing equations to algebraic equations. The viscosity is computed based on Sutherland formula. A typical 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 nozzle 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. The code has successfully validated with the help of benchmark solutions. Fig. 2 shows the physical model of the primary nozzle and the locations of the supersonic jet nozzles (L_1-L_3). The nozzle flow features have been examined at three different key locations between the nozzle exit and the throat with different jet pressures and jet angles.

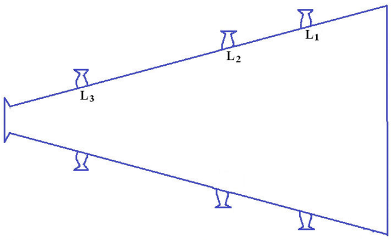

Fig. 2 Physical model of the primary and secondary jet nozzles

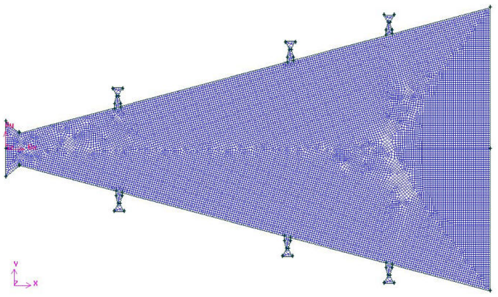

Fig. 3 Grid system in the computational domain

III. RESULTS AND DISCUSSION

In addition to providing a propulsive force to a flying vehicle or a rocket, a rocket propulsion system can also provide certain control mechanisms to change vehicle's attitude and trajectory via thrust vector control systems. Vehicles that fly outside the atmosphere, aerodynamic control surfaces are ineffective, so thrust vectoring is the primary means of attitude control. In this paper the forces produced by the exiting exhaust gases are manipulated from the axial direction to produce a side or vertical force by injecting a secondary jet with different jet pressures from various divergent locations of the primary nozzle to examining the best location, jets interaction angle and the desirable secondary jet characteristics for devising an efficient TVC system. Note that after injecting the secondary supersonic jet to the primary flow the resulting force vector will have an axial component in line with the body that propels the aircraft forward and a radial or side force that will result in a turn angle of the body. The supersonic fluid jet induces a bow shock in the supersonic stream followed by a deflection of the flow and high pressure on the downstream side of the shock (see Fig. 4). This influence over a segment of the nozzle drastically alters the pressure distribution on the nozzle surface in an unsymmetrical way about the nozzle axis. This produces the necessary moments to the vehicle (pitch, yaw and certain extent to roll also). The magnitude of the side force increases as the injection port is moved towards the throat as also when the injectant mass flow rate increases – both being in the nominal working range.

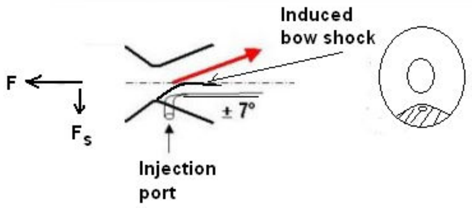

Fig. 4 Demonstrating the formation induced bow shock

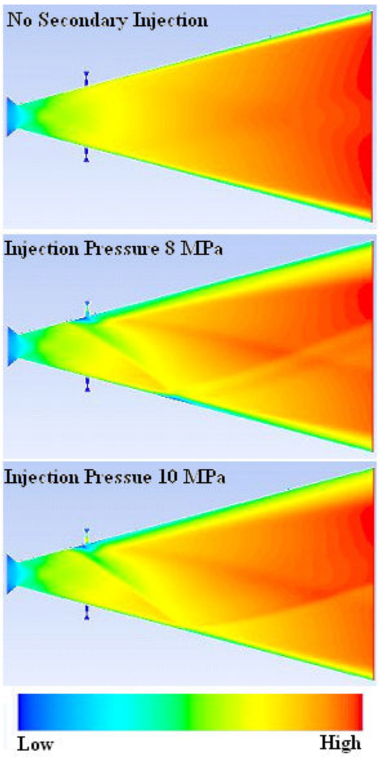

Fig. 5 (a) Mach contour

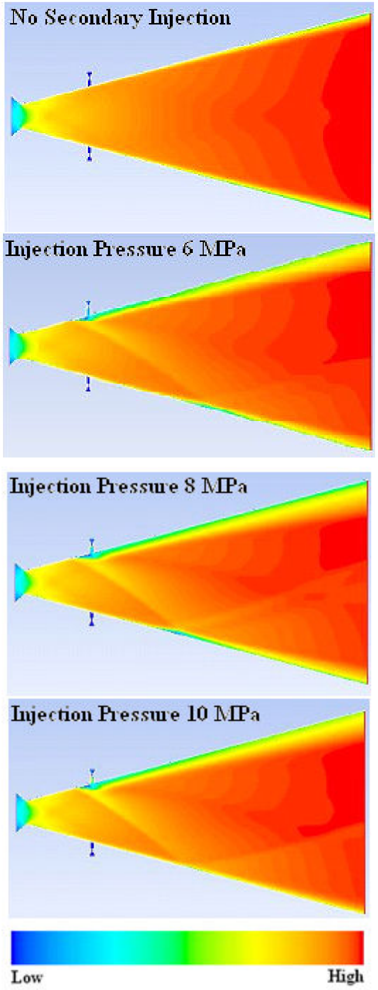

Fig. 5 (b) Velocity contour

In this paper the forces produced by the exiting exhaust gases are manipulated from the axial direction to produce a side or vertical force by injecting a secondary jet with different jet pressures from various divergent locations of the primary nozzle to examining the best location and the desirable secondary jet characteristics for devising an efficient TVC system. Note that after injecting the secondary supersonic jet to the primary flow the resulting force vector will have an axial component in line with the body that propels the aircraft forward and a radial or side force that will result in a turn angle of the body. With the side injectant, the axial thrust level also increases to certain extent because of the enhanced mass flow. But at higher injection rates the shocks affect the bulk of the flow, thus bringing down the axial thrust values. At still higher injection rates, the interaction with the opposite walls tends to lower the side force also. In all the cases ratio of primary to the secondary mass flow is kept constant. Secondary jet pressure is varied from 6 to 10MPa to facilitating different primary to secondary mass flow rate ratios for the design optimization of TVC system.

As a first step primary nozzle flow features are examined without having any secondary jet nozzle geometry for model validation. Note that Case-1 corresponds to the baseline case without secondary jet and Case-2 corresponds to location L_1, Case-3 corresponds to location L_2, Case-4 corresponds to location L_3 (see Fig. 2). Figs. 5, 6 show very clearly the variations of contours, before and after vectoring with supersonic secondary jets, with 6MPa, 8MPa and 10MPa jet pressures. Shock waves are evident in all the cases near the secondary jets. Note that the secondary jets influence, over a segment of the nozzle drastically, alters the pressure distribution on the nozzle surface in an unsymmetrical way about the nozzle axis. This produces the necessary moments to the vehicle (pitch, yaw and certain extent to roll also).

We have observed from these studies that the magnitude of vectoring increases as the location of the secondary injection port is 2 to 4 times of the primary nozzle throat diameter from the primary nozzle throat location. We have also observed that with the secondary injection, the axial thrust level also increases to certain extent because of the enhanced mass flow.

But at higher injection rates the shock affect the bulk of the flow, thus bringing down the axial thrust values and marginally decreases the vehicle acceleration. Note that at higher injection rates, the interaction with the opposite walls tends to lower the side force also. Fig. 7 shows the comparison of Mach number contours without secondary injection and with secondary injection at three different jet interaction locations opposing the core flow at an angle of 40^{o} to the longitudinal axis of the primary nozzle. Fig. 8 shows the comparison of Mach number contours at two different jet interaction angles at the same location demonstrating the variations of peak Mach number. Figs. 9-11 show the nozzle exit radial velocity profile corroborating the various qualities of vectoring produced with different secondary jets locations, directions and jet interaction angles with the same primary to the secondary mass flow rate. All these studies lead to say that in addition to the primary to the secondary flow rate, the jet pressure, location, jet interaction angles and characteristics of jet are important for the quantitative estimation of thrust vectoring for aerospace applications.

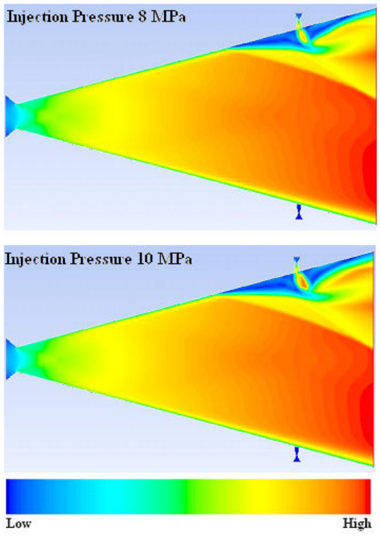

Fig. 6 (a) Mach number contour\

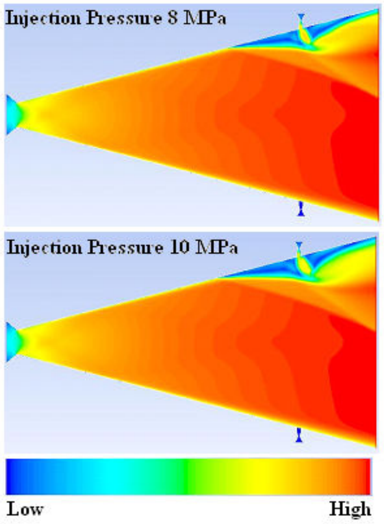

Fig. 6 (b) Velocity contour

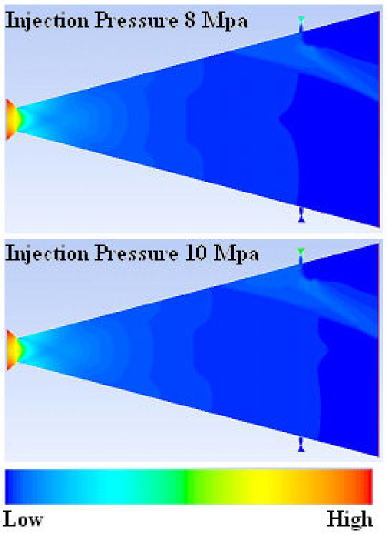

Fig. 6 (c) Static pressure contour

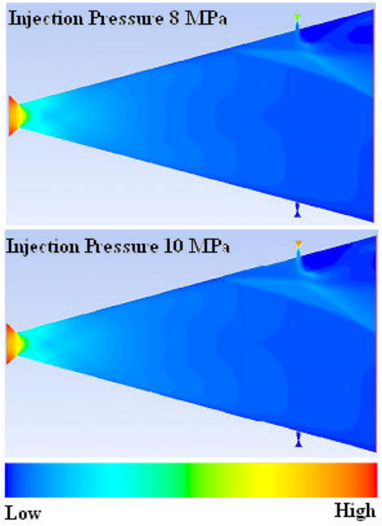

Fig. 6 (d) Density contour

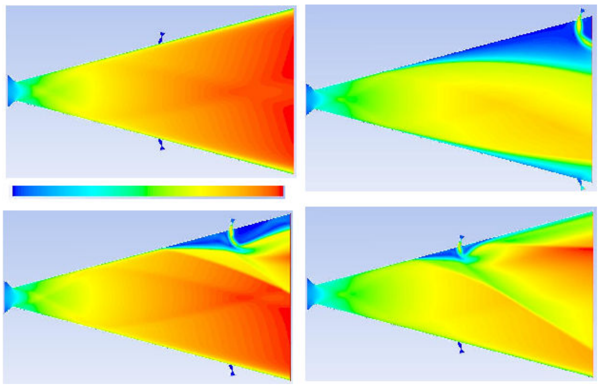

Fig. 7 Comparison of Mach number contours without secondary injection and with secondary injection at three different jet interaction locations opposing the core flow at an angle of 40° to the longitudinal axis of the primary nozzle.

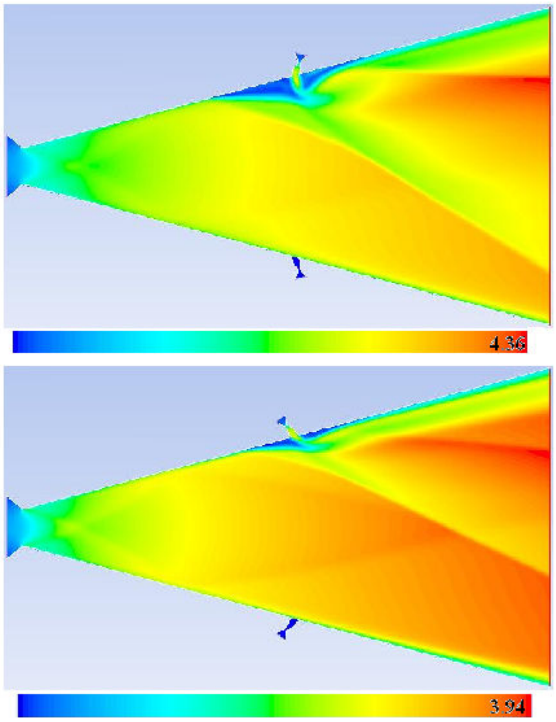

Fig. 8 Comparison of Mach number contours at two different jet interaction angles at the same location demonstrating the variations of peak Mach number.

From these parametric studies though we have observed that the location of the secondary injection port is 2 to 4 times of the primary nozzle throat diameter from the primary nozzle throat location with a secondary jet pressure of 10 MPa with a jet angle of 40° to the longitudinal axis opposing the core flow will facilitate better thrust vectoring. However, the designer should select the secondary jet location, jet angle and characteristics judiciously after detailed analyses with all the operating ranges of the aerospace vehicles for a lucrative design. During the parametric study the effects of secondary jet pressure, jet location with a fixed injection angle on secondary jet pressure on vectoring performance is studied for a typical rocket nozzle with a conical diverging cone.

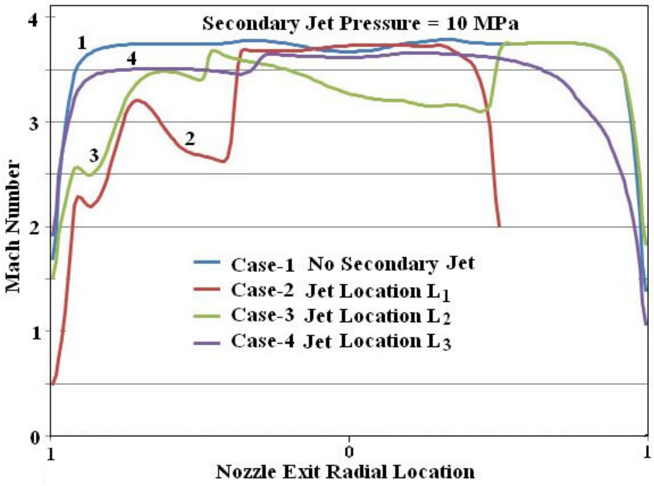

Fig. 9 Comparison of the nozzle exit velocity profile without and with supersonic secondary jet perpendicular to the longitudinal axis at a jet pressure of 10 MPa

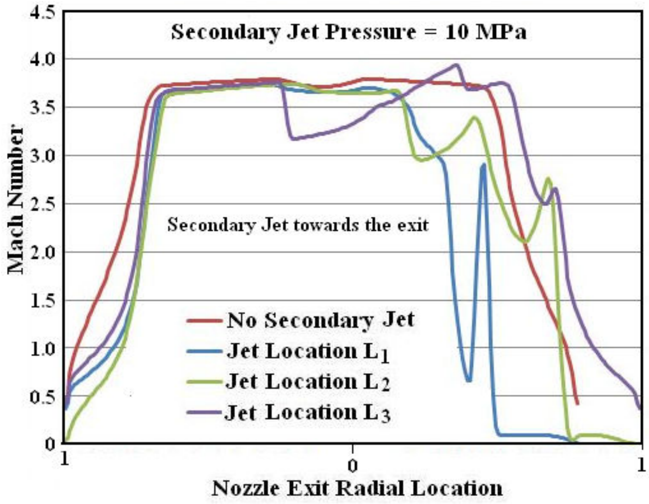

Fig. 10 Comparison of the nozzle exit velocity profile without and with supersonic secondary jet towards the exit. at a jet pressure of 10 MPa

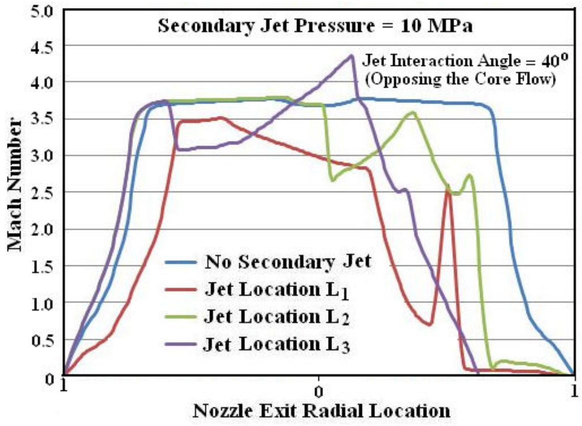

Fig. 11 Comparison of the nozzle exit velocity profile without and with supersonic secondary jet opposing the core flow at an angle of 40° to the longitudinal axis at a jet pressure of 10 MPa

In this paper several numerical simulations are run to yield the assessment of performance of vectoring system, and the results stated that for a nozzle with small divergence angle: downstream injections such as injection port with distances of 2 to 4 times of throat diameters from the nozzle throat, as the case may be, lead to higher efficiencies over a certain range of total pressure ratios (i.e., mass flow rate ratios). The impingement and reflection of shock waves should definitely be prevented for better performance. A remedy might that the upstream injections should be aligned more to the nozzle axis (i.e. higher injection angles, α) with moderate injection mass flow rates and for the moderate injection locations such as 2-2.5 throat diameters from the nozzle throat, this angle can be adjusted to the neighborhood of 45 degrees, as succinctly stated by Erinc Erdem [4]. However one thing to keep in mind is that the momentum ratio of the secondary jet to the primary one is the essence of secondary injection thrust vectoring, increasing injection angle reduces the effect of the interaction of crossing streams. Injection locations too much downstream may result reversed flows on nozzle exit, which reduces the vectoring performance. Note that after injecting the secondary jet to the primary flow the resulting force vector will have an axial component in line with the body that propels the vehicle forward and a radial or side force that will result in a turn angle of the body.

IV. CONCLUDING REMARKS

The causes of the deflection or more appropriately the side force to create deflection over the body are primarily the downstream asymmetrical pressure distribution on nozzle wall due to the strong bow shock and secondarily the normal component of the momentum of the secondary injectant. This is because of the fact that the injected fluid acts as an obstruction in the supersonic flow creating strong bow shock, and consequently 80-90% of the side force is due to the downstream asymmetrical pressure distribution (or pressure rise) on the nozzle wall whereas the momentum of the injected fluid is responsible for the rest. Another aspect of SITVC is that the moment arm of the resultant force is bigger than the mechanical TVC techniques enabling to have lesser side forces since the ratio of the side force to the axial force allowed by this technique is limited. We comprehended that enhanced wall treatment is essential to accurately capture the complex phenomena occurring both upstream and downstream of the injection port. Even though it is computationally demanding, the resolution of flow features very close to the wall results a better estimation of side force, which is the integral of pressure on the nozzle wall added to the momentum of the secondary injectant. We observed that the supersonic secondary jet opposing the core flow with jets interaction angle of 40° to the longitudinal axis far downstream of the nozzle throat facilitates better thrust vectoring than the secondary jet with same direction as that of core flow with various interaction angles. We concluded that fixing of the supersonic secondary jet nozzle pointing towards the throat direction with suitable angle at a distance 2 to 4 times of the primary nozzle throat diameter, as the case may be, from the primary nozzle throat location could facilitate better thrust vectoring for the supersonic aerospace vehicles.

ACKNOWLEDGMENT

The authors would like to thank Shankar Vanavarayar, Joint Correspondent of Kumaraguru College of Technology, Coimbatore – 641 049, Tamil Nadu, India for his extensive support of this research work.

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Open Science Index, Aerospace and Mechanical Engineering Vol:7, No:8, 2013 publications.waset.org/16212.pdf