International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:9, No:6, 2015

Numerical Studies on Thrust Vectoring Using Shock-Induced Self Impinging Secondary Jets

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Abstract**—**Numerical studies have been carried out using a validated two-dimensional standard k-omega turbulence model for the design optimization of a thrust vector control system using shock induced self-impinging supersonic secondary double jet. Parametric analytical studies have been carried out at different secondary injection locations to identifying the highest unsymmetrical distribution of the main gas flow due to shock waves, which produces a desirable side force more lucratively for vectoring. The results from the parametric studies of the case on hand reveal that the shock induced self-impinging supersonic secondary double jet is more efficient in certain locations at the divergent region of a CD nozzle than a case with supersonic single jet with same mass flow rate. We observed that the best axial location of the self-impinging supersonic secondary double jet nozzle with a given jet interaction angle, built-in to a CD nozzle having area ratio 1.797, is 0.991 times the primary nozzle throat diameter from the throat location. We also observed that the flexible steering is possible after invoking ON/OFF facility to the secondary nozzles for meeting the onboard mission requirements. Through our case studies we concluded that the supersonic self-impinging secondary double jet at predesigned jet interaction angle and location can provide more flexible steering options facilitating with 8.81% higher thrust vectoring efficiency than the conventional supersonic single secondary jet without compromising the payload capability of any supersonic aerospace vehicle.

Keywords**—**Fluidic thrust vectoring, rocket steering, self-impinging secondary supersonic jet, TVC in aerospace vehicles.

I. Introduction

THRUST VECTOR CONTROL (TVC) is the ability of a craft to maneuver the direction of the thrust from its engine, in order to control the angular velocity of the vehicle or its direction of motion. Fluid thrust vectoring is a technology that deflecting the main flow of an engine jet from the centerline in order to transfer some force to the targeted axis through primary and/or secondary fluid interaction. By that imbalance a momentum is created and it changes the direction of motion. Use of fluid thrust vectoring is implying less complexity and faster dynamic response compared to other TVC systems. The injection of secondary fluid through the wall of the nozzle into the main gas stream has the effect of forming oblique shocks in the nozzle diverging section, thus causing an unsymmetrical distribution of the main gas flow, which produces a side force [1]. Fluid thrust vectoring involves either injecting fluid or removing fluid from the boundary of the primary jet. Removing fluid from the primary jet has sufficient advantage but also has problems like affecting exit velocity of main jet and it reduces the mass flow rate at the exit due to fluid removal for thrust vectoring. Therefore in this paper we have focused on the design optimization of a novel self-impinging secondary double jet TVC system.

The pioneer user of TVC by secondary fluid injection into the primary exhaust jet dates back to 1949 and it's credited to [2]. Although many studies have been carried out by the previous investigators on fluidic thrust vectoring the lucrative design optimization of TVC system using self impinging jets is not reported in any open literature [2]-[16]. Nevertheless, many studies have been reported on self impinging injectors for other aerospace applications [1]. It is well known that the impinging jets provide an effective and flexible way to transfer energy or mass in industrial applications. Literature review reveals that the collision between two cylindrical liquid jets is one of the canonical configurations for atomizers used in many propulsion, energy-conversion, material processing, and chemical engineering systems [1], [17]-[19]. Impingement of liquid jets is a very efficient method for atomization and mixing, where the dynamic head of the liquid jet is used to destabilize the opposing stream, typically within a short distance from injection. The resultant sheet destabilizes, breaks, and disintegrates into a spray of droplets under the influence of surface-tension, viscous, inertial, and aerodynamic forces. The process eventually leads to fragmentation of the injected liquid into ligaments and droplets [20]. A rich variety of flow structures, ranging from single oscillating jets at low flow rates to violent disintegration of flapping sheets at higher flow rates, have been observed, depending on the Weber and Reynolds numbers of the jets. These are succinctly reported by [21], which merits further studies on its application for TVC systems. Although many experimental and theoretical studies have been performed to explore the underlying mechanisms of impinging jet

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atomization there are none in thrust vectoring applications.

In this paper we focus on the merits of collision of self-impinging secondary double jet with the primary flow in lieu of a secondary single jet with same mass flow rate for gaining more momentum using the particle collision theory proposed by [22]. The self-impinging double jet nozzle is nothing but splitting the mass flow into two and allowing them to impinge at a predesigned angle and location with the primary flow for getting more momentum due to particle collision thus causing the highest unsymmetrical distribution of the main gas flow due to shock waves, which possibly produces a desirable side force more lucratively for vectoring.

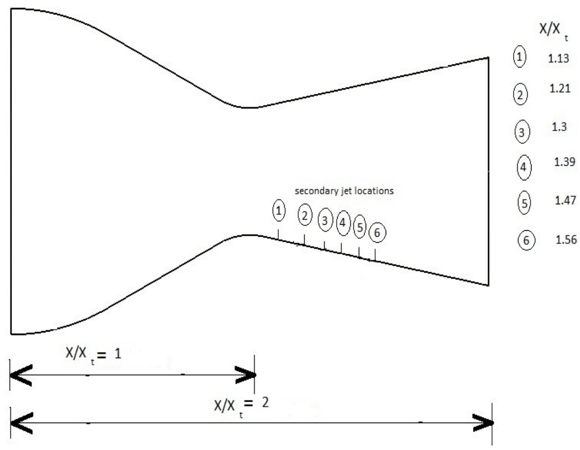
II. Numerical Method of Solution

Numerical simulations have been carried out with the help of a two-dimensional standard k-omega turbulence model using both cold and hot flow analyses. Ideal gas is considered in all the analyses. The model uses a control volume based technique to convert the governing equations to algebraic equations. The viscosity is computed based on Sutherland formula. In all the cases low subsonic inflow condition is prescribed. 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 to be *a priori*. Initial wall temperature, inlet total pressure and temperature are specified. At the solid walls a no slip boundary condition is imposed. In all the cases CFL was selected as 5.0. The code has successfully validated with the experimental results of Craig A. Hunter carried out at NASA Langley Research Center [23]. Figs. 1 (a) and (b) show the physical models of the primary nozzle and the self-impinging supersonic double jet nozzles. Fig. 2 shows the grid system in the computational domain of the selected CD nozzle with self-impinging supersonic double jet nozzles. The nozzle flow features have been examined at six different key locations (see Fig. 1 (a)) between the nozzle exit and the throat and compared with the base model without secondary jet. The base model of the convergent-divergent (CD) nozzle is same as that of the experimental nozzle [NPR = 8.945] used for model validation.

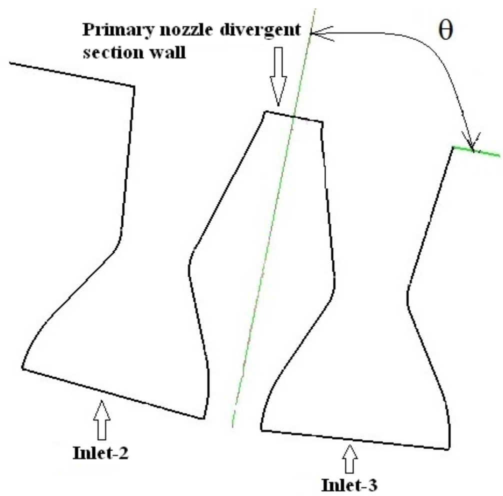
As a first step numerical results generated from all the available models are compared with the experimental results of Craig A. Hunter [23]. Figs. 3 (a) and (b) show the comparison of experimental and computational results of flow through a CD nozzle (NPR = 8.945) using various models showing the centerline pressure. It is evident from Figs. 3 (a) and (b) that the standard k-omega turbulence model is more closely predicting the experimental results Craig A. Hunter [23]. Hence in all the parametric analytical studies standard k-omega turbulence model is used.

III. Results and Discussion

In this paper the forces produced by the exiting exhaust gases are maneuvered from the axial direction to produce a side or vertical force by injecting a supersonic self-impinging secondary jet with a predesigned jet interaction angle and jet pressures from various divergent locations of the primary nozzle to examining the best location for devising an efficient TVC system. In the first phase of this study self-impinging secondary sonic jet is selected for TVC system optimization. We observed that the location $X/X_t = 1.47$ (see Fig. 1 (a)) is the best location for both sonic and supersonic self-impinging secondary jet compared to other locations ($1<X/X_t\leq1.56$). We also observed that solution was not converged when X/X_t was higher than 1.56 and it leads up to the nozzle exit presumably due to the unfavorable boundary conditions for the said regions ($1.56 < X/X_t \leq 2$). Note that after injecting the self-impinging secondary 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. This produces the necessary moments to the vehicle (pitch, yaw and certain extent to roll also) for vectoring.



(a)



(b)

Fig. 1 Physical models of the primary and the self-impinging secondary nozzles: (a) Primary Nozzle ($A_e/A_t = 1.797$) (b) Self-impinging secondary nozzles (enlarged view)

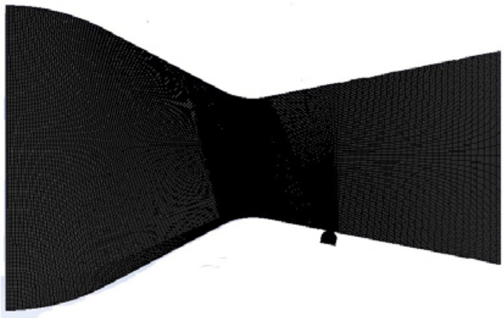
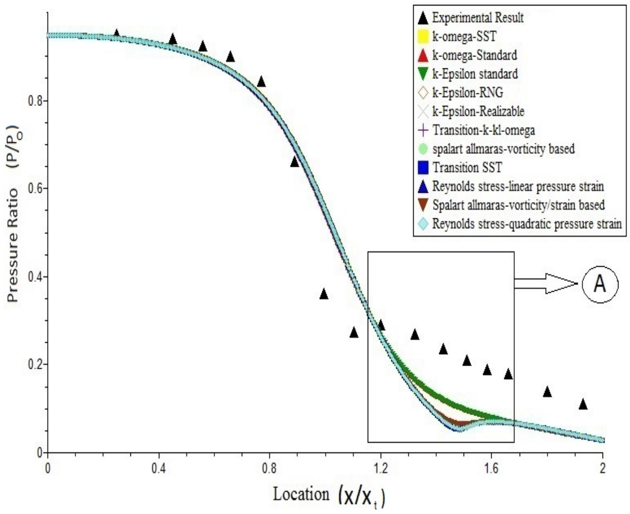
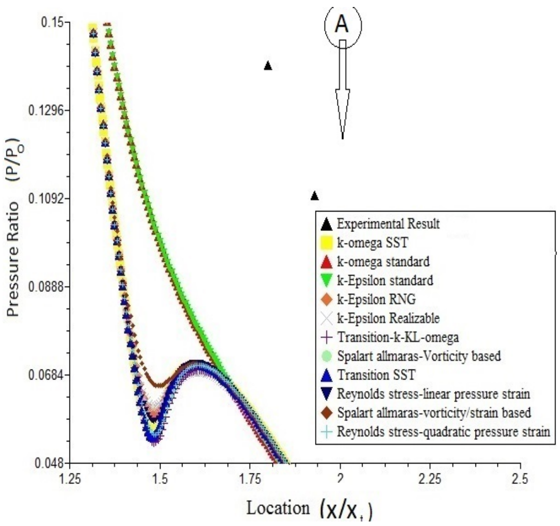


Fig. 2 Grid system in the computational domain of a CD nozzle



(a)



(b)

Fig. 3 Comparison of experimental and computational results of flow through a CD nozzle (NPR = 8.945) using various models showing the Centerline pressure: (a) Comparison of experimental and computational results of axial pressure ratio of a CD nozzle using various models (b) Enlarged view of centerline pressure corresponding to Fig. 3 (a)

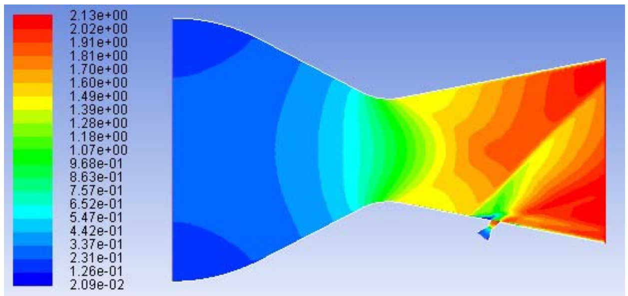


Fig. 4 The steady state Mach number contour during vectoring by using supersonic secondary single jet with primary flow through a CD nozzle

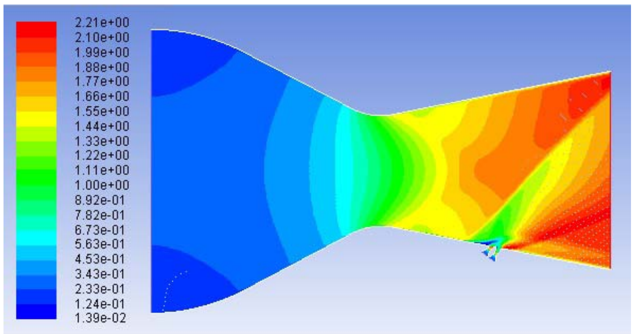


Fig. 5 The Mach number contour during vectoring using self-impinging supersonic secondary double jet with primary flow through a CD nozzle

In the second phase of this study self-impinging supersonic secondary jet is selected. In both sonic and supersonic self-impinging double jet cases jet interaction at two different angles (60^0 and 90^0) 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. It is evident from the Mach contours reported in Figs. 4 and 5 that bow shock is more dominant in self-impinging supersonic secondary injection case than a typical case of single supersonic secondary jet reported in Fig. 4. Note that the bow shocks influence over a segment of the nozzle, which drastically alters the pressure distribution on the nozzle surface in an unsymmetrical way about the nozzle axis causing vectoring. The magnitude of the side force increases as the secondary injection port is moved towards the exit. Note that at higher injection rates the shocks affect the bulk of the flow, thus bringing down the axial thrust values. Figs. 6 and 7 are demonstrating the static pressure variations corresponding to the supersonic single secondary jet and self-impinging supersonic secondary double jet respectively. We observed through various parametric analytical studies that thrust vectoring could be improved by replacing supersonic secondary nozzle with self-impinging supersonic secondary jet nozzles. After several numerical simulations with different jet interaction angles and divergent locations we observed that the best axial location of the self-impinging supersonic secondary double jet nozzle with a given jet interaction angle, built-in to a CD nozzle having area ratio 1.797, is 0.991 times the primary nozzle throat diameter from the throat location. We also observed that impingement of two supersonic secondary jets on the primary flow could increase the thrust vectoring efficiency on the order of 8.81 % while comparing the case with a supersonic single secondary jet nozzle at the same location presumably due to the momentum gained through particle multiple collisions.

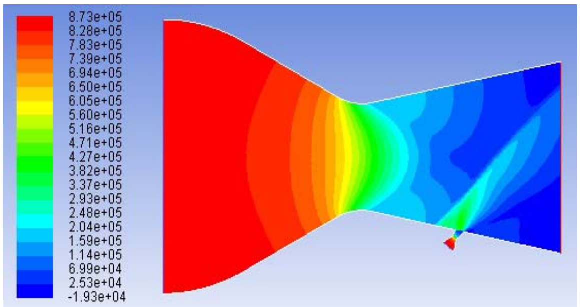


Fig. 6 The steady state static pressure contour during vectoring by using supersonic secondary single jet with primary flow through a CD nozzle

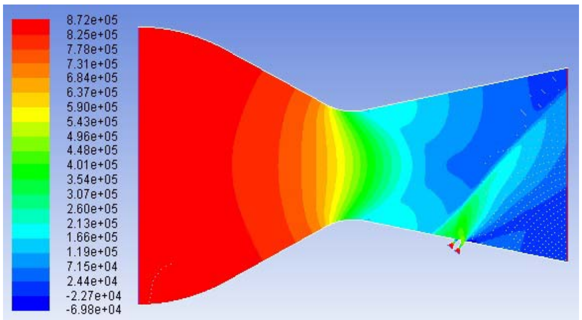


Fig. 7 The static pressure contour after vectoring using self-impinging supersonic secondary double jet with primary flow through a CD nozzle

Fig. 8 shows the comparison of nozzle exit Mach number profile with base model (without secondary jet) and with a case having supersonic secondary injections at a jet interaction angle of 60° with the divergent wall of the primary nozzle at six different locations. Fig. 9 shows the comparison of nozzle exit Mach number profile with base model (without secondary jet) and with a case having self-impinging supersonic secondary double jet injections at a jet interaction angle of 60° with the divergent wall of the primary nozzle at six different locations. We observed that in both cases highest vectoring discerned at location 5, where $X/X_t = 1.47$. Fig. 10 shows the comparison of nozzle exit Mach number profile with base model (without secondary jet) and with a case having supersonic secondary injections at a jet interaction angle of 90° with the divergent wall of the primary nozzle at six different locations. Fig. 11 shows the comparison of nozzle exit Mach number profile with base model (without secondary jet) and with self-impinging supersonic secondary jet injections at an angle of 90° to the divergent wall at different locations. Figs. 10 and 11 are corroborating that $X/X_t = 1.47$ is the best location for secondary injection for overall better vectoring though its axial vectoring efficiency is relatively lesser than a case with $X/X_t = 1.56$. Fig. 12 shows the Mach number comparison of cold and hot flow jets in primary nozzle with self impinging supersonic secondary double jet at the prescribed location $X/X_t = 1.47$. It is evident from Fig. 12 that for the preliminary TVC design considerations one can go for cold flow analysis with the benefits of computation time on the order of 70 % compared to the hot flow analyses.

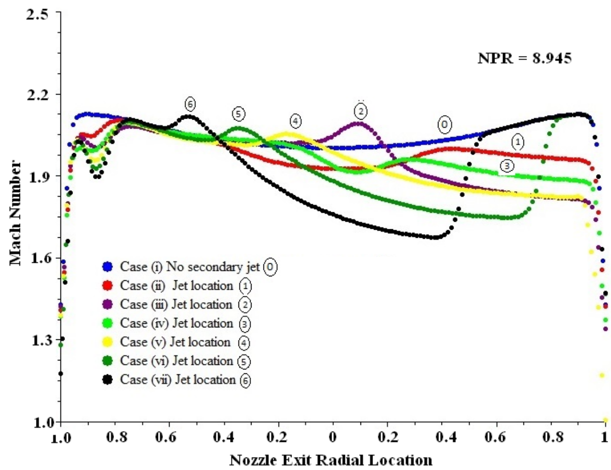


Fig. 8 Comparison of nozzle exit Mach number profile with base model (without secondary jet) and with a case having supersonic secondary injections at a jet interaction angle of 60° with the divergent wall of the primary nozzle at six different locations

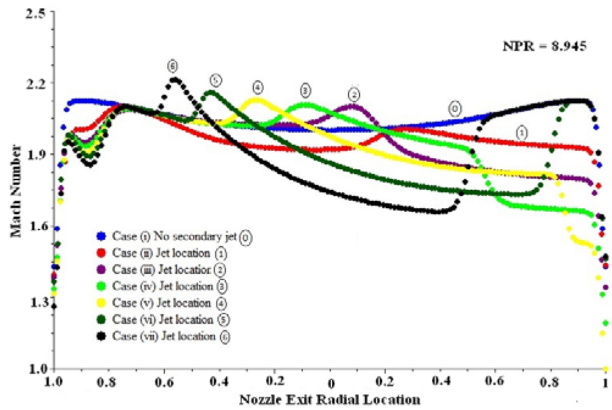


Fig. 9 Comparison of nozzle exit Mach number profile with base model (without secondary jet) and with self-impinging supersonic secondary injections at an angle of 60° to the divergent wall at different locations

Fig. 13 is demonstrating the flexible steering of the craft by comparing the unsymmetrical distribution of Mach number at the exit due to alternatively closing and opening of the self-impinging supersonic secondary jet. It is evident from Fig. 13 that self-impinging supersonic secondary double jet got significant bearing on the thrust vectoring. One can also discern that the flexible steering is possible after invoking ON/OFF facility to the secondary nozzles for meeting the onboard mission requirements. Fig. 14 shows the Mach number comparison of primary nozzle with both supersonic secondary jet and self-impinging supersonic secondary double jet at the exit [NPR=8.945, jet interaction angle $60^{0,}$ X/X_t = 1.47). Table I shows the comparison of vectoring angles and the corresponding axial vectoring efficiency comparison of two different cases (single and self-impinging double jet) of supersonic secondary jets at two different jet interaction angles (60^0 and 90^0) and six various secondary injection locations (see Fig. 1 (a)) carried out using cold flow analyses. It is evident from Table I that the self-impinging double jet will provide the highest thrust vectoring compared to the conventional secondary single jet for aerospace applications.

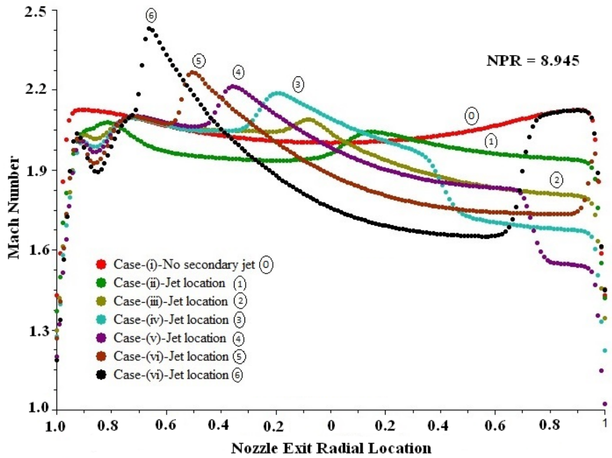


Fig. 10 Comparison of nozzle exit Mach number profile with base model (without secondary jet) and with a case having supersonic secondary injections at a jet interaction angle of 90° with the divergent wall of the primary nozzle at six different locations

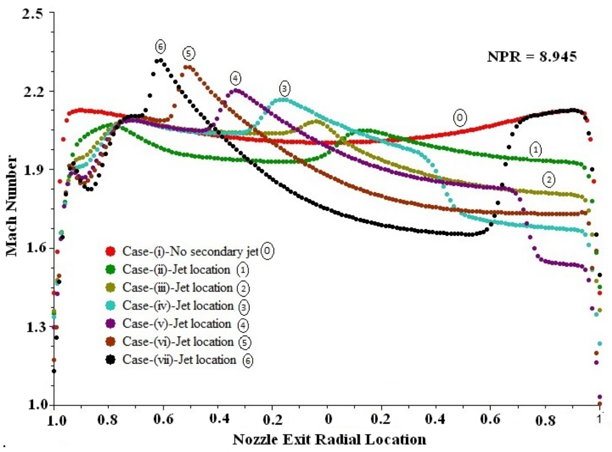


Fig. 11 Comparison of nozzle exit Mach number profile with base model (without secondary jet) and with self-impinging supersonic secondary injections at an angle of 90° to the divergent wall at different locations

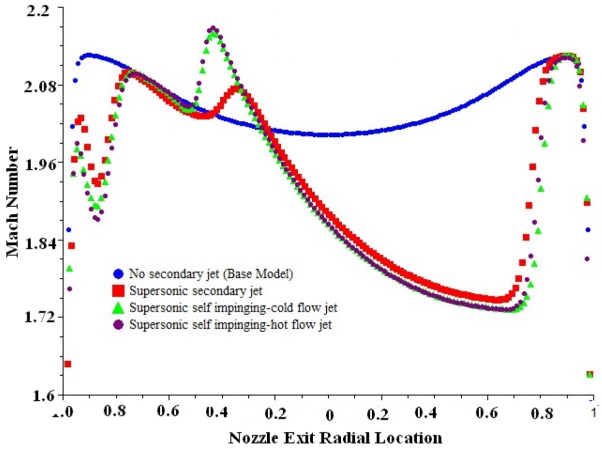


Fig. 12 Mach number comparison of cold and hot flow jets in primary nozzle with self-impinging supersonic secondary double jet

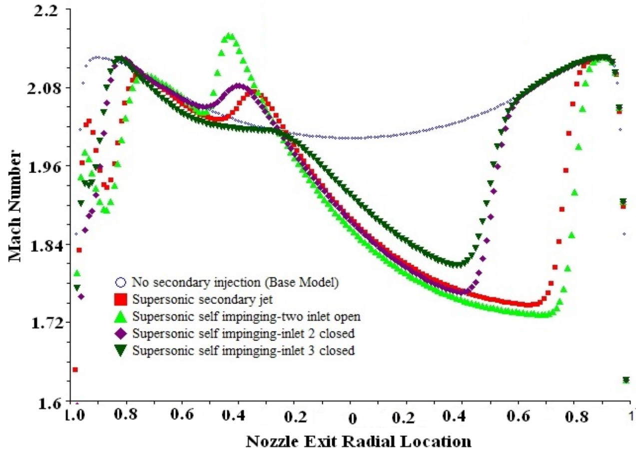


Fig. 13 The flexible steering of the craft by comparing the unsymmetrical distribution of Mach number at the exit due to alternatively closing and opening of the self-impinging supersonic secondary jets

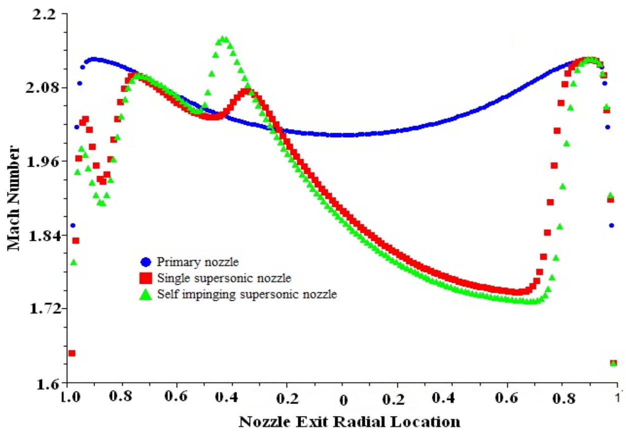


Fig. 14 Mach number comparison of primary nozzle with both supersonic secondary jet and self-impinging supersonic secondary double jet at the exit [NPR=8.945, jet interaction angle $60^{0,}$ X/X_t = 1.47]

TABLE I
AXIAL THRUST VECTORING EFFICIENCY COMPARISON

Orientation of secondary nozzles with divergent wall (θ degree)	Location of secondary nozzles from inlet X/X_t	Axis vectoring at the exit due to supersonic secondary single jet (δ degree)	Axis vectoring at the exit due to self-impinging secondary double jet (δ degree)	Efficiency of axial thrust vectoring due to supersonic secondary single jet (δ/90)100 %	Efficiency of axial thrust vectoring due to self-impinging secondary double jet (δ/90)100 %
	1.1249	-3.1493	-4.0027	3.5	4.4474
	1.2114	-1.6375	-2.1383	1.82	2.3758
60	1.2991	-3.0406	-2.6831	3.38	2.9812
	1.3845	-0.2414	-0.1272	0.27	0.1414
	1.4710	2.6400	2.8918	2.93	3.2131
	1.5575	6.1160	6.5843	6.8	7.3160
	1.1249	-5.8894	-5.6249	6.54	6.2499
90	1.2114	-8.7040	-7.2099	9.67	8.0110
	1.2991	3.0275	-3.0515	3.36	3.3906
	1.3845	-0.2245	-0.5952	0.25	0.6613
	1.4710	2.3993	2.5162	2.67	2.7958
	1.5575	5.8900	6.0815	6.54	6.7572

IV. CONCLUDING REMARKS

The results from the parametric studies of the case on hand reveal that the shock induced self-impinging supersonic secondary double jet is more efficient in certain locations at the divergent region of a CD nozzle than a case with supersonic single jet with same mass flow rate. We observed that the best axial location of the self-impinging supersonic secondary double jet nozzle with a given jet interaction angle, built-in to a CD nozzle having area ratio 1.797, is 0.991 times the primary nozzle throat diameter from the throat location. We concluded that the flexible steering is possible after invoking ON/OFF control facility to the secondary nozzles for meeting the onboard mission requirements. Through our case studies we also concluded that the supersonic self-impinging secondary double jet at the predesigned jet interaction angles and location can provide more flexible steering options facilitating with 8.81 % higher thrust vectoring efficiency than the conventional supersonic single secondary jet without compromising the payload capability of any supersonic aerospace vehicle. This study is a pointer towards for the design optimization of a TVC system for future craft.

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 for completing this research work.

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