Numerical and Experimental Studies on Supersonic Free Jet with Various Cross-Sectional Tab Configuration

Srinivasa Rao Lavala, Partha Mondal, and Sudip Das

Abstract Supersonic free jet studies were made with tabbed nozzle configurations having different cross-sections. Experimental and numerical simulations were adopted to obtain the basic flow field features. Pitot tube measurements and Schlieren flow visualization were carried out in experiments, whereas an in-house build, 3D-Euler flow solver was used to obtain the results. The results obtained from the investigation show the basic flows indicating shock distortion, Mach disk location, reduction in core length of the jet, and other features for tabbed configuration.

Keywords Supersonic · Free jet · Blockage ratio · Tab · Shock cell · Nozzle pressure ratio

1 Introduction

Compressible jet applications are commonly used in many aerospace industry problems. The jet configuration mainly depends on the differential pressure, which is defined as the ratio of pressure of exit fluid to ambient fluid. The isolated jet configuration also has a major issue with noise characteristics. The noise emanating from such jets is termed as aeroacoustic problems which are being influenced by its way of generation, the source type, and also the location of such sources. Over the years researchers studied isolated jet configurations and flow structures. The compressible jets flow structure has a periodic quasi-shock cell structure, shock wave interactions, shear layers, wave instabilities, and mode shapes like axisymmetric (toroidal), lateral (flapping), and helical. The interactions of shockwaves, shear layers, and instability waves generate the acoustic waves. These acoustic waves propagate upstream and downstream of the jet and could be detrimental to structures housing them.

Eliminating and reducing such acoustic waves are of prime importance. In past years, researchers have been using two types of control which are active or passive techniques. For active control, there is a need of energy, and passive control does

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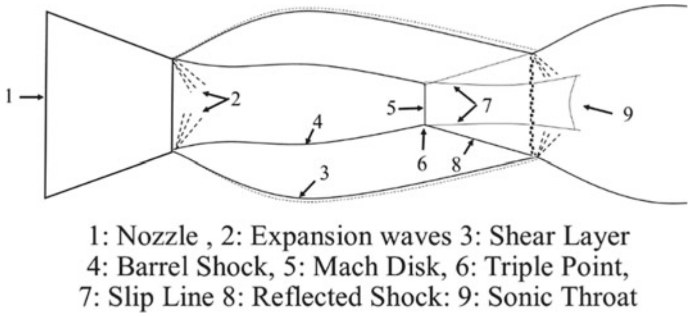

Fig. 1 Isolated jet flow features

not require any force of energy. Present investigation attempts to adopt the passive techniques by using tab configuration shapes like triangular, square, or cylinder. The tabs were inserted at the exit of the jet to face the flow, which produces a pair of vortices, which traverses in the downstream direction along with the jet. The basic features of the jet are the shear layer, barrel shock, Mach disk, reflecting shock, triple point, slip line… etc. as illustrated in Fig. 1. In the present investigation, three rows of elongated tabs were placed circumferentially at 120° apart, so as to block the entire jet exit by a blockage percentage of 11%. The tests were made at a nozzle pressure ratio of 6.0.

2 Literature Review and Objective

Theoretical and mathematical calculations of formation of shock cell and estimation of first shock cell length, with variation of pressure ratios, were reported by Pack [1]. Studies of sonic and supersonic jets experiment results and theoretical predictions were reported by Love et al. [2].

The screeching sound was first investigated by Powell [3], who suggested the emission of feedback mechanism, and the acoustic waves traveling upstream and downstream direction of the jet. The generation of screech tone by a moving source was investigated by Umeda and Ishii [4], and the jet has four stages of modes, which are axisymmetric (A1, A2), lateral (B), helical (C), and lateral (D). The major source dominant helical mode generates the screech tone.

The axisymmetric nozzles tab configurations were first introduced by Bradbury and Khadem [5], who investigated parameters, like boundary layer thickness, flow angle, turbulence level, and tabs. The tab configuration influenced the centreline of the core jet. Various tab configurations were studied by Zaman, et al. [6], and they reported the elimination of screech and mixing enhancement. Axisymmetric heated and unheated jets were investigated by Ahuja and Brown [7], where it has been reported about effective mixing enhancement and screech tone elimination by adopting, three, four-tab configurations at the exit of the jet.

Impinging jets were investigated by Krothapalli [8], who observed two types of discrete tones, one was a screeching tone that was emitted from the third shock cell, and the second one was an impinging tone that was emitted from the impinging region on the rigid plate. Axisymmetric jets was investigated by Singh and Rathakrishnan [9] and reported to weaken shock cells and enhance mixing. Shock cell distortion and core extent reduction were observed using a configuration of Crosswire and tabs investigated by Lovaraju et al. [10]. Axisymmetric convergent-divergent nozzles were investigated by Rathakrishnan [11] and reported that cross wire and tab configurations induce core length reduction, enhance mixing, and reduction/elimination of screech.

Intrusive and non-intrusive methods were investigated by Nagel et al. [12], where they studied on screech elimination, and shock cell distortion using intrusive technique. Investigations to obtain details of the flow field of the first shock cell of the fluid structure interactions were made by Hortensius et al. [13], using PSP, PIV, Schlieren, and oil flow imagery. Axisymmetric jets were investigated by Mitchell et al. [14], using PIV measurements. Imagery analysis of the flow physics of the mode operation of the jet especially the helical mode source from second to fourth shock cell and its generation mechanism was made using proper orthogonal decomposition.

3 Experimental Setup and Methods

Experiments were conducted in a jet flow facility at the Aerodynamic laboratory of Birla Institute of Technology, Mesra, Ranchi. The facility has a settling chamber size with a diameter of 254 mm (10 in.), and a length of 914 mm (36 in.), as illustrated in Fig. 2. Dry air is supplied to the air balloon by 2 Ingersoll Rand compressors in the range of 100–150 psi. For the present investigation, Mach 2.0 nozzles were designed and fabricated (BN) having an exit diameter of 20 mm. The tabs were introduced having cross-sectional shapes as triangle (TT), square (ST), and circular (CT), as shown in Fig. 3. Blockage ratio (BR) is defined as the projected tab area to the exit area of the jet, which for the present investigation is considered as 11%. All the tests which are presented here correspond to a nozzle pressure ratio (NPR) of 6.0.

In-house-built Pitot tubes having OD of 1.8 mm were adopted to measure the jet center line characteristics of the jet. The Pitot probe was mounted on a 2D-traverse unit to investigate the streamwise jet characteristics with a resolution of 1.25 μm. The sensor was connected to the Pitot tube to measure the pressure values. The high-speed data acquisition card is used to acquire the data which is connected to the sensor with a Pitot tube.

The standard 6-Inch Z-type schlieren setup was used to visualize the flow. The images were captured using a BASLER camera (ACA-1300-60gc), having a resolution of 1280 × 1024, and using a NI-vision frame grabber.

Numerical computations were made using an in-house built 3D-Euler code for the purpose and were used to corroborate the experimental and computational results. The grid generations and computational domain are depicted in the Fig. 4.

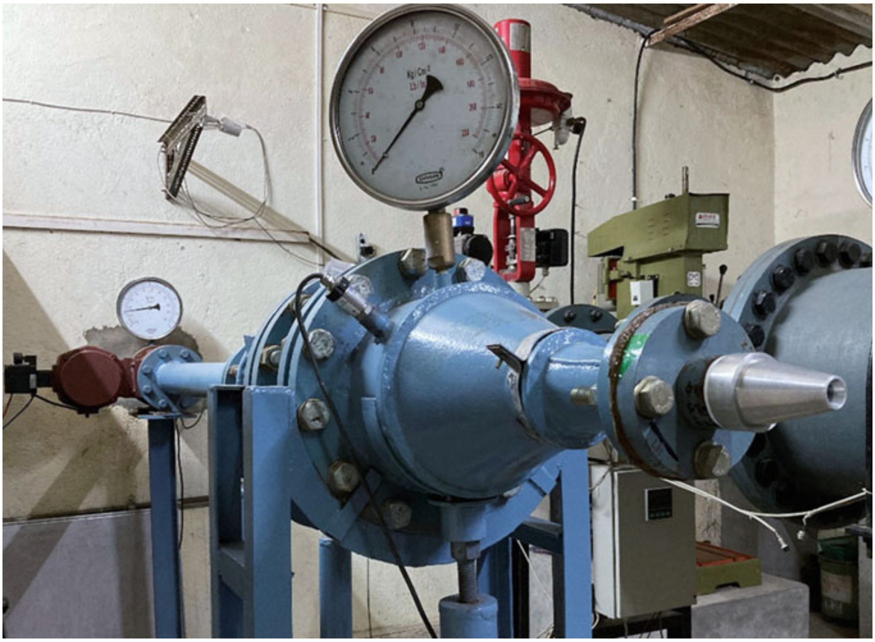

Fig. 2 Free jet facility

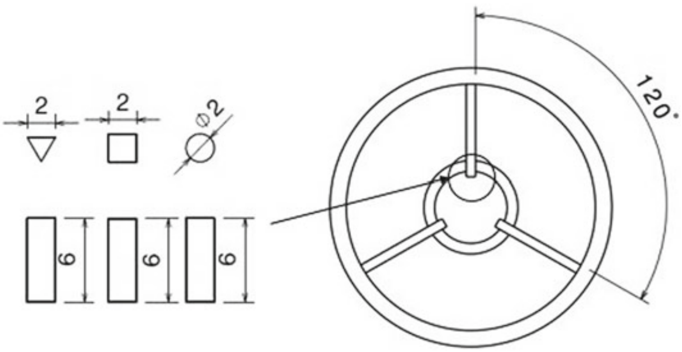

Fig. 3 Tab configuration details and the orientation at the exit of the nozzle

4 Results and Discussion

In the present investigation, tabbed nozzle exit configurations were tested at Mach number of 2.0 with nozzle pressure ratio of 6. The cross-sectional feature of tabs was emphasized here and the shapes with Triangle (TT), Square (ST), and Cylinder (CT) were used. The arrangement of tabs was made such that the blockage ratio at the exit of the nozzle was 11%. The circumferential placement of tabs were 120° apart.

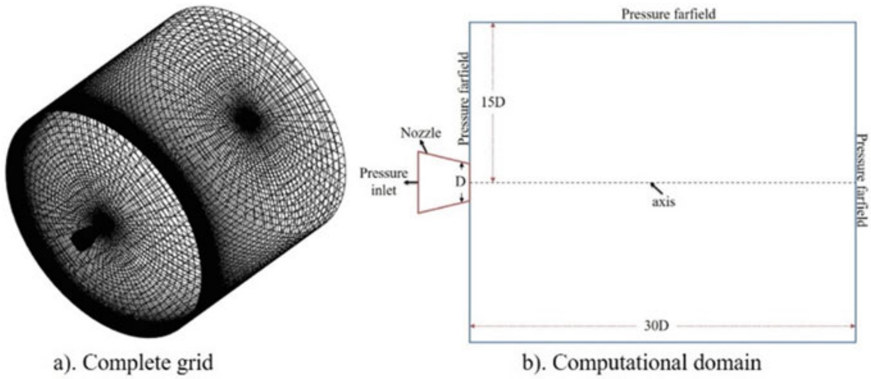

Fig. 4 Grid topology

Figure 5 shows the time averaged schlieren flow visualization photographs of the base and nozzles with the tabbed configurations. The nozzle without tabbed configuration (BN) shows clearly the flow field features and the shock cells. The Mach disk, compression and expansion regions, shock-shock interactions, triple point, shear layers, etc. are having a distinguished representation in the figure. There is a clear difference in jet flow field structure for all tabbed configurations showing distorted shock cells, bulk flow, bisecting and diverting to azimuthal direction, early diffusion, etc. Among all tabbed configurations, the cylindrical tab nozzle shows many patterned features compared to others. The square and triangular tabs indicate almost similar behavior.

The pitot pressure measured along the centreline of jet axis for base nozzle and with various configurations of tabs used in the experiment is shown in Fig. 6. The Pitot tube measurements indicate the pressure oscillation, core jet length, and shock cell details of the jet plume. The rise and fall of total pressures indicate the shock cell formation and compression or expansion waves in the jet. The jet from the base nozzle without tab (BN) configuration clearly indicates the pressure oscillation in the core location of the jet, and diffusing after some extent to the downstream, showing the mixing and entrainment behavior. Adopting of all the tabbed configurations indicate reduction in core length of the jet and shock cells. However, the circular tab shows a comparatively shorter core length among all tabbed configurations.

Figure 7 shows the pitot pressure measurement made in the transverse direction at nine locations downstream of the jet spread. Here also, as indicated by Schlieren and centreline pitot survey, the base nozzle shows a longer and wider jet spread. All the tabbed configurations shows a minimal jet spread in longitudinal as well as lateral directions. The lateral spread for all configurations die down by $X/D = 4$, whereas for base nozzle the influence is seen even at $X/D = 14$. Among the tabs, the cylindrical tab shows the most minimum influence of the jet spread. The lateral pattern of distribution of pitot pressures show distinguished difference between the base nozzle and all tabbed configurations.

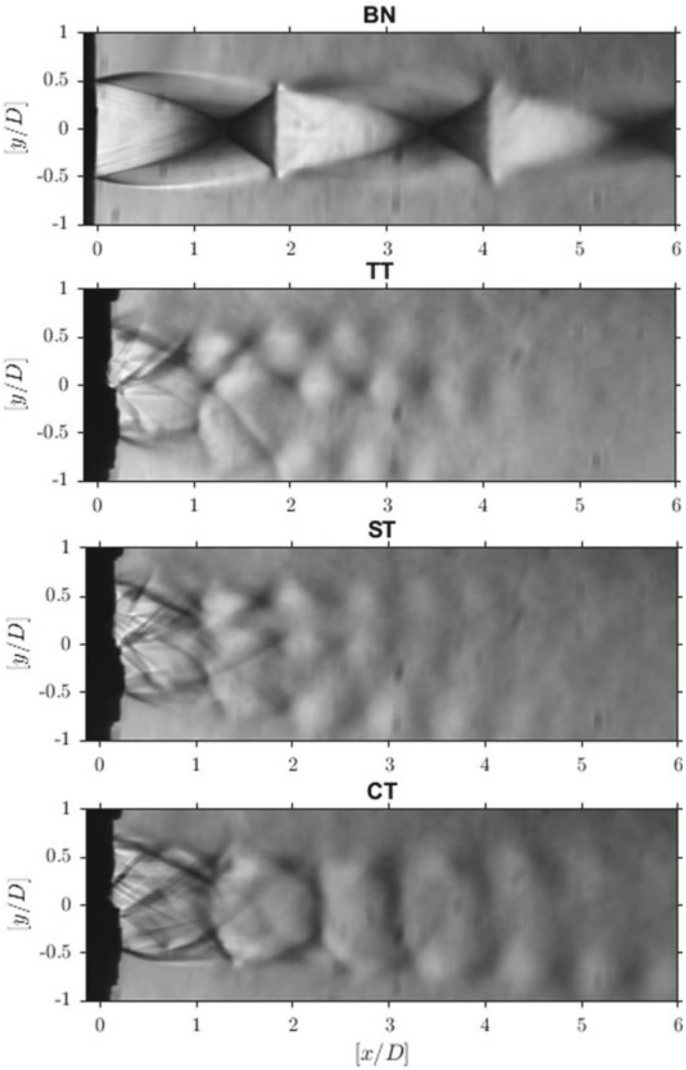

Fig. 5 Schlieren flow visualization of base nozzle and various configurations of tabbed nozzles at NPR = 6.0 and BR = 11%

Table 1 shows the measured first shock cell distance, Mach disk locations, and percentage reduction in core length based on schlieren and pitot measurements for all the configurations tested. The square and triangle tabs show partially disappearance of the shock cells and its distance and Mach disk locations, and the core length reduction was observed for cylinder tabs more than for square and triangular tabs.

Figure 8 shows the comparison of the computed lateral direction static pressure distribution of baseline (BN) and tabbed configuration at a location of $X/D = 4$ from

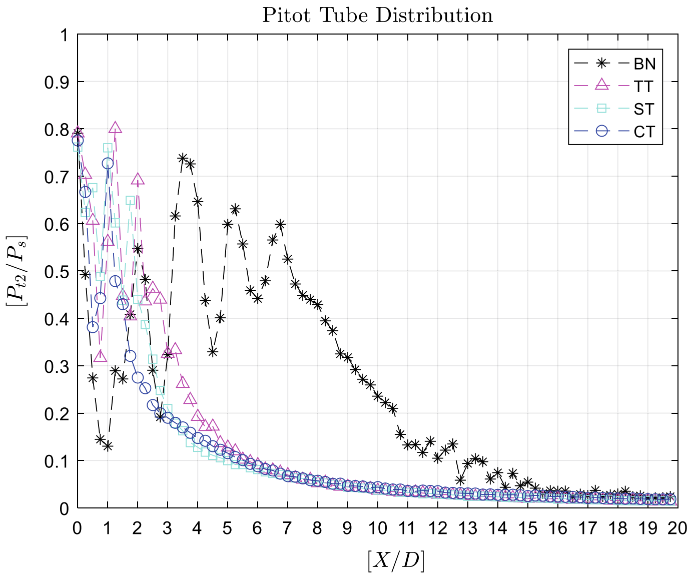

Fig. 6 Measured Pitot tube distribution for base nozzle and nozzle with tabbed configurations at NPR = 6.0 and BR = 11%

the jet exit, which clearly shows jet spread to be more in longitudinal and lateral direction for baseline nozzle than tabbed configuration. This result corroborates the experimental pitot survey measurements.

Figure 9 shows the comparison of the Mach contours with and without tab configurations, downstream of the cross-plane for five *X*/*D* locations. The clear disparity pronounced here shows three directional tadpole shapes aligning the tab axis. These shapes vary with different tab configurations. A clear indication of planar flow variation with tabs compared to base nozzle case is observed through the series of figures.

5 Conclusions

Axisymmetric supersonic jet with various tabbed configuration shapes with asymmetric orientation arrangement has been studied in the present investigation. The qualitative and quantitative measurements have been carried out. Core extent was significantly reduced by using tabbed configurations. The shock cell distortion, shock cell, and Mach disk locations disappeared in the triangular and square tabbed configurations. The core length reduction was observed more for cylindrical tab configuration. The computational Mach contours gave tab insight mechanism in the downstream axis of the jet.

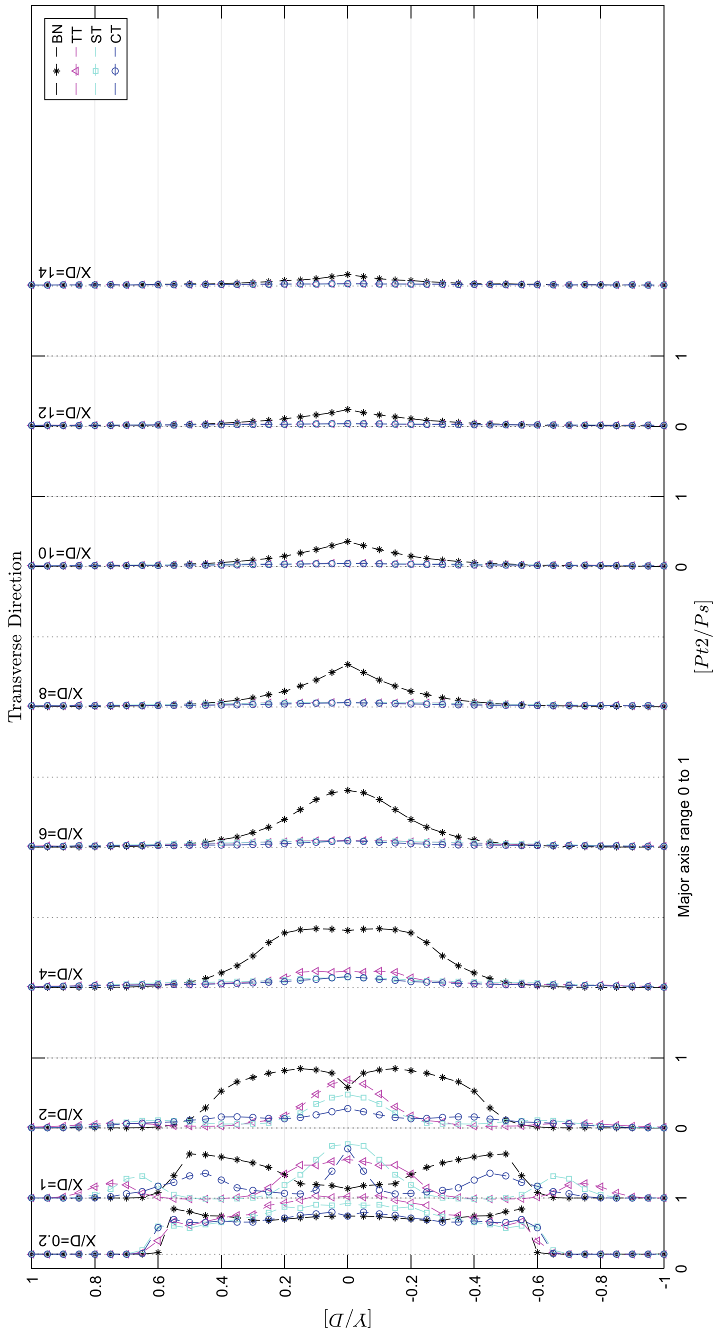

Fig. 7 Measured Pitot tube distribution across the jet (transverse direction) for base nozzle and nozzles with tabbed configuration at NPR = 6.0 and BR = 11%

Table 1 Estimated shock cell distance, Mach disk location, and core length reduction from schlieren flow and Pitot tube measurements of baseline and tabbed configuration at NPR = 6.0 and BR = 11%

	First shock cell distance	Mach disk location	% reduction of core length
BN	1.89	1.30	–
TT	Disappear	Disappear	77
ST	Disappear	Disappear	88
CT	1.39	1.16	93

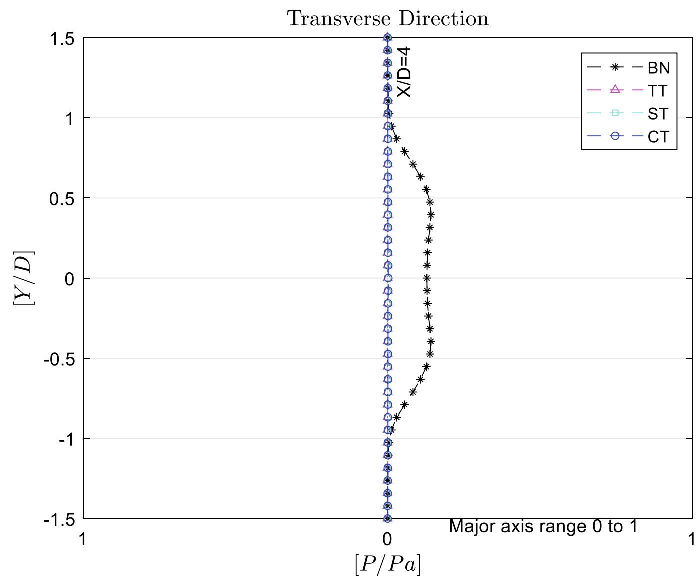

Fig. 8 Computed lateral pressure distribution for all configurations at $X/D = 4.0$

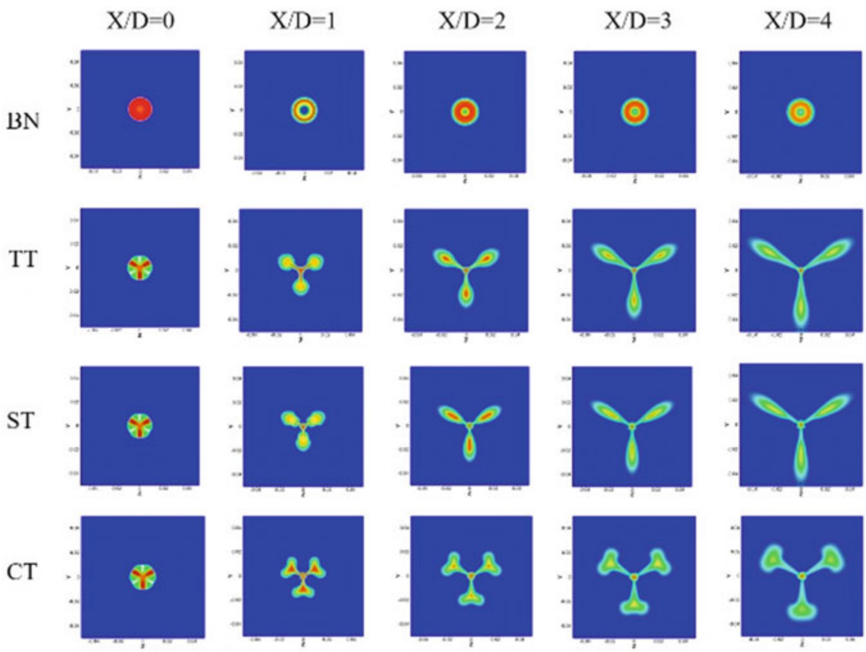

Fig. 9 Mach contours of downstream cross planes at various X/D locations for base nozzle and different tabbed nozzle configurations

Nomenclature

P	Static pressure (N/m^2)
P_e	Exit pressure (N/m^2)
P_a	Ambient pressure (N/m^2)
P_{t2}	Pitot total pressure (N/m^2)
P_s	Settling chamber pressure (N/m^2)
X	Longitudinal axis of the jet (mm)
Y	Transverse axis of the jet (mm)
D	Diameter of the nozzle (mm)
BR	Blockage ratio (–)
NPR	Nozzle pressure ratio (–)

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