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An Experimental Analysis of Co Flowing Subsonic and Sonic Jets with Chevron Nozzle

Thanigaiarasu S,
Department of Aerospace Engineering, Madras Institute of Technology, Chennai , India.
Saravanan A R,
Department of Aerospace Engineering, Madras Institute of Technology, Chennai, India.
Vivekkumar P,
Department of Aerospace Engineering, Madras Institute of Technology, Chennai, India.

ABSTRACT

Study of jet mixing has a prime role to suppress the noise developed by the jets. The present research is about the chevrons effect over the co-flowing jets. The chevron itself produces the vortices between the jet and the atmospheric air. To enhance the mixing the chevrons are used at the nozzle exit plane which leads to generate stream wise vortices along the sides of chevron . The experiment has been conducted for three cases mainly low subsonic, high subsonic and sonic conditions. The respective Mach number at the nozzle exit are 0.4, 0.6, 0.8 and 1.0. The present investigation about only on jet mixing characteristics and no noise effects. The centre line Mach number is decaying by increasing the exit Mach number. The maximum reduction in potential core length is achieved by the exit Mach number 1.0 for the co-flowing chevron nozzle. The peak percentage of reduction in potential core length is 38.71%. The base line nozzle and co-flowing chevron nozzle with exit Mach number M_e = 0.4 is taken into account for the comparative studies.

KEY WORDS*: *Truncated chevrons, Stream wise vortices, Co-flowing jets, Potential core.

NOMENCLATURE

M	Jets local Mach number
M_e	Nozzle exit Mach number
D	Nozzle exit Diameter
X	Jet axial location
NPR	Nozzle Pressure Ratio

1. INTRODUCTION

An attempt is made to investigate about the behaviour of co flowing jets with chevrons, which are the repeated saw-tooth pattern cut at the circumference of the nozzle exit. The chevron which creates the stream wise vorticities is able to decay the potential core elongation as well as increasing the mixing characteristics of co flowing jets. The proper understanding of co flowing jets leads to enormous advantages not only in aircraft propulsion also industrial domain also. To reduce the Mach wave noise and screech effect the co flowing jet gives the promising results. Also implement the chevrons at the co-annular nozzle results considerable amount of noise reduction as well as screeching effect. The mixing characteristics of co flowing jet also depends the nozzle lip thickness. While increasing the nozzle the lip thickness the potential core elongation will be reduced due the vortex generation behind the lip along the jet direction. Thicker lip provides the better mixing than the thinner lip. [1]P.S.Tide et al carried out his extensive numerical work to study the effect of chevrons with a tapper angle of 5° and 10° over the subsonic cold and hot jets. The base line (No Chevrons) spectra are less effective at high frequencies. The chevron nozzle with zero taper angles has reduction in jet noise from 7dB to 3dB for cold and hot jets. But the chevron nozzle with a 5° tapper angle increases the jet noise level approximately 2.5dB. The chevrons with a taper have significantly altered the potential core length, velocity decay and fluctuates the turbulence intensity and viscosity. [2]Once again P.S.Tide et al carried out an experimental work on effect of chevron parameters such as chevron count (Number of chevrons) and chevron penetration. He investigated the nozzles which are having various chevron design like 4,6,8 chevron count along with 0°,5°,10° penetration angle. After the extensive experimental work he gave some promising results. The 4 lobed chevrons reduce the noise level approximately 1dB from the base line design (Nozzle with no chevron). While increasing the chevron count from 4 to 6 and 8 the reduction in jet noise level achieves 2 dB to 4dB. Chevrons with four lobes with a penetration of 5°and 10° results more noise than the baseline design at low value of NPR. For high NPR chevrons with high penetration angle gives a favourable results for noise reduction. [3]Brenda Henderson et al from NASA Glenn Research centre has experiments the effect of chevrons over the subsonic and over expanded jets. The bi-conical C-D supersonic nozzles with a design Mach number of 1.51 and 1.65 are utilized for this experiment. The chevrons with a low penetration produces limited impact during on shock associated noise for all NPR. For this case the maximum peak noise reduction is 1.7dB. High penetration results significant reduction in supersonic jet noise. The amount of reduction for supersonic case is higher than the subsonic case. High penetration chevrons results the maximum peak noise reduction of 3.8dB at over expanded jet case. In case of subsonic Mach number $M_e = 0.3$ the maximum peak noise reduction is 6.5dB which is much greater than the over expanded case. [4]Fan shi Kong et al carried out his experimental work for the supersonic ejector diffuser system with a nozzle having 10 chevron lobs. The jet entrainment ratio was improved with an average value of 14.8 percent. Also he found out 8.5 percent increment in pressure recovery.[5]Naren Shankar.R and Thanigaiarasu.S from MIT carried out their Numerical studies for a co flowing jets with a various nozzle lip thickness namely $0.2D_P$, $1.0D_P$,$1.5D_P$ (D_P = Diameter of Primary nozzle). While increasing the lip thickness generates the re-circulation zone between the primary jets and secondary jets because of this turbulence intensity will also be increases. They found that lip thickness also a parameter for passive control of jets.[6]Pinnam Lovaraju and E Rathakrishnan carried out an experimental studies on Co flowing at various cases like subsonic, correctly expanded and under expanded sonic conditions. They identified that the core flow elongation were achieved 40 percent at correctly expanded case and 80 percent elongation for under expanded case (NPR 7) due to the presents of co flow only. [7]Arun Kumar P and Rathakrishnan E investigated regarding to enhance the mixing of Axisymmetric jet with a Mach number 2. They used various corrugated tabs with a corrugation shape of semi-circle, triangles and square geometry etc. At NPR 8 the peak reduction of 90 percent in potential core length due to semi- circular corrugated tabs. But at low NPR range from 4 to 6 the performance of semi circler and square shape corrugation gave a comparable results. Here, performance of square corrugated tabs slightly dominated the semi circler corrugated tab. [8] Rathakrishnan.E investigated about the controlling of subsonic and sonic jets by using the rectangular tabs of aspect ratio 4. The maximum decay of potential core length was 32.3 percent for the plain rectangular tabs. For corrugated rectangular tabs the reduction in potential length was achieved 17.63 percent. This is due to the plain rectangular tab having higher blockage 4.2 percent compared to the corrugated rectangular tab with a blockage of 3.6 percent. [9]P Arun Kumar and E Rathakrishnan conducted experimental investigation about the supersonic jet control using truncated triangular tabs. They used two triangular tabs with sharp and truncated vertices. At NPR 8 the reduction of potential core length was achieved maximum the value of 87 percent. At the same NPR the reduction of potential core length for sharp edged triangular tab and rectangular tabs were 83 and 25 percent respectively. [10]Steven Martens from GE Aircraft engines explains the Chevron nozzle might considerably reduce the jet noise due to the generation of stream wise vorticities which enhancing the mixing between the two streams. So, the peak noise automatically reduced due to reduction of peak velocity. The tabbed nozzle moves the energy from low frequency to high frequency. Chevron nozzle must be designed with an aim to reduce the low frequencies while leaving the high frequency acoustic characteristics.[11]N. Heeb et al carried out an experimental study about the influence of chevron spacing and distribution over the supersonic jets. The evolution of jet shape drastically changes from circular shape to various shapes like elliptic, Triangle etc. For bevelled and clustered chevron configurations the reduction in large amplitude screech tone was in the range of 10dB to 20dB at the all operating conditions. The maximum reductions in shock cell length were achieved by the clustered chevron configuration with the 90 degree displacement between the adjacent clusters.

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2. EXPERIMENTAL PROCEDURE

2.1 EXPERIMENTAL ARRANGEMENT

The experiments were carried out using our open jet facility at the High speed jet laboratory, MIT campus. The experimental test facility consist of Compressed air charging unit and open jet facility setup.

2.1.1 COMPRESSED AIR CHARGING UNIT

This unit consists of two air cooled high pressure reciprocating stationary compressors they are linked with two large air receiver tanks with the capable storage pressure 150 Psi. The compressor is driven by the electrically powered induction type motor. It maximum capacity of storage pressure by the compressor is 30 bar. The power requirement to drive the compressor is 19.98hp (14.9 Kw). The volumetric flow rate of the compressor is Min 6 m^3/h and Max 67.96 m^3/h. The compressed air charging unit consists of various subsystems like intake air filters, inter-stage cooler, moisture drain traps, air receiving tanks, piping networks, filters, regulators and lubricators. The intake air filters are used to prevent foreign dust particles entering into the compressor through intake air. The inter stage cooler are used to increase the compressor efficiency by reducing temperature of compressed air before entering into the next stage. The moisture drain traps are used to remove the moisture content from the compressed air. These traps are manual mode. The piping network links the high presser compressor, air receiver tanks and open jet facility setup. These pipes can be able to with stand the pressurized air delivered by the air receiver tank.

2.1.2 OPEN JET FACILITY SETUP

The experiments at various Mach number was conducted by using the open jet facility. The settling chamber is the Major component to conduct the experiment at the particular stagnation pressure. Stagnation pressure means the pressure measured when the fluid velocity reduced to zero by isentropic manner. The cylindrical settling chamber having an inner diameter of 200 mm and length of 600 mm. The settling chamber is linked with air receiver tanks by using the heavy duty pipes. In between the pressure regulator is placed to vary the settling chamber pressure. The pressure regular consisted with pressure gauge with the division of 1 kg/cm^2. Throttling the pressure regulator the settling chamber pressure can be adjusted. The settling chamber also constructed with a stagnation pressure port used to measure the exact stagnation pressure inside it. A pressure gauge with a division of 1 kg/cm^2 was installed at the port. The models are installed at the end of the settling chamber by the slot holder arrangement. A pipe with an external threads extrude from the settling chamber. The protrusion was enclosed by an O-ring with internal threads. The O-ring having an internal diameter of 98 mm. The threads are free from leakage. The model can studied by placing over the O-ring and fixed tightly with the help of holder permanently attached with the O-ring.

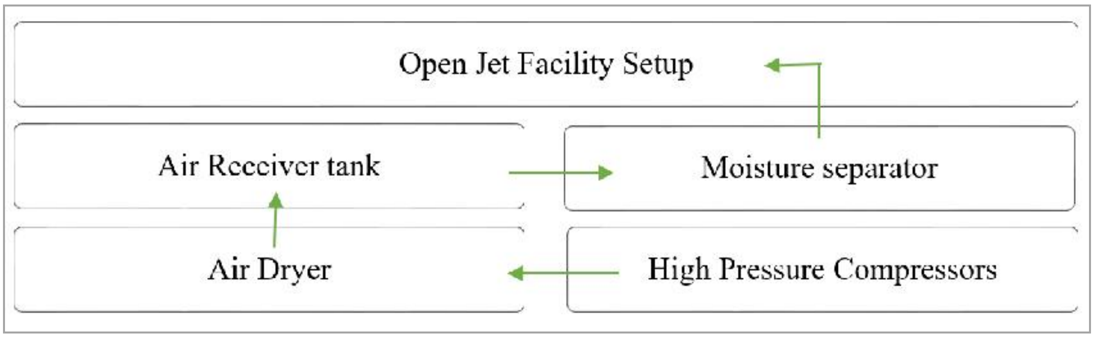

Fig 2.1: Layout of High speed jet Laboratory

The experiments were conducted at various Nozzle Pressure Ratios (NPR). NPR is defined as the ratio between stagnation pressure (P_o) and the back pressure (P_b). In our experiment stagnation pressure is the controlling parameter.

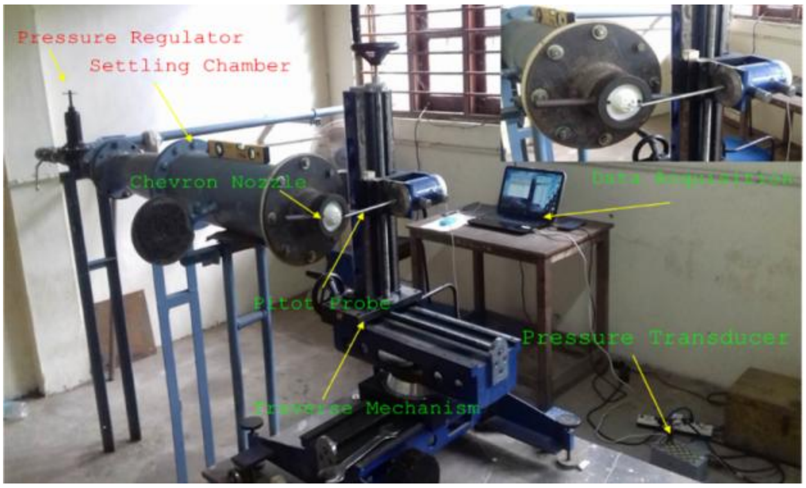

Fig 2.2: Open jet facility setup

It can be varied by regulating the pressure regulator valve. Throughout the experimental run the settling chamber pressure is maintained constant for the particular case. The fluctuations in the stagnation pressure was within the range of $\pm$0.5%. The back pressure was assumed to be laboratory ambient pressure. Throughout the experimental studies the ambient temperature was lies in between the range of $\pm$1%. The ambient temperature was measured by using the numerical thermometers.

2.1.3 TRAVERSE MECHANISM

The traverse mechanism is used to move the Pitot probe in X, Y and Z directions. These axis are mutually perpendicular each other. The screw handler is used to move the Pitot probe in the desired direction. One complete revolution of screw leads 2mm displacement of bed.

Fig 2.3: Traverse mechanism

The Pitot probe is mounted with the bed. The each movable bed was constructed a scale with an accuracy of 1mm. The scale is used to locate the movable bed at various location. The Pitot probe location relative to the bed location. So adjusting the bed location is nothing but positioning of Pitot probe at various locations across the jets.

2.1.4 DATA ACQUISITION

The Pitot pressures are calibrated by using the 16 channel pressure transducer model 9116. The accuracy of the pressure transducer is $\pm$0.05%. The pressure range can be measured by the pressure transducer is 2.5kpa to 5200kpa. This kind of pressure transducer is classified under system 9000 pneumatic intelligent pressure scanners. The generated data file were post processed by the user inter-face software called net-scanner.

Fig 2.4: Pressure transducer

3. FABRICATION

3.1 DESIGN

The chevron nozzles was designed based upon the available experimental setup. The chevron nozzle configuration basically a co-flowing jets. To minimize the fabrication difficulty the nozzle configuration was designed individual parts and they were assembled. They are core chevron nozzle and annular chevron nozzle. Each nozzle having a separate base plate. By using the base plate the nozzle components were assembled. Both components were aligned axially. The respective models are symmetry about their axis. The co-flow can be maintained by circular ports around the core nozzle. The ports were created over the core chevron nozzle base plate. The chevrons which were designed with a conventional triangular shape. To get the chevrons the nozzle trailing edge surface slotted tangentially with the shape of triangle as per the required dimensions.

3.2 MODEL

The designed model was fabricated using the CNC machine. The white nylon material was used for the fabrication. The nylon material never get rusted. Machining the nylon material is very easy. Compared to aluminium or mild steel the machining time for the nylon rod is less. Nylon has awesome wear resistance as well as low frictional properties. Weight of the material also very less approximately around 1/8 of bronze. The nylon solid rod with a diameter of 100mm was chosen for fabrication. The tolerance was made $\pm$1%. After the fabrication we have to assemble the nozzle components. So both the base plate were threatened and assembled using the crown bolt M14-0.5 X 65mm.

Fig 3.1: Photographic view of chevron nozzle with co-flow

4. RESULTS & DISCUSSION

The total pressures were measured in axial direction using the Pitot probe at each 2mm location from the nozzle exit plane. In radial direction the total pressure were measured at each 1mm location with respect to the particular X/D location. The model is symmetry about its axis. So the radial data were gathered from the centre line of jet to 14 mm distance in radial direction. Here X indicates axial direction and D represents the

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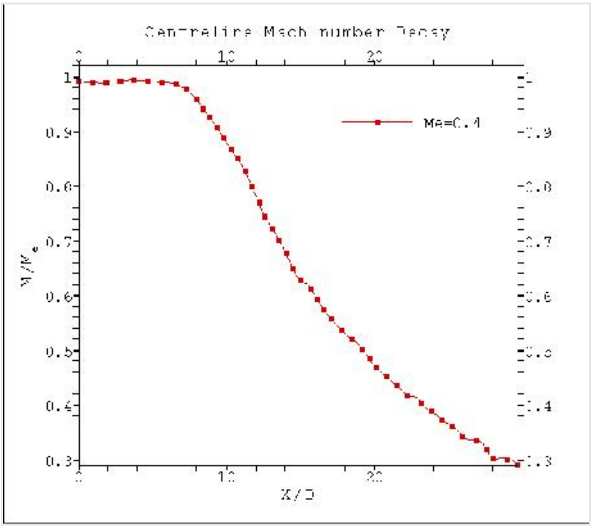
inner diameter of the core chevron nozzle which is 8.55 mm. The nozzle exit static pressure is assumed to be ambient pressure 101.325kPa.

4.1 CENTRELINE MACH NUMBER PROFILES

The experiments were conducted at various NPR by using the fabricated model. The experiments were conducted at following the NPR 1.12, 1.27, 1.52 and 1.89 respectively which means that achieved nozzle exit Mach number 0.4, 0.6, 0.8 and 1.0.

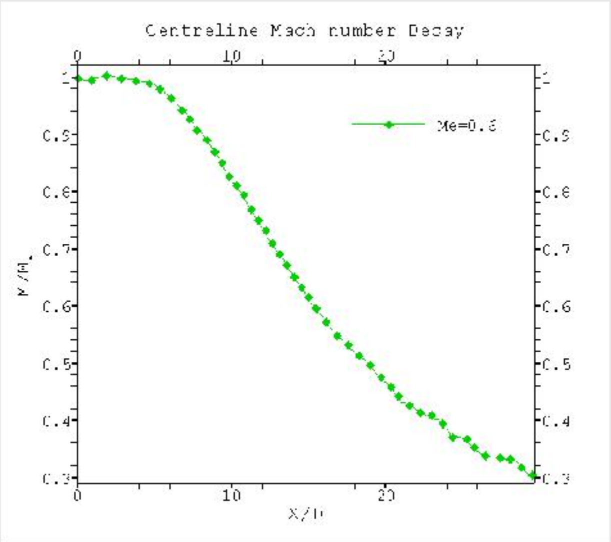
4.1.1 CENTERLINE MACH NUMBER DECAY FOR $M_e = 0.4$



Graph 4.1: Centreline Mach number decay for $M_e = 0.4$

From Graph 4.1, For M_e = 0.4, the potential core at co-flow chevron configuration is preserved in axial direction up to X/D=6.2. In case of nozzle with out co-flow the potential core extended up to X/D = 4.43 only [8] which is 28.54% lesser than chevron nozzle. Nozzle without co-flow constructed with plain tab (Blockage 4.2%) the potential core extended up to the location X/D = 3.47[8] which is 44.1% lesser than the present study. In case of Nozzle without co-flow constructed with corrugated tab (Blockage 3.6%) the potential core extended up to the location X/D = 3.94[8]. Comparatively, the chevron nozzle has 36.45% increased potential core region axially.

4.1.2 CENTERLINE MACH NUMBER DECAY FOR $M_e = 0.6$



Graph 4.2: Centreline Mach number decay for $M_e = 0.6$

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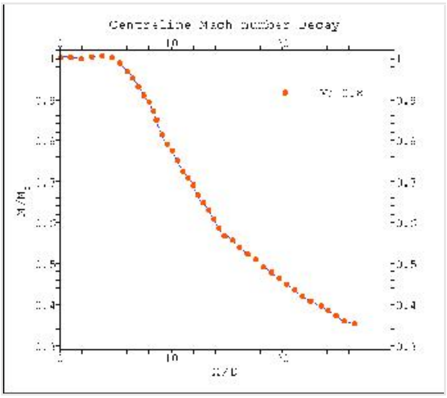
From Graph 4.2, For M_e = 0.6, the potential core preserved up to X/D = 4.7 at chevron configuration. This region extended up to X/D = 4.02 for nozzle without co-flow [8] which is almost 14.5% lesser that the present work. In case of nozzle with a plain tab (Blockage 4.2%) the potential core extended up to X/D = 3.05 distance [8]. So, the co-flowing chevron nozzle has higher potential core region which is 35.12%. Nozzle with a corrugated tab (Blockage 3.6%) without co-flow the potential core has preserved up to X/D = 3.51[8] which is 25.32% lesser than the present work. The co-flowing nozzles preserves the potential core region up to the X/D = 5.6 axial distance [6]. The present chevron nozzle has 16.1% reduction in potential core region comparatively. By varying the nozzle lip thickness like 0.2D, 1.0D, 1.5D the potential core region preserves up to X/D = 8.7, 2.8 and 2.4 respectively[5]. For nozzle lip thickness 0.2D having 45.97% higher potential core region compared to present work. In case of 1.0D nozzle lip thickness the potential core reduced 40.4% compared to co-flow chevron nozzle. In case of 1.5D nozzle lip thickness the potential core reduced 48.9% compared to co-flow chevron nozzle.

4.1.3 CENTERLINE MACH NUMBER DECAY FOR M_e = 0.8

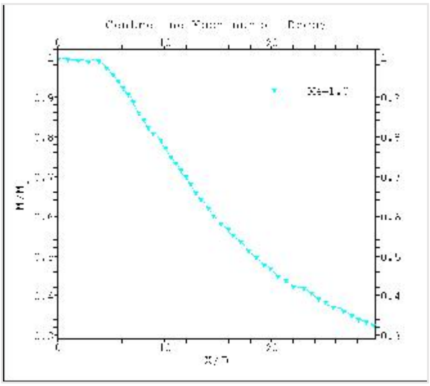
From Graph 4.3, For M_e = 0.8, the chevron nozzle extends the potential core region up to X/D = 4.5. At this condition the nozzle without co-flow preserves the potential core up to X/D=4.5[8].



Graph 4.3: Centreline Mach number decay for M_e = 0.8

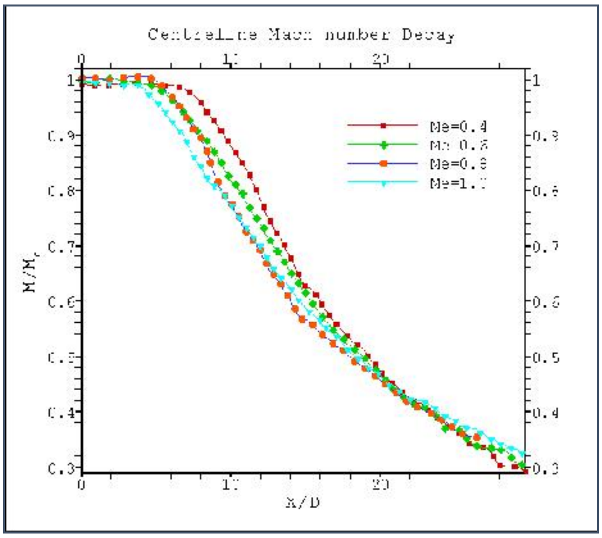
Because of the transonic effect the co-flowing chevron nozzle and plain nozzle behaves almost same manner. In case of nozzle with a plain tab (Blockage 4.2%) without co-flow preserves the potential core region up to X/D = 3.36[8] which is 25.33% lesser than the chevron nozzles potential core. The plain nozzle with a corrugated tab (Blockage 3.6%) extends the potential core region up to X/D = 3.93 axial location [8]. The co-flowing chevron nozzle having 12.67% higher potential core region. The co-flowing nozzle with chevron extends the potential core up to X/D = 5.3 distance [8]. The chevron nozzle reduces the potential core region almost 15% comparatively. At this transonic condition co-flowing chevron nozzle behaves differently compared to co-flow nozzle unlike plain nozzle which means chevrons are effective in co-flows.

4.1.4 CENTERLINE MACH NUMBER DECAY FOR M_e = 1.0



Graph 4.4: Centreline Mach number decay for M_e = 1.0

At sonic condition it was dominated by the plain nozzle. The chevron nozzles attain the maximum reduction of potential core at sonic condition. In case of nozzle with a plain tab (Blockage 4.2%) the potential core extended up to X/D = 3.03 distance [8]. So, the co-flowing chevron nozzle has higher potential core region which is 25%. Nozzle with a corrugated tab (Blockage 3.6%) without co-flow the potential core has preserved up to X/D = 3.69[8] which is 2.89% lesser than the present work. The co-flowing nozzles preserves the potential core region up to the X/D = 7 axial distance [6]. The present chevron nozzle has 45.7% reduction in potential core region comparatively.



Graph 4.5: Centreline Mach number decay for various M_e

The sonic jet results the maximum reduction in potential core compared to remaining subsonic Mach numbers. Up to X/D = 20 the jets behaviour are different in nature after that they merged together. After that there is no evidence for the presence of potential core region. Further downstream location the radial Mach number ratio was almost linear which results that the jet attains the self-similar region (Fully turbulent region). The Graph 4.5 explains about the centreline Mach number decay. From the graph we concluded that the potential core is preserved for $M_e = 0.4$ and $M_e = 0.6$ up to X/D of 6.2 and 4.7 respectively. The Percentage of reduction in potential core length is 24.19. For $M_e = 0.8$ and $M_e = 1.0$ the potential core are preserved up to X/D = 4.5 and X/D = 3.8 respectively. In terms of percentage the reduction in potential core is 27.42 and 38.71 for $M_e = 0.8$ and $M_e = 1.0$ respectively.

5. CONCLUSION

From the experimental results while increasing the Mach exit number there is a reduction in length of the potential core length of the co-flowing chevron nozzle. In case of nozzles without any chevron configuration the length of the potential core increases with respect to increment in exit Mach number. For this case the percentage of reduction in potential core region across the jet axis for the exit Mach numbers 0.6, 0.8 and 1.0 are 24.19, 27.42 and 38.71 compared to $M_e = 0.4$ case. For sonic jet the potential core reduced Maximum level.

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