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Subsonic and Transonic Jet Control with Cross-Wire

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Cross-wire effectiveness for subsonic and sonic jet control is reported in this paper. Mach 0.4, 0.6, 0.8, and 1.0 axisymmetric jets from a convergent nozzle with cross-wire along a diameter at the exit were studied. The cross-wire was found to be effective in promoting jet mixing right from the nozzle exit, at all Mach numbers. For the underexpanded sonic jet at nozzle pressure ratio 3, 5, and 7, the cross-wire influenced the core and the shock cells, causing significant reduction of core length and weakening of the shocks at all levels of underexpansion. The jets from the nozzle with cross-wire spread faster in the direction normal to the cross-wire.

Nomenclature

D = nozzle exit diameter
M = local Mach number
M_e = jet exit Mach number
P_a = ambient pressure
P_t = pitot pressure
P_0 = settling chamber pressure
R = coordinate in the radial direction
X = coordinate along jet axis
Y = coordinate normal to cross-wire
Z = coordinate along the cross-wire

I. Introduction

FREQUENTLY the jet geometry is dictated by the nature of application. In most cases, the designer wishes to use a configuration that ensures rapid mixing of the jet flow with the surrounding fluid. In industry, jets find widespread applications in high-speed metal cutting procedures, air-conditioning systems, etc. However, their most significant application, requiring control of mixing, is in the field of aerospace technology, where they form an important part of the exhaust systems of propulsion units. In mixing devices such as combustion chambers, chemical reactors, etc., jets are required to enhance the mixing between reactants at molecular level for an efficient chemical reaction. With air-to-air warfare becoming more complicated with the introduction of sophisticated weaponry and radar systems, the aircraft designer these days is also concerned about the stealth capabilities of modern flying machines. As such they are more inclined towards the use of complex nozzle geometries such as a wide, thin nozzle rather than a circular one. These nozzles generally provide a reduced infrared signature which is of prime importance because most of the short range air-to-air and ground-to-air missile radar rely upon infrared sensors. The best way, therefore, is to reduce the infrared signature/detectability by cooling the engine exhaust temperatures by an efficient mixing with the surrounding cool air. This requires rapid mixing of hot gases with the ambient air through improved nozzle design and employing mixing techniques at the nozzle exit. This also helps to reduce far-field noise. When a jet is used for mixing purposes, a large mass entrainment, especially near the nozzle exit, is desired. The technological challenge of mixing enhancement in compressible flow stems from the inherently low growth rates of supersonic shear layer. The problem becomes all the more complicated when the nozzles are operated under off-design conditions. At high altitudes the jet is necessarily underexpanded, unless it is exiting from a variable area nozzle. It is well known that an underexpanded jet leads to expansion waves at the exit of the nozzle which extend to the free pressure jet boundary and reflect as weak compression waves. These compression waves coalesce to form the intercepting shocks in the interior of the jet and thus, the core of the underexpanded jet is dominated by periodic shock cell structures. The presence of these shock cell structures results in additional noise.

In an effort to increase mixing in jet flows, passive control methods, such as vortex generators in the form of mechanical tabs employed at the nozzle exit have been investigated in the past several years. The most notable work on the effect of the tabs and tablike device on the jet flowfield is that of Bradbury and Khadem [1]. These investigators studied the effect in a subsonic jet, and also observed a significant increase in the centerline velocity decay caused by the tabs. Zaman et al. [2] studied influence of tabs and found that tabs can distort the jet cross section and increase the jet spread rate significantly. They conjectured that a tab with height as small as 2% of the jet diameter, but larger than the efflux boundary layer thickness, produces a significant effect. They identified that variation of tab length for a given width did not seem to make much difference as long as the length was larger than the boundary layer thickness. Singh and Rathakrishnan [3] investigated on the argument that the projection of tabs beyond the boundary layer thickness is ineffective. They identified that, for the same projected area, length of the tab is more effective in enhancing the mixing than its width. Further, they postulated that when the streamwise vortices are introduced right up to the jet centerline, it may prove to be an advantage in enhancing the mixing. Therefore, it can be justifiably stated that the limit for tab length is the nozzle radius and not the boundary layer thickness. This limit of tab length is termed as *Rathakrishnan limit*. Sreejith and Rathakrishnan [4] investigated, instead of tabs, a wire running across an exit diameter (cross-wire) as a passive control to enhance the jet mixing. The cross-wire was found to weaken the shocks in the jet core significantly. This cross-wire was found to be effective at all levels of expansion. As high as 50% reduction in core length was achieved for Mach 1.79 at nozzle pressure ratio (NPR, P_0/P_a) 5.66. Lovaraju et al. [5] investigated the effectiveness of cross-wire in subsonic and sonic axisymmetric jets for mixing enhancement. They demonstrated that for jets with cross-wire the potential core length is reduced drastically and in some cases the length becomes insignificant.

In spite of these studies, the details of the jet flowfield as affected by the cross-wire have largely remained unclear. The aim of the present study, therefore, is to understand the flow mechanism behind the influence of cross-wire on subsonic and sonic jets.

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II. Experimental Facility and Procedure

The experiments were conducted in an open jet facility at the High-Speed Aerodynamics Laboratory, Indian Institute of Technology Kanpur. A schematic diagram of the open jet test facility is shown in Fig. 1. High pressure air enters the settling chamber through a tunnel section with a gate valve followed by a pressure regulating valve and a mixing length. The settling chamber is connected to the mixing length by a wide angle diffuser. The flow is further conditioned inside the settling chamber by closely meshed grids. The test model was fixed at the end of settling chamber with "O" ring sealing to avoid leaks. During the runs the settling chamber temperature was the same as the ambient temperature and the back pressure was the ambient pressure of the ambient to which the jets were discharged. A convergent circular nozzle of exit diameter 10 mm was used in the present investigation. A stainless steel wire of 0.5 mm diameter was used as cross-wire. The wire was fixed at the nozzle exit, running across a diameter. A photograph of the nozzle and cross-wire assembly is shown in Fig. 2. The geometric blockage due to the cross-wire at the nozzle exit, defined as the ratio of cross-wire projected area blocking the nozzle exit divided by the nozzle exit area, is 6.3%.

Pressure measurements were made using a 9016 model pressure scanner manufactured by Pressure Systems, Inc., a Western Company of Roxboro Group. It has 16 DH200 transducers with full scale pressure range from 2.5 to 5200 kPa. Application software was developed using LabView to interface the transducer with a computer. A pitot probe of 0.4 mm inner diameter (ID) and 0.6 mm outer diameter (OD) mounted on a rigid traverse measured the pressures along the jet axis (X), the direction normal to the cross-wire (Y) and along the cross-wire direction (Z), at 1 mm intervals. Detailed pressure measurements were made in only one quadrant of the jet at various axial locations downstream of the jet nozzle, ensuring a reasonable degree of symmetry in the other quadrants by measuring pressures at selected locations of symmetry in the opposite quadrants. To gain an insight into the nature of the waves in the controlled and uncontrolled jets, the flow was visualized by shadowgraph. The jet flow from the controlled nozzle was visualized by viewing in the directions normal to the cross-wire and along the cross-wire. The nozzle was operated at Mach 0.4, 0.6, 0.8, and 1.0 correct expansion states. For underexpansion studies, NPR 3, 5, and 7 were used.

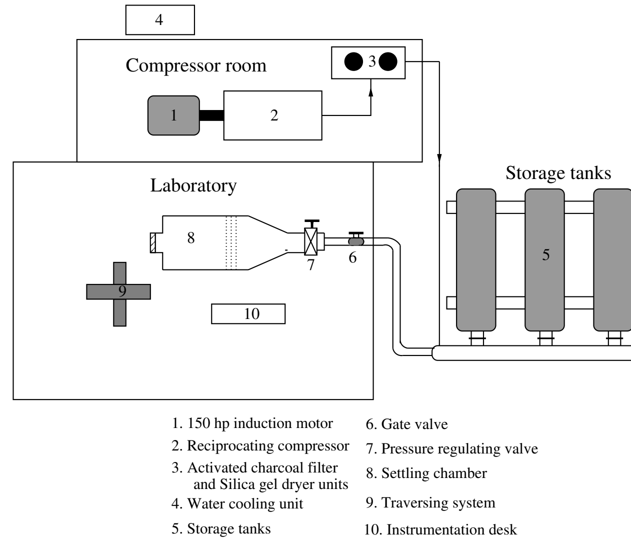


Fig. 1 Layout of the jet facility.

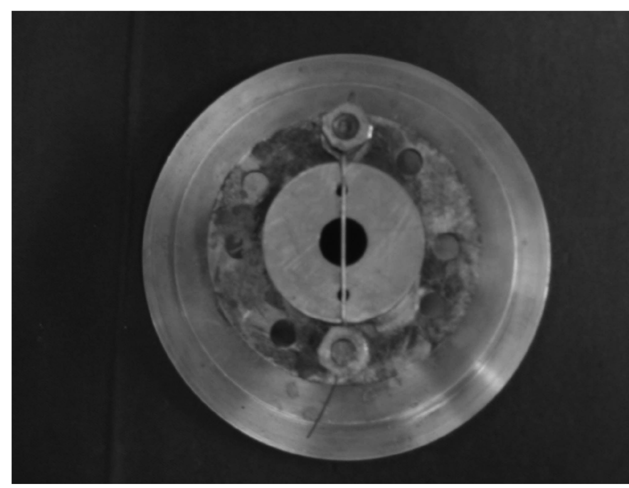


Fig. 2 Experimental model.

III. Results and Discussion

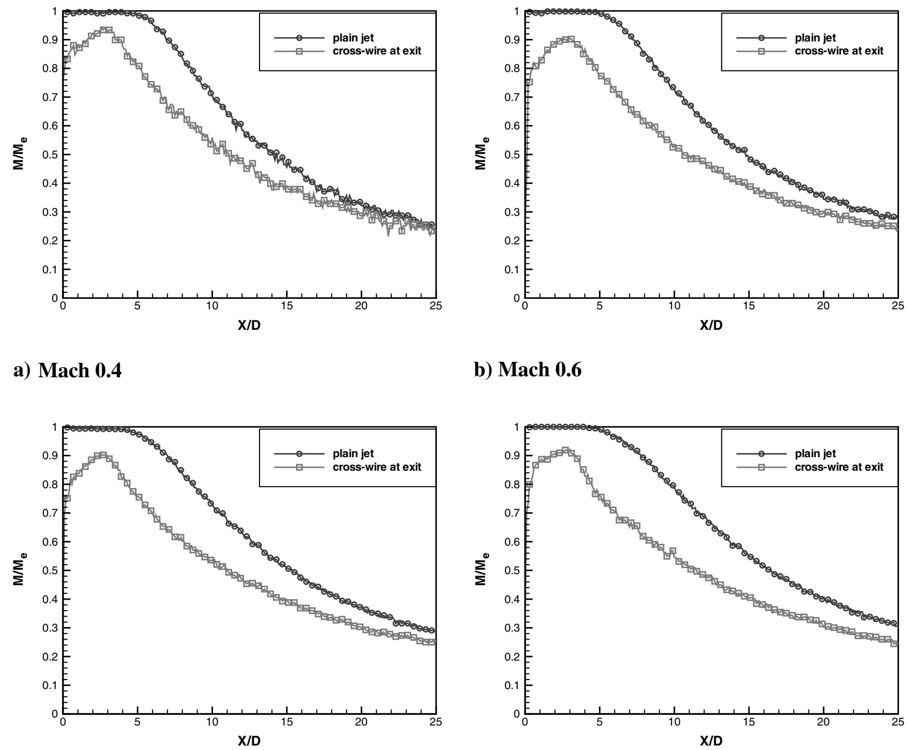
A. Effect of Cross-Wire on Subsonic and Correctly Expanded Sonic Jets

1. Centerline Decay

The measured pitot pressure along the centerline with the assumption that the static pressure in the jet field is the atmospheric pressure, were converted to Mach numbers using the isentropic relation. This assumption on the static pressure is valid for all subsonic Mach numbers, because they are always correctly expanded. For Mach 1.0 jet also, this can be regarded as a valid assumption for correctly expanded jets. The calculated Mach numbers were normalized by the corresponding nozzle exit Mach number. The Mach number (M/M_e) variation along the axial distance (X/D) for different jet Mach numbers are given in Fig. 3. For the uncontrolled jet, the core extends up to about $X/D = 6.0$ for all the Mach numbers. But when the cross-wire is introduced, taking the core as the axial extent at which the characteristic decay begins, it is seen that the core ends as early as X/D less than 3.0 for Mach 0.4 jet. The core for the controlled jets is defined as the axial extent at which the characteristic decay begins, because along the jet axis, just behind the cross-wire, the flow experiences a low pressure region over a short distance because of the wake caused by the wire. But on either side of the wire, in the direction normal to the wire, the potential core is undisturbed at the nozzle exit. Because of the low momentum in the wake of the wire, the surrounding fluid at higher momentum is deflected towards the lower momentum zone. This results in an active transverse exchange of momentum, because the flowfield is turbulent. Therefore, the cross-wire essentially divides the jet field into two smaller jets. Because of this initiation of rapid transverse momentum exchange, the flow along the centerline gains momentum rapidly, attains a peak followed by characteristic decay, typical of free jet. Therefore, the axial extent at which characteristic decay begins can be justifiably taken as the core length for jet from nozzle with cross-wire. For Mach 0.6 also, the core of the jet with wire control ends as early as $X/D = 3.0$. But for Mach 0.8, the core is made much shorter than the lower Mach numbers, terminating at X/D slightly less than 3.0, whereas for Mach 1.0, the core for the jet with cross-wire extends to about $X/D = 3.5$. These results clearly demonstrate that the cross-wire can efficiently control the jet mixing to result in considerably reduced core length compared to an uncontrolled jet. Also, the effectiveness of cross-wire depends on the jet Mach number. This may be because the mixing action of the streamwise vortices shed by the cross-wire depends on its vorticity and the interaction time available for it. Because the jet Mach number influences the convective velocity of the vortex shed, it is bound to influence its efficiency. Thus, the jet Mach number in combination with the strength of the axial vortex dictates the efficiency of the control.

2. Cross-Wire Effect on Jet Spread

To obtain a picture of the jet structure as it grows in the Y–Z plane at various axial locations (X/D), iso-Mach contours have been obtained from the grid pressure measurement in the jet flowfield. The outermost contour in the iso-Mach contour plots is with $M/M_e = 0.1$



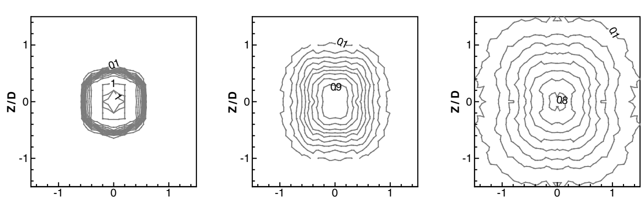
a) Mach 0.4

b) Mach 0.6

c) Mach 0.8

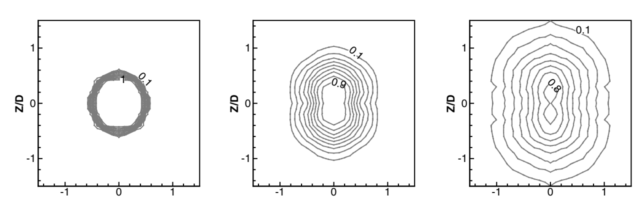
d) Mach 1.0

Fig. 3 Centerline Mach number decay of axisymmetric jet.



a) X/D = 1.0 **b) X/D = 5.0** **c) X/D = 9.0**

Fig. 4 Iso-Mach contours of Mach 0.8 plain jet.

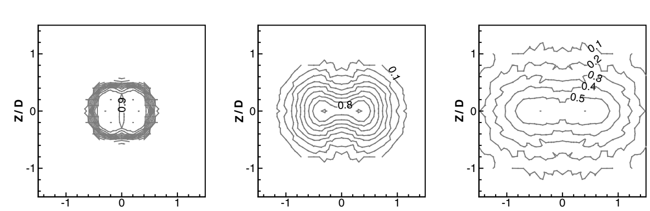


a) X/D = 1.0 **b) X/D = 5.0** **c) X/D = 9.0**

Fig. 5 Iso-Mach contours of Mach 1.0 plain jet.

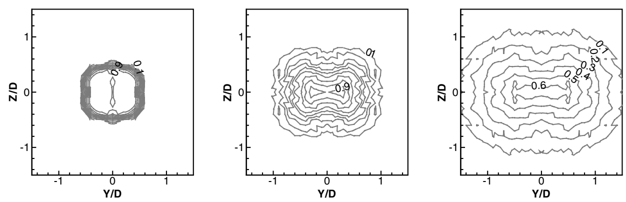
with intermediate contours uniformly stepped by a value of 0.1. Iso-Mach contours for a plain circular jet and jet with cross-wire are presented for Mach 0.8 and correctly expanded sonic case. Figures 4 and 5 show the iso-Mach contours for the plain circular jet at $X/D = 1.0$, 5.0, and 9.0, for Mach 0.8 and 1.0, respectively. The shape gets distorted from the expected circular shape as the jet propagates downstream. This may be due to the asymmetric shear activity along the periphery of the jet, where active entrainment is taking place, which need not be symmetric even though the exit geometry is symmetric. That is, the axisymmetric jet is rendered asymmetric due to the mass entraining vortices generated at the jet periphery owing to differential shear. Because every vortex is associated with a strength and frequency, it is natural that they cause the jet to become asymmetric. It is interesting to note that the asymmetry at a given X/D is greater for high Mach number. This may be because with increased Mach number the vorticity content of the vortex structures at the jet periphery is higher due to increase in differential shear.

A comparison of the iso-Mach contours at the same axial stations for the plain and cross-wire controlled jets clearly illustrates the effect introduced in the flowfield by the presence of cross-wire at each operating condition. It is seen from the contour plots that the cross-wire controlled jets grow fast in the plane normal to the cross-wire and slowly in the plane of the cross-wire at all the operating conditions investigated. Figures 6 and 7 show the iso-Mach contours for cross-wire controlled jets at Mach 0.8 and correctly expanded sonic case. Keeping in mind that a smaller spacing between the Mach number contours indicates lesser entrainment into the jet and vice versa [6], it is observed that the cross-wire controlled jets grow with larger spacing between the contours in the downstream direction compared to uncontrolled jets. For controlled Mach 0.8 jet as seen in Fig. 6, the cross-wire alters the jet cross-sectional structure significantly right from the nozzle exit. However, the spacing between the contours are not increased up to the $X/D = 5.0$ compared to uncontrolled jets, which indicates almost there is no variation in the mass entrainment. The larger spacing between contours is observed thereafter, which implies higher mass entrainment into the jet (Fig. 6c). The innermost contour level is decreased by 0.1 up to $X/D = 5.0$, and it reaches 0.5 at $X/D = 9.0$ for Mach 0.8 controlled jet. The decrease in the number of contours with a significant decrease in corresponding contour levels can be



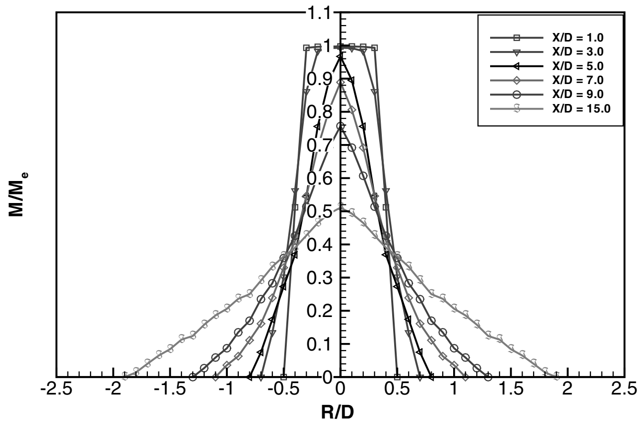
a) X/D = 1.0 **b) X/D = 5.0** **c) X/D = 9.0**

Fig. 6 Iso-Mach contours of Mach 0.8 jet with cross-wire.

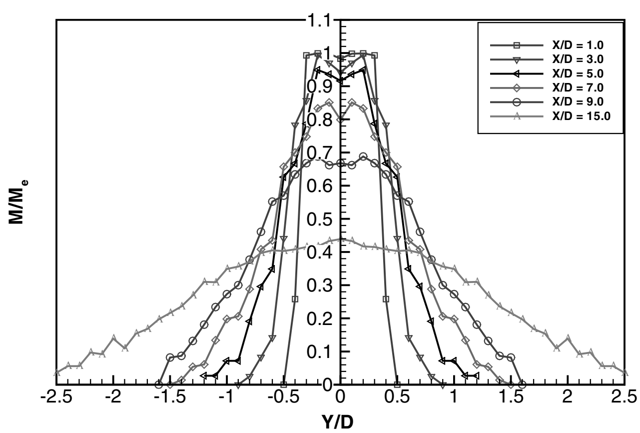


a) X/D=1.0 b) X/D=5.0 c) X/D=9.0

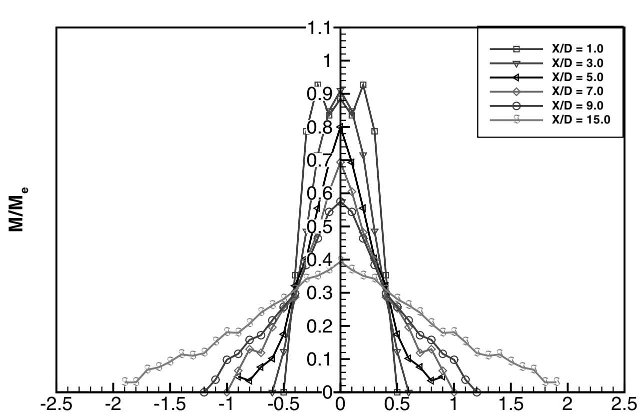
Fig. 7 Iso-Mach contours of Mach 1.0 jet with cross-wire.



a) Plain jet



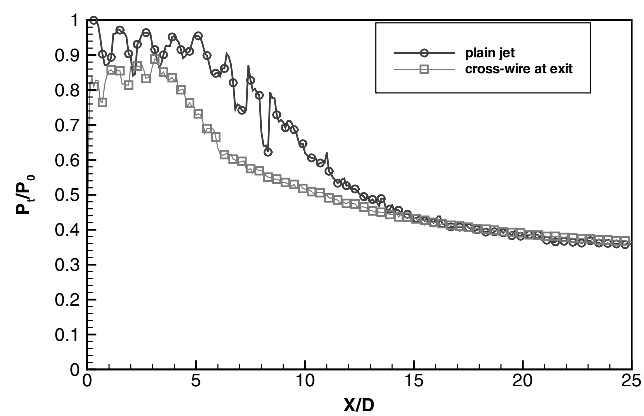
b) Y-profiles for jet with cross-wire



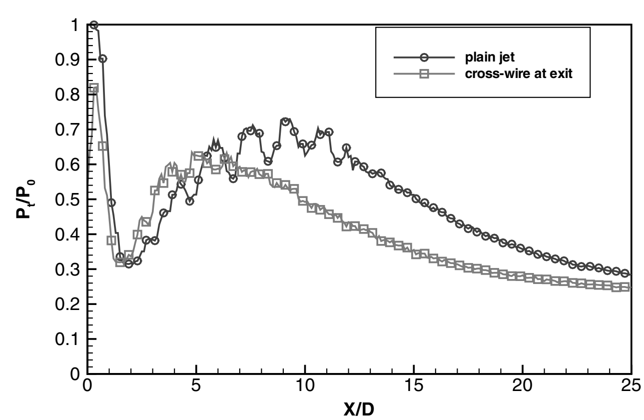
c) Z-profiles for jet with cross-wire

Fig. 8 Mach profiles of correctly expanded sonic jet.

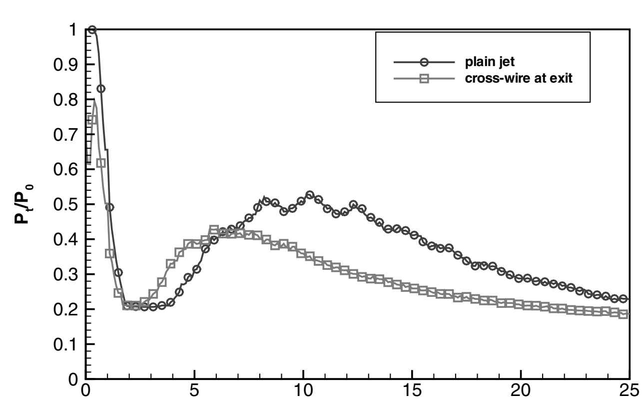
regarded as an indication of faster decay. Figures 6b and 7b show how the cross-wire tends to split the jet into two with high Mach number cores on either side of the cross-wire. By employing the cross-wire (Figs. 6b and 7b) the jet ejects flow outward in the direction normal to the cross-wire and ingests flow in the direction along the cross-wire. The cross-wire is found to be equally effective in controlling the correctly expanded sonic jet (Fig. 7). The cross-wire is effective in bringing down the contour levels and reducing the number of contours, which is a good measure of rapid jet decay. A discontinuity introduced in the circular jet in the form of a cross-wire is seen to form four sharp corners on either side of the cross-wire. These sharp corners provide low velocity regions, which on interaction with the mean flow of the jet seem to alter greatly the uniform growth of vortices in that plane. The sharper curvature at the location of the cross-wire relative to the remaining portions of the



a) NPR 3



b) NPR 5



c) NPR 7

Fig. 9 Centerline pitot pressure distribution of underexpanded sonic jet.

exit results in local bending of the vortex, and hence causes self-induced azimuthal deformations, which are responsible for mixing enhancement.

3. Mach Number Profiles

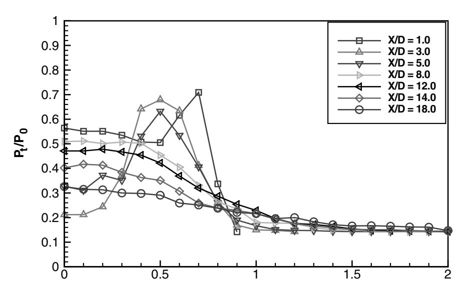
Figure 8a presents the radial Mach number variation of plain jet. The variation of Mach number in the plane perpendicular to the cross-wire (X–Y plane) and along the cross-wire (X–Z plane) at various axial locations are presented in Figs. 8b and 8c, respectively, for the sonic nozzle operated at correct expansion. The extent of potential core for the controlled jet, normal to the cross-wire (Y-direction), can be observed in Fig. 8b. For the plain jet the potential core extends up to $X/D = 5.0$ as seen from Fig. 8a, whereas for the controlled jet the extent of the potential core in the Y-direction is only up to $X/D = 1.0$ and no such characteristic thereafter, as seen in Fig. 8b. It can be easily seen in Figs. 8b and 8c that the nozzle with cross-wire causes the jet to spread asymmetrically, being wider in the plane perpendicular to the cross-wire. Note that the Mach number at the jet centerline is smaller than the nearby locations, when measured in the plane perpendicular to the plane containing the cross-wire. This could be related to the jet bifurcation. Figure 7b, and Mach profile at $X/D = 5.0$ in Fig. 8b, support this bifurcation effect. Figure 8b demonstrates the sudden rise in Mach number away from the centerline (in the Y-direction) at axial locations $X/D = 1.0$–9.0, then decreasing to approach the jet outer edge. This is observed only in the plane perpendicular to the cross-wire, suggesting that this phenomenon is related to the cross-wire and the resulted sharp corners in the nozzle exit plane. A possible explanation may be found from the earlier studies on subsonic jets. Hussain and Hussain [7] observed off-center peaks in the velocity profiles of elliptic jet. They noted that these peaks were caused by two vortex cores produced by the bifurcation of the initially elliptic structure. The dip at the centerline, together with a larger jet diameter, are signs of the bifurcation of the jet [2]. Comparing the profiles from $X/D = 3.0$ to $X/D = 9.0$, it may be noticed that the peaks are shifted away from the centerline, which suggests that the vortices move away from the nozzle axis as they propagate downstream [8]. Off-center peaks are not observed along cross-wire direction, beyond $X/D = 1.0$, as seen in Fig. 8c. This implies that vortices got dissipated in that direction [9].

B. Controlled Underexpanded Sonic Jets

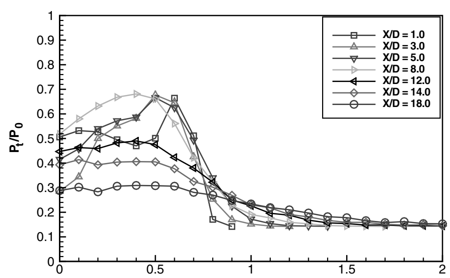
In the supersonic region of the jet flow, the measured pitot pressure corresponds to the total pressure behind the standing bow shock in front of the pitot probe. The bow shock wave near the probe centerline, however, is almost normal to the probe axis, therefore the pitot probe measures the total pressure behind the normal shock wave. The pressure oscillations in the core region of the supersonic flow are due to the formation of shock cells in the jet. Because of probe interference with the shock structure, there could be some measurement error and hence, the results represent the qualitative nature of the flow. Nevertheless, the pitot pressure distributions along the jet centerline are accurate enough to capture the overall features, such as the extent of the supersonic core region, the number of shock cells, the spacing between them, and the rate of pressure decay after the core region, etc. [8].

1. Centerline Pitot Pressure Distribution

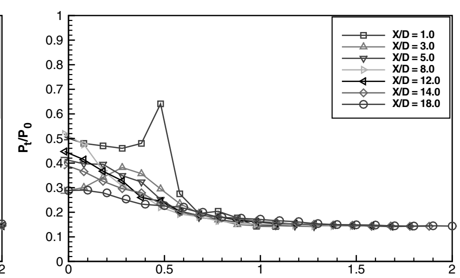
The supersonic core length is the axial extent up to which supersonic flow exists [10]. The core length of the supersonic jet can be taken as a direct measure of the mixing and spreading characteristics of the jet [10]. The measured pitot pressure distribution along the jet centerline is nondimensionalized with the settling chamber pressure and plotted against the nondimensionalized axial distance, X/D. Centerline pitot pressure distributions for controlled and uncontrolled sonic jets operated at NPR 3, 5, and 7 are compared in Fig. 9. The axial extent up to which measured pitot pressures show oscillatory trend represents the supersonic core. The increase in the amplitude of the pitot pressure oscillations denotes the presence of strong shocks in the supersonic core. Figure 9a indicates a drastic reduction of about 62% in length of the jet core under the action of the cross-wire for the NPR 3 case. The reduced amplitude of pitot pressure oscillations at all the operating conditions by the presence of cross-wire suggest that shock cell structure is significantly weakened. At higher levels of underexpansion, for the jets from the plain nozzle, near the nozzle exit, a sharp drop in the pitot pressure followed by a rise is observed, which signifies the presence of normal shock wave commonly referred to as the Mach disc (Figs. 9b and 9c). With the cross-wire, the first shock cell behaves identically similar to those from the plain nozzle at NPR 5 and 7. Figures 9b and 9c indicate a reduction of about 46% and 50% in the jet core under the action of cross-wire for the NPR 5 and 7 cases, respectively. The total pressure decay begins at $X/D = 6.4$ and 6.0 for cross-wire controlled jets at NPR 5 and 7 cases, respectively. Unlike at NPR 3, at higher NPRs of 5 and 7, the cross-wire control could be able to cause a rapid decay of the jet all along the centerline up to $X/D = 25.0$. This control could able to greatly enhance the jet mixing with increase of favorable pressure gradient.



a) plain jet

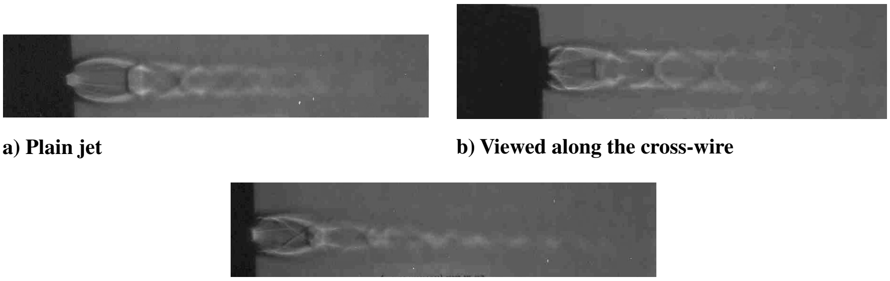


b) Y-profiles for jet with cross-wire



c) Z-profiles for jet with cross-wire

Fig. 10 Pitot profiles of sonic jet at NPR 7.



a) Plain jet

b) Viewed along the cross-wire

c) Viewed normal to the cross-wire

Fig. 11 Shadowgraph pictures of sonic jet at NPR 7.

This trend is similar to that reported by Singh and Rathakrishnan [3] for tabs.

2. Effect of Cross-Wire on the Shock Structure

A study combining the pitot pressure distribution in the direction normal to the cross-wire and along the cross-wire, the centerline pitot pressure distributions, and shadowgraph visualization of the waves in the jet was carried out to gain an insight into the influence of cross-wire on the shock cells in the core. The pitot pressure distributions for the plain jet in the radial direction at various axial locations are presented in Fig. 10a, and pressure profiles for controlled jet in the direction perpendicular to the cross-wire (Y) and along the cross-wire (Z) at NPR 7 are presented in Figs. 10b and 10c, respectively. By employing the cross-wire, the pitot pressure distribution is made greatly asymmetric, which implies the asymmetric nature of the shock structure in the supersonic core. From Figs. 10b and 10c, it is evident that the controlled jet grows fast in the direction normal to the cross-wire and slowly in the direction along the cross-wire. The pitot profile from $X/D = 8.0$ onwards is in the range where the shock/expansion train had already decayed, and the flow was subsonic for the controlled jet at NPR 7. From Fig. 10b, at $X/D = 8.0$, the dip at the center, together with a larger jet diameter, are signs of the bifurcation of the jet. In the jet decay region around from $X/D = 8.0$ onwards, the pitot pressures assume lower values and become almost asymptotic to Z-axis at a shorter distance from the nozzle exit, compared to uncontrolled jets as shown in Fig. 10c. This implies faster decay of the controlled jet in the direction along the cross-wire. The shadowgraph photographs of the jet at NPR 7 are shown in Fig. 11. The effect of cross-wire on the shock structure is clearly seen from these pictures. Introduction of cross-wire results in asymmetry on the shock structure, as seen in Figs. 11b and 11c. A modified shock cell nature is very much evident from cross-wire controlled jet compared to the plain jet. The dispersion of shocks in the direction normal to the cross-wire is evident in Fig. 11b. This perhaps leads to the weakening of the cell structure in the case of cross-wire nozzles. It is well established that destruction/weakening of shocks in the supersonic zone will result in reduction of shock associated noise and hence the overall noise [4]. The asymmetric development of the controlled jet is observed at all the underexpanded conditions. A closer look into the vortex generation mechanism in the cross-wire controlled jets will explain the reason behind the preceding results. When the wire is placed in a subsonic flow it would shed vortices alternatively. These vortices become streamwise in nature soon after shedding and can travel long distance compared to spanwise or azimuthal vortices. Therefore, the streamwise vortices can efficiently serve as a mixing enhancement mechanism for jets. But in the underexpanded sonic jets, the core consists of a mixture of subsonic and supersonic Mach number zones. These streamwise vortices shed by the cross-wire have to pass through different Mach number zones in the jet field before losing their identity. This process would also result in mixing enhancement. The mixing level will vary from place to place in the supersonic jet because of the presence of the mixed subsonic and supersonic zones. Nevertheless, the mixing initiated by these streamwise vortices will result in significantly enhanced mixing of the supersonic jets, especially in the core region. This is the main cause for the shocks in the core to become weaker compared to the plain nozzle jet.

IV. Conclusions

Cross-wire control is found to be effective in enhancing the mixing at all the subsonic and fully expanded sonic jets. The cross-wire alters the potential core significantly and the core disappears completely within a short distance from the nozzle exit, followed by a rapid decay of the jet centerline Mach number. The iso-Mach contours indicate that the cross-wire is effective in bringing down the contour levels and reducing the number of contours, which is a good measure of rapid jet decay. The cross-wire tends to split the jet into two zones with high Mach number cores on either side of the cross-wire. The nozzle with cross-wire causes the jet to spread asymmetrically, being wider in the direction perpendicular to the cross-wire. The cross-wire is also effective in reducing the length of the supersonic core significantly. A reduction of about 46% and 50% in the jet core length under the action of cross-wire was achieved for the NPR 5 and 7 cases, respectively. The shock cell structures from the cross-wire controlled jets were found to be weaker than those of the plain nozzle.

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