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Effect of cross wire tab orientation on twin jet mixing characteristics

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ABSTRACT

The effect of the relative azimuthal orientation of the cross wires, placed at the exit of two identical converging-diverging nozzles, on the flow field of the twin jet is studied experimentally. The nozzle is designed for Mach number of 1.8, with the inter-nozzle spacing of 1.5 and 2.25 times the nozzle exit diameter. Pitot pressure surveys are conducted along the centerline and the cross-stream direction of the twin jet. Cross wire is shown to be successful in reducing the core length and enhancing the mixing characteristics at all the NPRs studied. The combinations of the horizontal and vertical orientation of the cross wire are found to significantly influence the development of the jet flow field for twin jets. Wires, both mounted vertically, are found to be superior in enhancing the mixing characteristics and reducing the core length. The shadowgraph images reveal that the wire bifurcates the jet and displaces the fluid away from the centerline. Strong shocks are formed near the cross wire, but the pressure losses and enhanced mixing of the jet fluid result in smaller supersonic core length with less number of shock-cells.

1. Introduction

Study of multiple jet configurations is important as it is used in many engineering applications. The supersonic twin jet arrangement is in particular common to high-speed propulsion systems in the aerospace industry. Supersonic jets when closely spaced, interact with each other in a complicated manner resulting in a flow field different from a single jet in a similar environment. Early experimental work done by Berndt [1] reported the presence of a very high level of pressure fluctuations in twin jet proximity that resulted in the structural damage of aircraft components. Further investigation by Seiner et al. [2] on twin plumes provided the evidence that the two plume flow fields are weakly coupled together at Mach number less than 1.2 and strongly coupled as the Mach number increases further. As the Mach number rises to 1.3 and 1.4, the repetitive sinusoidal motion is observed from both the jets that noticeably move the flow structures to and fro in the plane containing the jet axes [3]. It was also observed that the most prevalent spatial mode of instability is the jet flapping mode, with the B-type helical instability [2,3]. The phase coupling of these large-scale, coherent resonance modes is found to be responsible for large dynamic pressures and high amplitude screech tones in the inter-nozzle region. With an objective of suppressing the plume resonance, they used a small tab-like device mounted at the nozzle exit and a small notch at the nozzle exit as two passive control methods. Both the methods altered the wave structure to avoid the mutual coupling of the plume and thus found to be effective in suppressing the pressure and screech amplitudes.

One obvious aspect of side-by-side jets is the azimuthal asymmetry in the noise and the flow field. Two parallel jets result in less noise radiation in the plane containing the axes, as the sound waves from one jet is restricted by the other, called as acoustic shielding. A lot of analytical and experimental work is done to predict the effects of shielding phenomenon [4,5]. The physical mechanisms that govern the sound field of twin jet is the mutual refraction, diffraction and the reflection between the two jets. Jet heating is found to be the most effective means to increase the acoustic shielding [6]. Kantola [7] reported an increased acoustic shielding with an increase in nozzle spacing, as larger inter-nozzle spacing delays the merging of the jets in the symmetry plane, providing more opportunity for the absorption of the acoustic energy. Performing experiments on Mach 1.48 nozzle, Wlezien [8] reported that the noise produced by the mutual interaction of two supersonic jets is a strong function of nozzle spacing and the jet Mach number. When the nozzle spacing is small the jets merge before higher modes develop, and screech is thereby suppressed [8]. The screech amplitude however practically remained insensitive to the nozzle design Mach number. The maximum drop in screech tone amplitude is achieved when the nozzles are spaced somewhere in between 3 and 5 jet diameter depending on NPR [9]. He also concluded that the axial shifting of one nozzle to suppress screech tones is not effective. Studies by Raman and Taghavi [10] on supersonic rectangular jets suggested that the suppression and amplification of screech tone is a consequence of the anti-symmetric and symmetric mode of coupling because of the in-phase and out-of-phase motion of the jets in a plane normal to the plane containing the jet centers. They also reported that the two modes do not overlap, and the switching from the anti-symmetric to the symmetric mode is possibly because of an abrupt shift in the effective

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screech source from the third to the fourth shock cell. Lin and Shew [11] investigated the interaction of parallel turbulent plane subsonic jets and later Moustafa [12,13] studied the effect of pressure ratio and jet spacing on the supersonic twin jet structure, development, and propagation. The supersonic jet flow structure was found to be strongly influenced by the pressure ratio and jet spacing.

The entire flow domain of the twin jets can be divided into three regions: (1) Region 'A', the converging region; (2) Region 'B', the merging region; and (3) Region 'C', the combined region [11,14]. Region 'A' begins at the exit plane of the nozzle and extends to the location where the two jets touch each other. The shear layer separates the surrounding fluid from the high-speed jet fluid. Because of high gradients of velocity across the jet, the effect of viscosity is prominent in diffusing the momentum and thus plays an important role in jet evolution. A feature of the free jet flow is that the momentum across any cross-section of the jet remains conserved. This results in the entrainment of the surrounding fluid by the turbulent jet, which creates a lower pressure region between the nozzle exit plane and the merging point. The location of the merging point and the bending of the jet axes strongly depend on the jet spacing and the jet velocity. Region 'B' begins downstream of the merging point beyond which the two jets strongly interact around the mid plane, transporting momentum from individual jet core to the internozzle region of the twin jets. The twin circular jet interacts to merge and develop into the elliptic shape. Due to the azimuthal asymmetry of the elliptic jet, the spread in the minor axis direction is higher than that in the major axis, and the cross-section transitions from elliptic to circular with velocity maximum at the symmetric plane [11,13]. This transition is achieved by a strong nonlinear velocity growth and continues till the maximum streamline velocity is achieved in the central plane. Further downstream, the jets are said to be fully merged, but may not be fully developed. The Region 'C' is the region after the jets have merged, where the two jets combine to resemble a single-jet flow. The characteristics of mean flow in this region tend to become similar to those of a single-jet flow as the distance from the nozzle exit plane increases.

There is an ongoing effort to control the supersonic jet dynamics using different active and passive control techniques. Techniques that involve tabs, notches, microjets, plasma actuators, etc. for controlling single and twin jets have been reported in the literature [3,15–17]. Small tabs and vortex generators that are easy to implement have been found to be effective passive control techniques. Bradbury and Khadem [18] were the first to practically use this concept and reported a rapid decay of the centerline velocity of a low-speed jet when two small tabs were placed around the perimeter of a nozzle. Motivations from these results led further investigations by Ahuja et al. [19] and Zaman et al. [20] for high-speed and heated jets, and were in good agreement with the previous findings. In the same study, they found that the tabs are not only effective for low-speed jets but can also enhance mixing at high-speed and high-temperature conditions. They reported a decrease in core length and enhanced mixing as a result of the suppression of large-scale coherent structures and an increase in fluid entrainment into the jet. Much of the work had been carried out to explore the influence of the tabs and the physical mechanism responsible for the effects like mixing enhancement, jet spread, screech suppression, etc. The same has been discussed in detail in the open literature [21–24]. It is established that a tab placed normal to the flow generates a pair of counter-rotating vortices throughout the span of the tab geometry. The possible source for the vorticity generation is the hindrance caused by the tab, which results in an excessive pressure rise just upstream of the tab, producing a pair of primary counter-rotating streamwise vortices. Also, the pressure gradient across the tab surface causes the fluid to roll up from high pressure side to low pressure side along the edges. This causes secondary spanwise vortices to shed and convect downstream resulting in rapid enhancement and cross-stream mixing of the jet fluid. The size of the vortices strongly depends on the shape and orientation of the tab. Several studies have focused on the effectiveness and optimization of tabs in terms of shape, size, number and orientation [20,24,25]. A thin tab sufficiently long to extend up to the radius of the nozzle exit is another variant that has shown good mixing enhancement characteristics for circular and elliptic jets for subsonic and supersonic Mach numbers [26,27]. Recently, Rathakrishnan [28] performed systematic analysis for control of single jets using a cross wire with a blockage ratio less than 10% for Mach 1.6, 1.79 and 2.0. The cross wire was found to enhance the mixing of the jet mass and reduce the core length at all the pressure ratios studied. As high as 50% reduction in the core length was observed at correct expansion for all the jets. The weakening of the shock waves was shown to result in the reduction of shock-associated noise and thus overall jet noise.

It can be concluded from the preceding discussion that most of the work done on tabs as passive flow control device is primarily focused on a single jet. The dynamics of twin jet can, however, be very different particularly when the jets are closely placed. For example, use of very small tabs mounted arbitrarily at the nozzle axis by Seiner et al. [2] and Shaw [9] decoupled the instability modes of the two jets resulting in suppression of dynamic pressure and acoustic spectrum. The cross wire can be used as a simple and very effective means for altering the twin jet flow features. Wires are easy to mount and does not require any alteration in the nozzle geometry. The mutual orientation of the two wires can play a dramatic/dominant role in jet flow development. It is the objective of the present study to demonstrate the effectiveness of a cross wire as a passive control for twin axisymmetric supersonic jet and to optimize its orientation for a better mixing and shock cell attenuation. Mean flow features such as centerline pressure survey, core length and shock-cells are analyzed for comparative purposes. Flow visualization is done by the shadowgraph technique.

The remainder of the paper is presented as follows. In Section 2, experimental setup and procedures are discussed. Section 2.1 describes the instrumentation and data accuracy employed in this work. Results based on this work are discussed in the next section, Section 3. Finally, the conclusions are presented in Section 4.

2. Experimental setup and procedure

Experiments have been carried out in the open jet facility at the high-speed aerodynamics laboratory, Indian Institute of Technology Kanpur, India [29]. The facility consists of three storage tanks, having a capacity of 85 m^3. The tanks are charged by multi-stage reciprocating compressors capable of delivering 0.17 m^3/s of air at a pressure of 3.5 MPa. The pressurized (up to 300 psi) dry air from the storage tanks is ducted to the settling chamber through a control valve. A mixing length of 2 m is placed between the valve and the settling chamber to reduce the flow disturbances caused by the control valve. The settling chamber is a cylindrical section with a wire mesh located inside to filter the air before it is passed to the nozzle.

The experimental model used in the present experiments consists of a circular nozzle block of 80 mm diameter and 40 mm length with a 10 mm flange for mounting. The nozzle block has 4 converging-diverging conical nozzles with different spacings between them. Dimensions of the nozzle and the nozzle block are shown in Fig. 1. For the present study, only three nozzles were used marked as N1, N2 and N3 in Fig. 1a. Single block ensures that all the nozzles are subjected to same initial conditions. Depending on the inter-nozzle spacing required, two nozzles were selected and the other two were blocked at the inlet for that experiment. Thus, at a particular time only two nozzles were in operation. All the nozzles are similar, designed for the Mach number 1.8 with 8 mm throat diameter. Nozzles were made in brass block with CNC wire cutting method. All the nozzles were calibrated for the designed Mach number. The exit diameter, d, of the nozzle is 9.6 mm and the Reynolds number based on the exit diameter is 4.9×10^6 and 1.0×10^6 for the minimum and the maximum NPRs of 4 and 8, respectively. The cross wire of diameter 0.5 mm was used as a passive control in the present study. The blockage caused by the cross wire is 7% of the nozzle exit