Effectiveness of secondary tabs for supersonic mixing

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Abstract The effect of vortex generators, in the form of small tabs projecting into the flow at the nozzle exit, aided by secondary tabs on either side, on the mixing characteristics of an axisymmetric jet at Mach number 1.7 is investigated. Experimental studies on the basic features of the jet from a nozzle with secondary tabs are conducted to assess the free jet characteristics as well as the momentum and thermal mixing behavior. The secondary tabs were found to increase the jet spread and distort the jet cross-section and were found to cause substantial enhancement of mixing of supersonic jets. Jet structure is observed using flow-visualization techniques. LLS images are employed to obtain cross-sectional views of the jet with the introduction of secondary tabs. The ability of secondary tabs to eliminate the screech noise of the supersonic jet is also observed.

1 Introduction

The use of passive mixing devices to enhance the mixing of compressible jets has been investigated extensively in the past decade. Nozzles with tabs have been shown to provide large-scale streamwise vortices that cause spread and mixing of the jet downstream. Bradbury and Khadem (1975) were among the first to document the effect of tabs in a low-speed jet with square tabs placed normal to the flow at the nozzle exit. Gross distortions in the jet development were observed, resulting in the jet splitting into two high velocity regions on either side of the diameter joining the tabs. Ahuja and Brown (1989) conducted a series of experiments on the effects of tabs on the mixing and acoustic aspects of supersonic jets. Zaman et al. (1994) surmised two possible sources of streamwise vorticity for the flow over the tab. The first and the foremost is the "pressure hill" created upstream of the tab, which produces a pair of counter-rotating vortices. The second is the vorticity shed from the side of the tab. Vorticity from the two sources add together, improving the effectiveness of the tabs. Zhang and Schneider (1995) confirmed the efficiency of tabs by observing the increased level of molecular mixing in the near field of the tabs. Experiments carried out by Zaman (1999) indicated that each tab introduced an indentation into the high-speed side of the jet shear layer by the action of streamwise vortices. Wishart (1993) conducted experiments by providing point disturbances within the supersonic nozzle. Small rods were inserted at several locations between the throat and the exit plane. They established the possibility of contouring the jet by the number and location of disturbances. Yu and Hou (1998) showed that secondary tabs could be effective in enhancing the strength of the streamwise vortices generated by the primary tabs. The effect of the addition of secondary tabs that are placed on either side of primary tab in the mixing of jets was studied also by Bohl and Foss (1997, 1999). The purpose for which they employed the secondary tabs was to enhance the naturally occurring outflow from the jet core. This modification increased the flux of vorticity and the rate at which the jet and ambient fluid interact. The effectiveness of secondary tabs in an incompressible regime was established in their experiments. The present study focuses primarily on the mixing characteristics of secondary tabs in supersonic streams.

2 Experimental details

The experiments were conducted on the coaxial dual stream blow-down facility of the Gas Dynamics Laboratory, Indian Institute of Technology, Madras. The schematic diagram of the test setup for cold and hot flow experiments is given in Fig. 1. The primary jet issues through the convergent–divergent supersonic test nozzle of Mach number 1.7. The test nozzle is a plain convergent–divergent (c–d) nozzle or a c–d nozzle with primary tabs or a c–d nozzle with primary and secondary tabs. The secondary jet issues from the annular convergent nozzle surrounding the primary jet from the test nozzle. For free jet studies, only the primary jet of the facility was used. In the case of dual jets, a mixing tube/duct was attached to the exit of the nozzles. Both the primary and secondary air supplies were regulated using separate valves. Intrusive methods were employed for measurements. A flat cut stainless-steel tube was used as the pitot tube (1 mm internal diameter and 1.3 mm outer diameter). A long cone supersonic probe with four static holes of 0.35-mm diameter, 90° apart was used for measuring static pressure. The area blockages of the pitot and static probes were 0.26% and 0.44% of the nozzle exit area respectively. A diaphragm-type pressure transducer (accuracy ±5%) along with a digital indicator was used to indicate pressure. A three-dimensional traversing mechanism was used.
to move the probes in the radial and axial directions of the flow field. Temperature measurements were carried out using total temperature probes, which incorporated a chromel–alumel thermocouple sensor.

The schlieren system employing a 50-W halogen lamp and two concave mirrors in an off-axis arrangement was used. The laser light sheet (LLS) method with water seeding in the secondary duct was employed for capturing the cross-sectional images of the jet. The schlieren and laser sheet images were captured using a CCD camera. The jet noise was measured with a piezoelectric transducer attached to the traverse mechanism. The transducer (Model 112A22, PCB Piezotronics) has a sensitivity of 100 mV/psi with a dynamic range from 0.00782 MPa to 0.782 MPa. The data were acquired using a 16-bit, 16-channel data acquisition device and processed using the fast Fourier transform (FFT) to give the output as sound pressure amplitude.

Figure 2a shows the schematic of the flow pattern and Fig. 2b shows the end view of the assembly of the nozzle and the mixing tube, showing the orientation of tabs into the flow. The primary tab used is a triangular one with a base of 3 mm and protruding into the flow at an angle of 45° with respect to the axis of the primary flow. The protrusion of the tab into the primary flow was maintained at 2.1 mm from the nozzle lip. The secondary tabs were placed in contact with the outer edge of the primary tab and were oriented at an angle of 10° with respect to the horizontal plane. The orientation of the secondary tab was chosen based on the earlier work by Yu and Hou (1998). The area occupied by the secondary tab was half in comparison with that of the primary tabs.

3 Results and discussion

3.1 Centerline pressure decay

In Fig. 3 the centerline decay of total pressure for the ideally expanded free jets is shown. The centerline total pressure \(P_{01}\) normalized by the reservoir pressure \(P_r\) is plotted against the axial distance normalized by the nozzle exit radius \(R_n\). The chamber pressure was maintained at 0.5 MPa for the ideally expanded case. It can be seen from the figure that the potential core for the tabbed nozzle is less compared with that of the jet from the conventional c–d nozzle. The jet from the nozzle with secondary tabs is mixing with the ambient at a distance 20 times the radius of the nozzle, while its counterpart from the c–d nozzle is mixed at 35 times the radius of the nozzle. The considerable reduction in length of the potential core can be attributed to faster mixing of the jet with the ambient. In the case of the nozzle with primary tabs, the rate of pressure decay along the axial direction is less compared with the case of the nozzle with secondary tabs, necessitating more axial lengths for pressure equalization with the ambient.

![Fig. 2. a The flow pattern. b End view of the nozzle-mixing tube assembly](image)

![Fig. 3. The centerline total pressure decay for the ideally expanded free jets](image)