MIXING ENHANCEMENT IN SUPERSONIC JETS BY DELTA-TABS

K.B.M.Q. Zaman
NASA Lewis Research Center
Cleveland, Ohio

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BACKGROUND

Collaborators: Prof. Mo Samimy and Mark Reeder
Ohio State University, Columbus, OH

Previous Work: K. K. Ahuja (NASA CR)
H. K. Tanna (JSV '77)
Bradbury & Khadem (JFM '75)

The investigation was initiated during the summer of 1990 when Prof. Mo Samimy from OSU came to visit as a Summer faculty fellow. He was accompanied by graduate student Mark Reeder. Mark came back as summer student during the following two summers to work with Zaman on the project.

Notable previous works on the subject are:

1. K. K. Ahuja and W. H. Brown, "Shear Flow Control by Mechanical Tabs," AIAA Paper 89-0994, 1989.

2. H.K. Tanna, "An Experimental Study of Jet Noise, Part II: Shock Associated Noise", J. Sound & Vibration, Vol. 50, 429-444, 1977.

3. L.J.S. Bradbury and A. H. Khadem, "The Distortion of a Jet by Tabs", J. Fluid Mechanics, Vol. 70, 801-813, 1975.

OBJECTIVES

Objectives:

Study Mechanism of Effect on *Free Jets*

- -Compressibility Effect
- -Tab geometry Effect

  ($\Rightarrow$ Delta-tab)

- -Quantify Mixing Enhancement
- -Streamwise Vorticity generation Mechanism

Publications:

- AIAA Paper No. 91-2263
- Proc. 8th Turb. Shear Flow Symp., '91
- AIAA Paper No. 92-3548

Carry out fundamental experiments studying mechanisms of effect: (1) experiments on subsonic and supersonic jets to assess influence of compressibility, (2) parametric study on tab geometry to optimize effect for given flow blockage (this effort led to 'delta-tab'), (3) quantify mixing enhancement in the jet, (4) analyze mechanisms of streamwise vorticity generation.

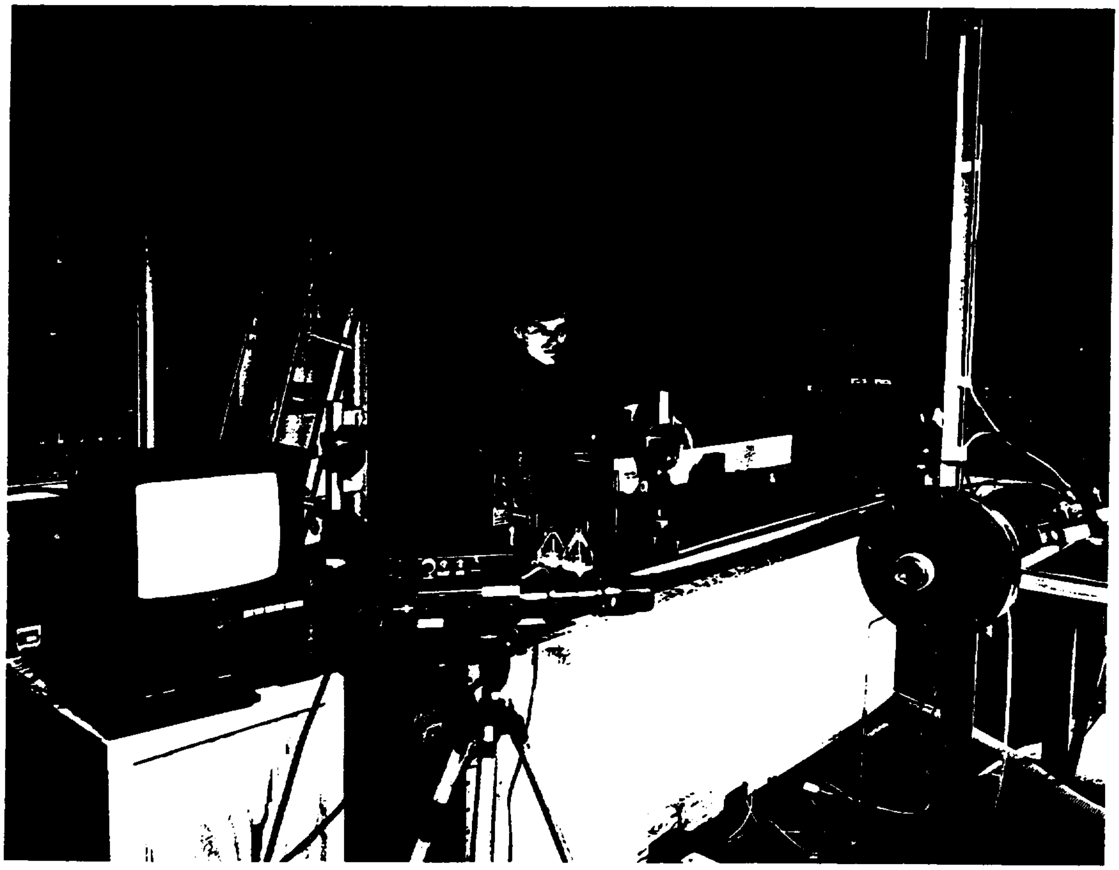
Prior publications on the investigation:

1. Samimy, M., Zaman, K.B.M.Q., and Reeder, M.F., "Supersonic Jet Mixing Enhancement by Vortex Generators", AIAA Paper No. 91-2263, 1991.

2. Zaman, K.B.M.Q., Samimy, M., and Reeder, M.F., "Effect of Tabs on the Evolution of an Axisymmetric Jet", Proc. 8th Turbine. Shear Flow Conference., Univ. of Munich, F. R. Germany, 1991.

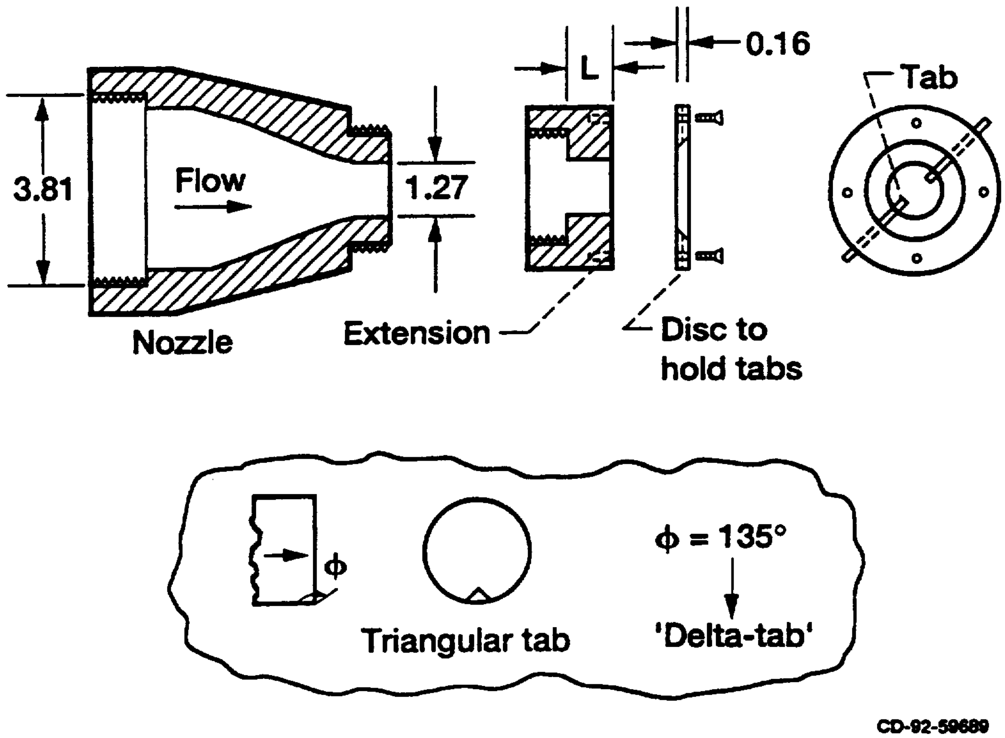
3. Zaman, K.B.M.Q., Reeder, M.F., and Samimy, M., "Supersonic Jet Mixing Enhancement by 'Delta-Tabs'", AIAA Paper No. 92-3548, 1992.

FACILITY



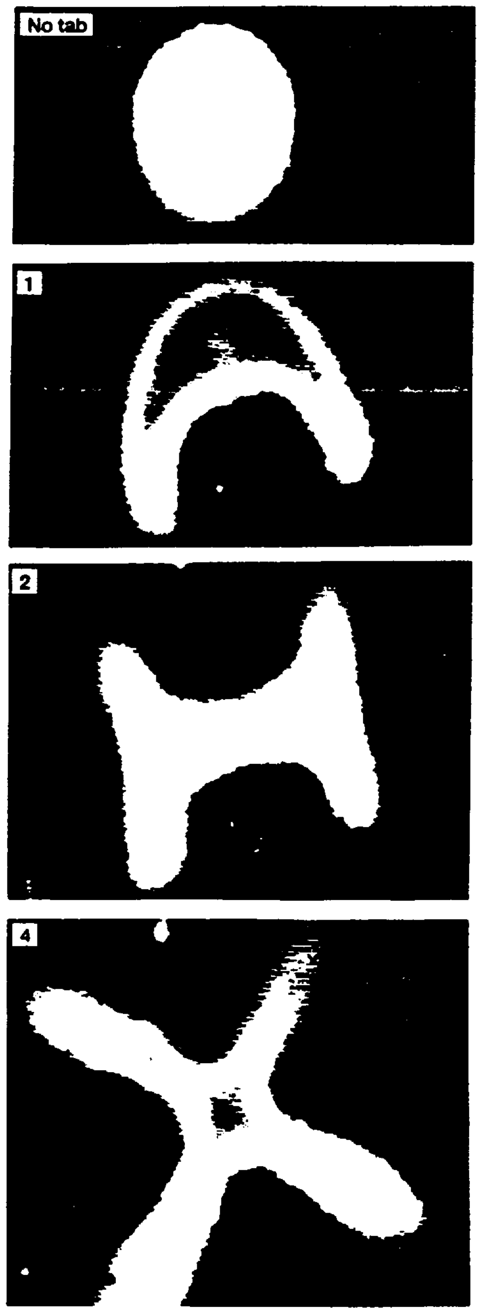
Shows overall experimental set up. Plenum chamber supplied with compressed air with maximum pressure of 70 psig. Jet discharges into the ambient. Flow visualization pictures recorded on Super-VHS recorder via image intensified CCD camera. 4-Watt Argon ion laser was light source. One-quarter inch microphone used to record far field noise spectra.

Schematic of Jet Nozzle



Schematic of 0.5 inch diameter, axisymmetric, convergent nozzle. Geometry of delta-tab shown in inset. Flow blockage due to each delta-tabs was between 1.5% to 2% of nozzle exit area.

FLOW VISUALIZATION



$M_j = 1.63$
$x/D = 2$

No tab

1 Delta-tab

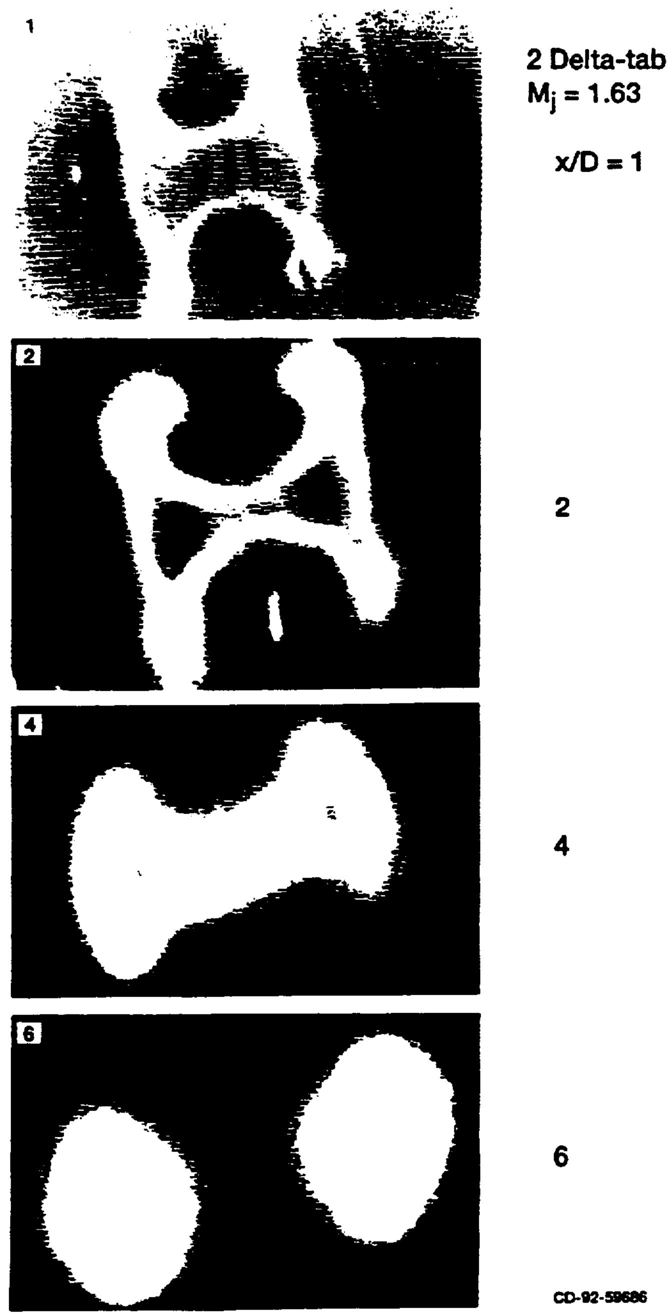
2 Delta-tab

4 Delta-tab

CD-92-59683

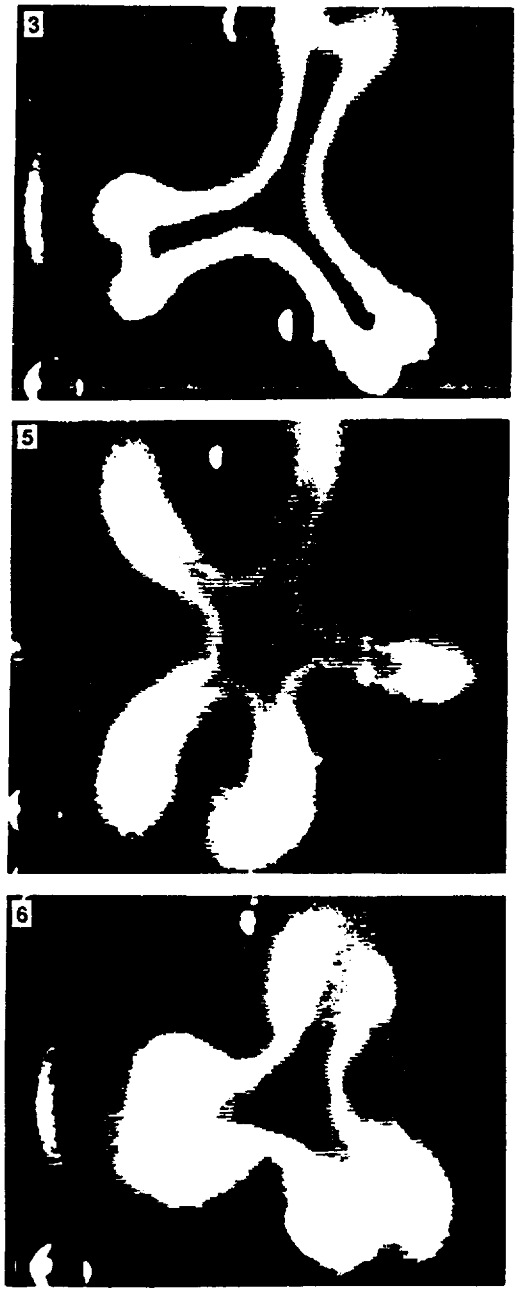
Effects of 1,2 and 4 delta-tabs on jet cross section at x/D = 2 compared to the no-tab case. Cold supersonic core of the jet caused moisture condensation from entrained air in the mixing layer. Thus, Laser sheet illuminated the mixing layer.

FLOW VISUALIZATION



Effect of 2 delta-tabs at indicated streamwise locations. Jet is completely bifurcated by x/D = 6.

FLOW VISUALIZATION



$M_j = 1.63$
$x/D = 2$

3 Delta-tab

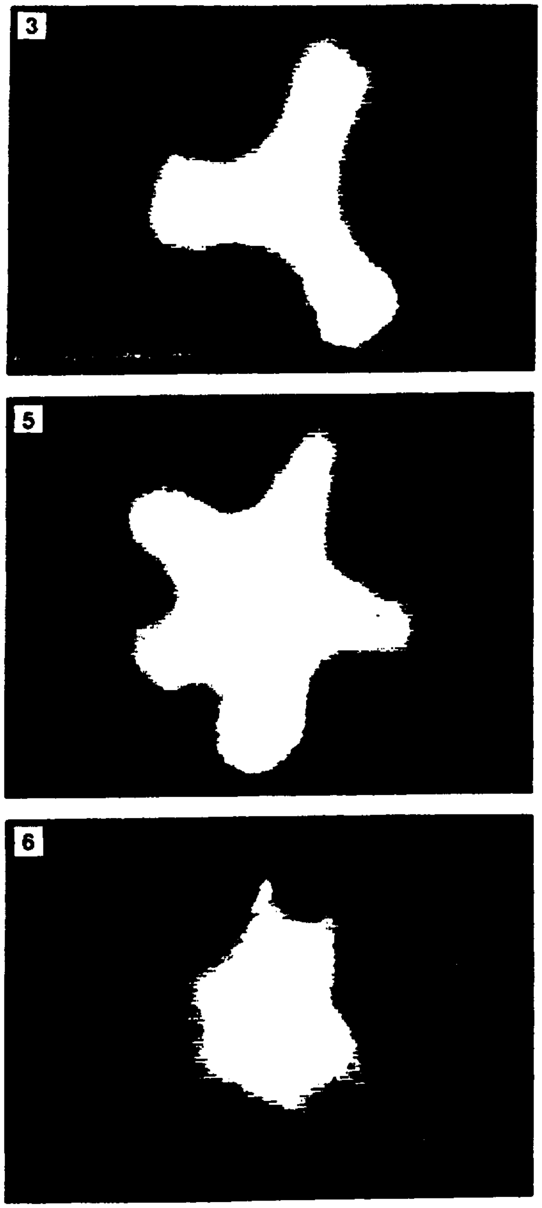
5 Delta-tab

6 Delta-tab

CD-92-59682

Effects of 3, 5 and 6 delta-tabs on jet cross section at $x/D = 2$. Jet cross section settles back to 'three-finger configuration', in the 6 delta-tab case, through interaction of streamwise vortices.

FLOW VISUALIZATION



$M_j = 0.3$
$x/D = 2$

3 Delta-tab

5 Delta-tab

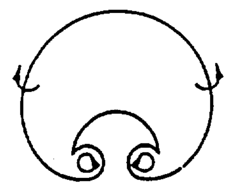
6 Delta-tab

CD-92-59688

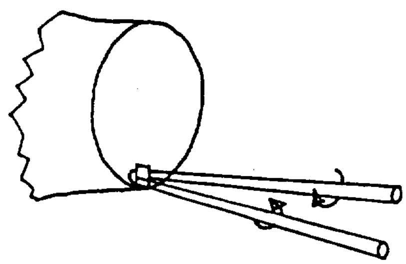
Exactly same tab geometries as in viewgraph #8. Effect on a subsonic jet. Pictures here are obtained by seeding the core of the jet with smoke. Effect is similar at subsonic and supersonic conditions.

SCHEMATIC OF VORTICES

LIKELY VORTICITY DYNAMICS



Vorticity distribution for 1-tab



Streamwise vortex pair from a tab

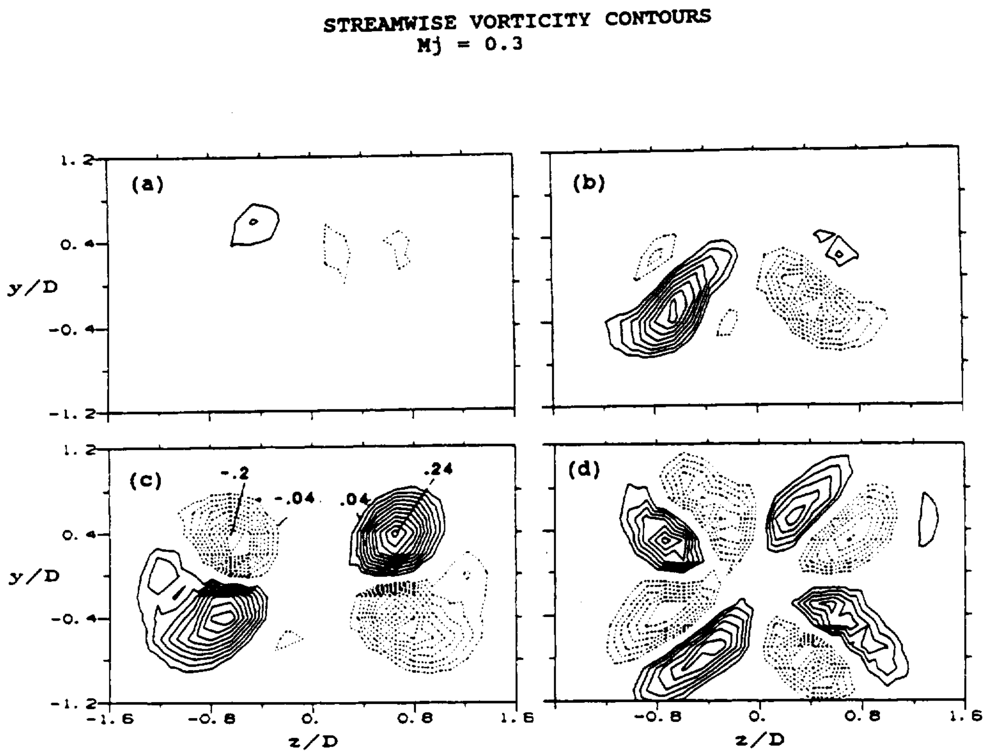
Pair of streamwise vortices from a tab as conjectured early on in the investigation.

FLOW VISUALIZATION

$M_j = 1.63$
$x/D = 2$
Delta-tab

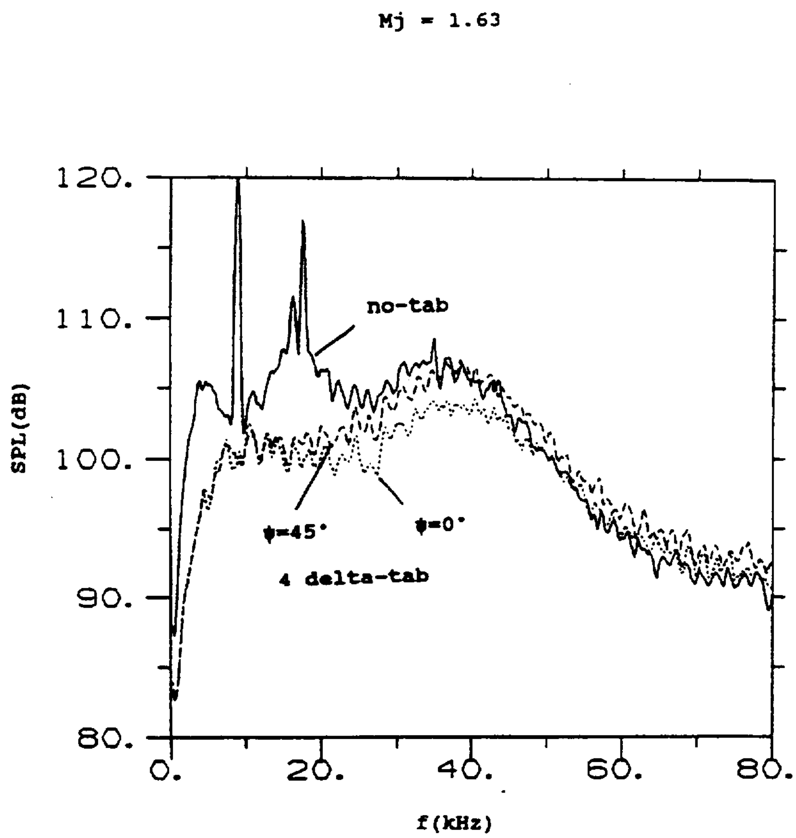
CD-92-59684

Locations of the cores of streamwise vortex pair originating from a delta-tab. View is from upstream, and ambient was seeded with smoke.



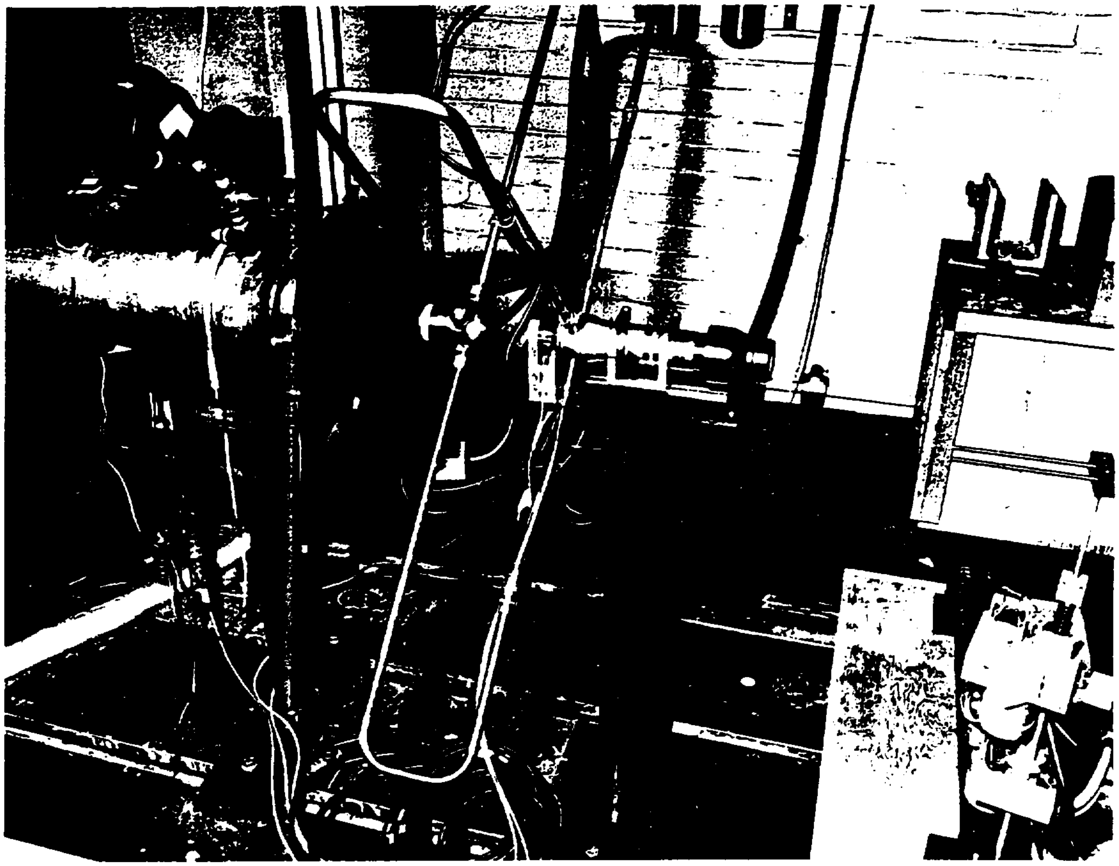
Contours of $\omega_x c/U_\infty$ measured at x/D = 3, for Mj = 0.3. (a) no-tab, (b) 1 delta-tab, (c) 2 delta-tabs, (d) 4 delta-tabs.

FAR-FIELD SOUND SPECTRA



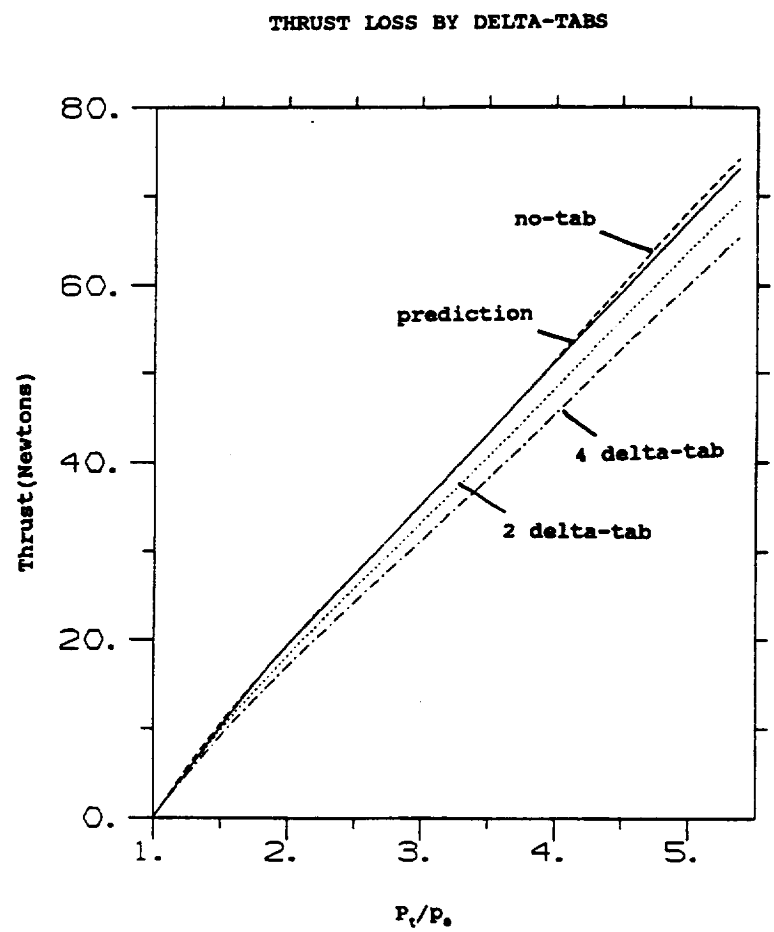
Effect of 4 delta-tabs, at two azimuthal angles relative to a delta-tab, compared with the no-tab case. Measurements are for r/D = 70 at the nozzle exit plane.

THRUST MEASUREMENT



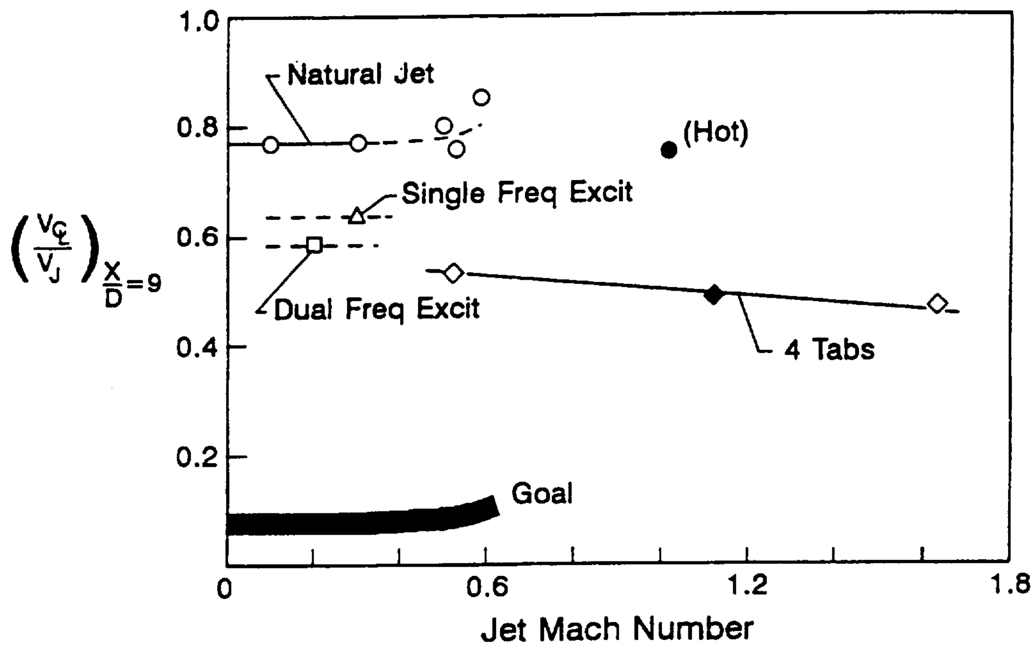
Experimental set up for thrust measurement.

THRUST DATA



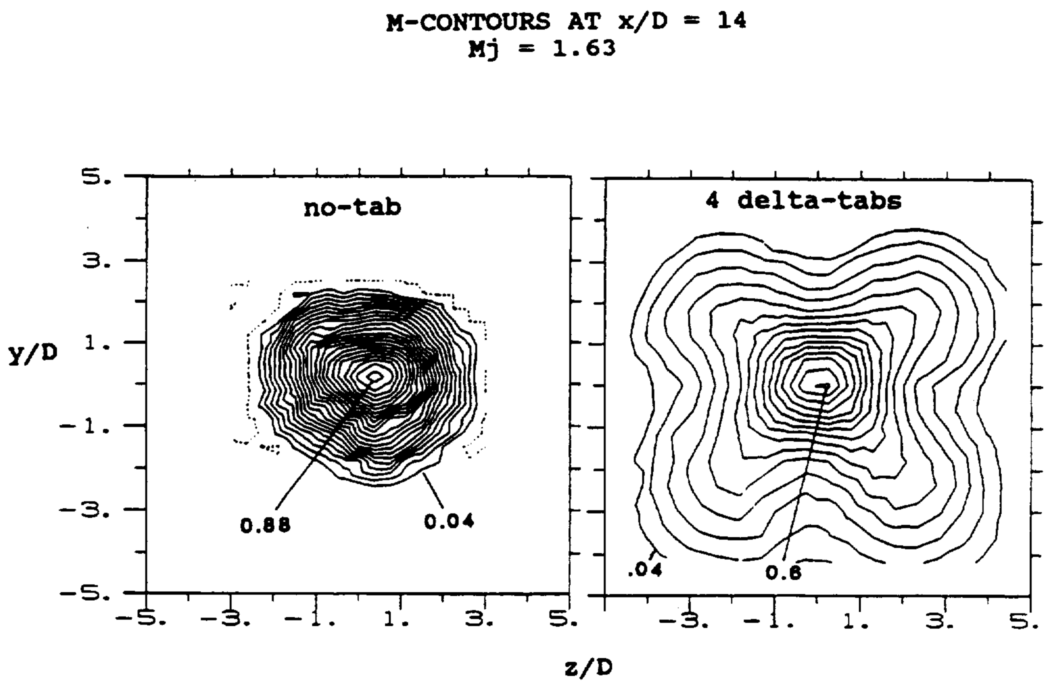
Thrust vs. nozzle pressure ratio for the effect of different numbers of delta-tabs. Prediction is with assumption of isentropic, plug flow. Gross thrust loss is approximately 3 percent per delta-tab (not taking into account the thrust loss due to the mere blockage.)

Jet Mixing Efficiency



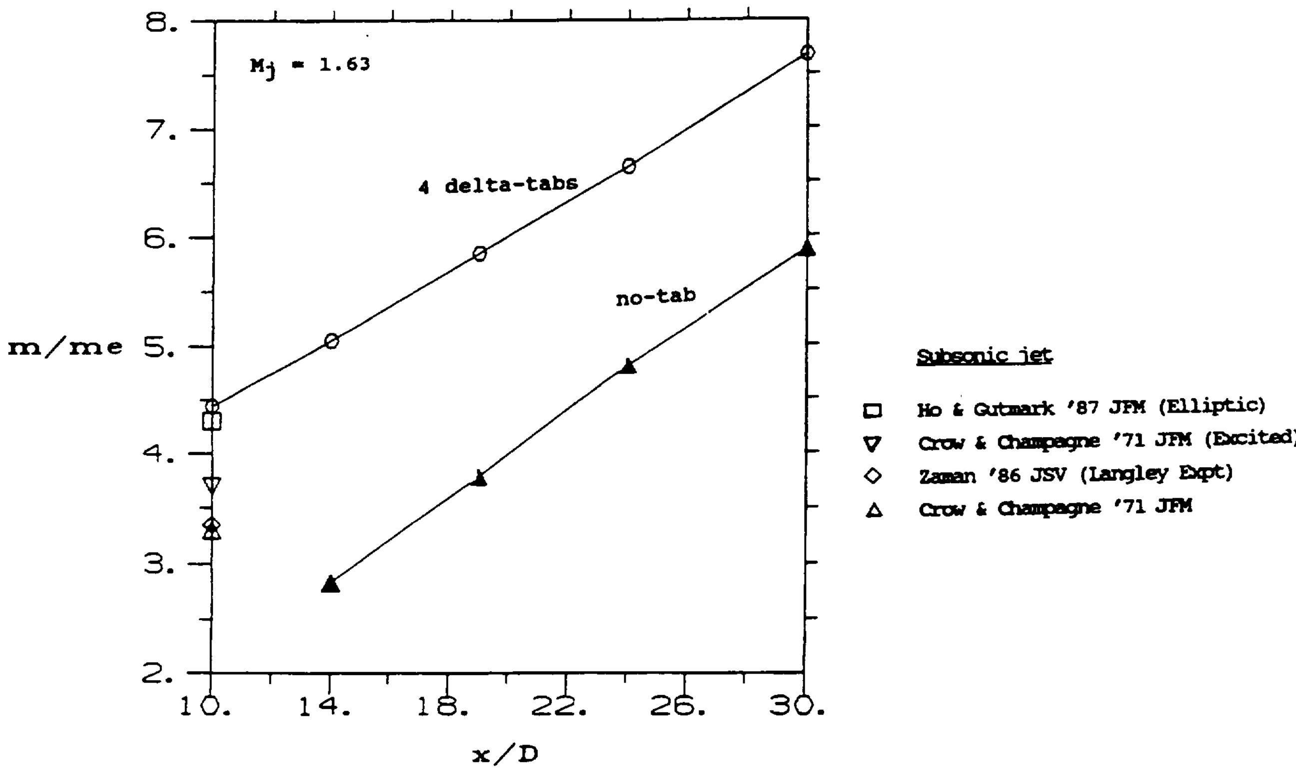
As indicated qualitatively by centerline velocity measured at 9D from nozzle exit (Lower value accompanied by faster spread.) Data for 'best case' single frequency acoustic excitation result, and dual frequency excitation result (inducing subharmonic resonance) are shown. 4 delta-tabs do better, and also work in supersonic regime (solid data point from Dr. Ahuja's experiment with hot jets and using simple tabs).

JET SPREADING



As indicated by Mach number contours, on a cross sectional plane at 14D from nozzle exit, measured with a Pitot tube. Four delta-tabs substantially increases jet spreading.

JET SPREADING



As indicated by mass flux, normalized by mass flux at nozzle exit, obtained by integrating data as in viewgraph #17. Effect of 4 delta-tabs compared with natural jet case. Four data points on left margin are from indicated References for subsonic jets. For the noncircular jet case, 'D' represents equivalent diameter (hydraulic diameter was used in the reference)

In calculating m_e (mass flux at the nozzle exit), the area change due the blockage by the tabs has been taken into account. This was not done for similar data shown in the references cited in connection with viewgraph #3. Furthermore, the data shown in those references were only estimates which were obtained by measuring four diametral profiles. The data in viewgraph #18 should be more accurate.

SUMMARY

- JET CROSS SECTION ALTERED ALMOST ARBITRARILY
  - -MIXING INCREASED SIGNIFICANTLY
- EACH TAB PRODUCES PAIR OF STREAMWISE VORTICES
  - EFFECT WITH DELTA-TAB ACCENTUATED
  - VORTEX PAIR OF OPPOSITE SIGN COULD BE PRODUCED
- EFFECT INDEPENDENT OF COMPRESSIBILITY
  - TABS DO NOT WORK IN OVEREXPANDED CONDITION
- EFFECT INDEPENDENT OF INITIAL BOUNDARY LAYER STATE
  - WORKS IN JET WITH HIGH CORE TURBULENCE
- APPROXIMATELY 3% THRUST LOSS PER DELTA-TAB

CURRENT AND FUTURE ACTIVITY

- MIXING WITH DIFFERENT NOZZLE GEOMETRIES WITH/WITHOUT DELTA TABS

  -RECTANGULAR, 3:1 ELLIPTIC, 6-LOBED MIXER

- FUNDAMENTAL EXPERIMENTS

  -VORTICITY EVOLUTION 2, 6 DELTA-TAB CASES

- ANALYSIS

  -STREAMWISE VORTICITY GENERATION MECHANISMS
  --WHY DELTA TAB WORKS BETTER
  --AXISYMMETRIC VS. PLANE GEOMETRY

  -ISSUE OF AREA CHANGE VS. VORTEX BREAKDOWN CAUSING MIXING ENHANCEMENT

- MARK REEDER & MO SAMIMY AT OSU

  -WATER TUNNEL MEASUREMENT
  --ADDRESS UNSTEADY ASPECTS

  -RALEIGH-SCATTERING BASED MEASUREMENT FOR SUPERSONIC JETS