NASA Contractor Report 182153

Three-Dimensional Viscous Flow Computations of a Circular Jet in Subsonic and Supersonic Cross Flow

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July 1988

Prepared for
Lewis Research Center
Under Grant NAS3-25266

NASA
National Aeronautics and
Space Administration

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E-4223

Abstract

Three-dimensional viscous flow computations are presented for 90 deg. injection angle jets in subsonic and supersonic cross flow. Comparisons with experimental data include jet centerline and vortex trajectories for the subsonic crossflow, and surface pressure measurement for the supersonic crossflow case. The vortices induced in the jet/freestream interaction are computed and illustrated. The vortices persist in subsonic flow and die out quickly in supersonic flow. The structure of the shocks in the unconfined supersonic flow is illustrated.

Introduction

Computations of three-dimensional jet/crossflow interaction in subsonic and supersonic flow address the processes of: mixing, entrainment, and vorticity generation and transport. Practical interest in deflected jets are due to their application in: turbojet combustors, ramjet and scramjet fuel injection, thrust vector control jets, and propulsive jets. The PARC3D[1] computer program is used in this study. The code solves the full three-dimensional Reynolds averaged Navier-Stokes equations in strong conservation form with the Beam and Warming approximate factorization algorithm. The implicit scheme uses central differencing for a curvilinear set of coordinates. The code was originally developed as AIR3D by Pulliam and Steger[2], and Pulliam[3] later added the Jameson[4] artificial dissipation and called the code ARC3D. Cooper[5] adapted the code for internal propulsion and called the code PARC. Previous studies with the codes at NASA Lewis are reported by Reddy and Harloff[6] and Harloff, Lai, and Nelson[7]. These studies provided confidence in the PARC codes for a variety of complex shapes and high speeds.

The goal of the present study is to examine the 3-D jet/crossflow flowfield and determine jet and vortex paths, and wall pressures. Comparison with experimental data is made where possible.

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Previous Numerical Studies

Previous three-dimensional numerical studies of the jet in a cross flow are believed to be limited to subsonic flow. Theoretical studies by Demuren[8], Patankar[9], Roth[10], Sykes et. al.[11] and Claus[12] are noted. Demuren compared theory with experiment for a jet to freestream velocity ratio, R, of 2. Numerical diffusion effects were also investigated. Patankar computed the three-dimensional flowfields for a 90 deg. jet in a low speed crossflow with the TEACH algorithm. Experimental results of Keefer and Baines[13], and Chassaing et. al.[14] were compared. The jet centerline trajectories were accurately predicted for R values from 2 to 10. Detailed flowfield results were not presented. Roth has recently presented three dimensional flowfield results for Fearn and Weston's[15-19] experimental data. The velocity ratios of 4 to 8 and Mach numbers from .12 to .2 were studied. Grids of 39x25x32 to 55x55x50 were used. Computed jet centerline and vortex trajectories agreed well with experimental values. The pressure coefficient behind the jet, on the plane of symmetry, were high by about 0.5. Sykes et al. presented a three-dimensional simulation of a turbulent jet in a uniform crossflow. The floor boundary layer was ignored as the emphasis was on the generation and convection of the vortices. A turbulence model was used where the length scale was a function of jet diameter and distance from the jet. Claus conducted a numerical study with the TEACH algorithm to assess the relative importance of turbulence model and numerical diffusion with a single jet and a plane of symmetry to simulate multiple jets. His study was for confined jets with a velocity ratio, R, of 2.3.

Experimental Studies

Subsonic

There have been many experimental studies. For example, the Chassaing et. al.[14] study examined the subsonic turbulent jets in a cross flow for cylindrical and coaxial jets. Velocity ratios of 2 to 6 were tested. Detailed

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velocity measurements were obtained and similarity plots for the jet velocity profile were given. The jet centerline scales with the jet diameter and R^2. Fearn and Weston[15-19] made detailed measurements of velocity and pressure in a round jet for jet injection angles of 45 to 105 deg. and velocity ratios 4 to 8. Many of the measurements were made to characterize the contrarotating vortices associated with the interaction. The data taken by Fearn et. al. is one of the most comprehensive sets of subsonic jet and crossflow data due to the extensive flowfield measurements taken it was chosen for simulation.

Supersonic

Cubbison et. al.[20] experimentally examined a sonic jet in an unconfined three-dimensional crossflow with freestream Mach number of 2.92 to 6.4 at Reynolds number of .84 to $7.7X10^6$/ft. Surface pressure measurements from -40 to 110 jet diameters axially and 60 jet diameters laterally were taken with jet total to freestream static Ptj/Pso of 677, 1247, and 2643. Separated flow upstream and downstream of the jet were observed on the plate and jet pressure had an effect with the separation extending up to 100 nozzle diameters downstream. Schetz et. al.[21-24] and Orth et. al.[25] have conducted many supersonic jet and crossflow experiments.

From the literature, the variables which control jet/crossflow interaction include: jet to freestream momentum ratio, jet velocity profile at the nozzle exit, boundary layer thickness at the jet, Mach number, shocks, and jet injection angle. Computations of supersonic crossflow were not found in the literature. The only readily available 3-dimensional set of data found for supersonic crossflow injection, with air, is that of Cubbison et. al. and it is simulated herein.

Current Study

Boundary Conditions

The boundary conditions used in the current study are:

Subsonic Cross Flow

(1) Uniform inflow total pressure and temperature
(2) Zero normal gradient flux conditions at the top and lateral boundary of the control volume
(3) Fixed flux at the jet boundary (grid points)
(4) Uniform static pressure outflow
(5) Adiabatic no slip on plate
(6) Symmetry about the jet centerline in the streamwise direction

Supersonic Cross Flow

(1) Uniform Flux inflow
(2) Uniform Flux at the top of the control volume
(3) Flux extrapolation at the outflow
(4) Fixed flux at the jet boundary (grid points)
(5) Adiabatic no slip on plate
(6) Symmetry about the jet centerline in the streamwise direction

Laminar flow was assumed for all calculations. A modified Baldwin-Lomax[26] turbulence model in the PARC code was investigated, for the R=4 case. The computed turbulent flowfield was not appreciably different from the laminar flowfield.

General Discussion of the fluid dynamics

The jet issuing into a crossflow undergoes a shearing force, and deflects and mixes with the freestream. The jet axis is straight until the centerline velocity begins to decay. In the subsonic freestream case, two separate vortices form due to the flow deflection around the jet and the separation at the rear of the jet. These vortices act to entrain flow and their rotation is such that they constructively interact at the jet centerplane.

Subsonic Crossflow

The expected flowfield for subsonic crossflow is shown in Fig. 1. The coordinate system for the computation is also shown. The control volume is 9 jet diameters upstream, X, 18 diameters downstream, 12 diameters from the plane of symmetry, Z, and 21 diameters from the plate, Y. A stretched grid is used of 69x59x39 in the X, Y and Z directions, respectively. Calculations of Fearn's 90 deg. injection at freestream Mach number of 0.1875 are presented below. The jet diameter is 4 in. and is 9 jet diameters from the plate leading edge. The velocity ratio, R, is 4 which is equivalent to a momentum ratio of 16.

Subsonic Crossflow Results

The predicted and experimental wall C_p values are compared in Fig. 2. Reasonable agreement is obtained with the test data upstream of the jet and very close to the jet. The agreement is worse in the downstream direction. The jet centerline is defined to be the locus of points with maximum streamwise velocity in the centerplane. The vortex centerline is obtained from the velocity magnitude cross sectional data. The vortex center can be identified from the contours of velocity in this plane. The predictions are compared to Fearn's test data in Fig. 2. The predictions of the jet centerline overpredict the test data and the vortex predictions are low. Computed Mach number contours in the jet are shown in Fig. 4. The jet trajectory was obtained from the symmetry contours in the jet from this figure. A corresponding vector plot is shown in Fig. 5 for 7.6 jet diameters downstream in the streamwise direction. Similar plots for supersonic flow will be discussed below. The primary vortex is clearly observed and a secondary vortex just off the wall is also shown. The secondary vortex is due to the viscous shear in the transverse (Z) direction. The interaction between the primary and secondary vortices forms a stagnation line along the wall originating from the jet boundary and extending downstream at an angle to the centerplane. This stagnation line is clearly visible on typical oil flow patterns. The constructive interference of the primary vortex, as observed by Fearn, is clearly shown.

Extensive studies were conducted which evaluated the effects of: gridding the hole region, of the gridsize and stretching, of turbulence, and of flow nonuniformities in the subsonic jet. The numerical experiments were not successful in improving the mismatch in pressure behind the jet or the jet and vortex trajectory locations. It is noted that Roth[10] obtained about the same level of agreement, as is shown here, with C_p, but showed much better agreement with the jet and vortex paths. One of the differences between the grids is that Roth's grid definition in the region of the jet was much finer.

Supersonic Freestream

A schematic of the expected flowfield for supersonic crossflow is shown in Fig. 6 (from Orth). The control volume used is 40 diameters upstream and 50 diameters downstream,X, 50 diameters from the plane of symmetry, Z, and 79 diameters above the plate,Y. A stretched grid is used of 50x31x21 respectively. Calculations of Cubbison's 90 deg. injection at freestream Mach number of 2.92 is presented below. The jet total to freestream static pressure is 677. The Reynolds number is $0.84X10^6$ per foot. The jet to freestream momentum ratio is 42.

A comparison between theory and test data for wall pressure coefficients in the symmetry plane is shown in Fig. 7. The predicted separation zone upstream of the jet is less extensive than the data. The pressures downstream of the jet are in reasonable agreement with the test data.

A side view of the Mach number contours are shown in Fig. 8 for plane of symmetry and Fig. 9 for 16.2 diameters from the plane of symmetry. The leading edge shock and the shock caused by the jet are clearly evident. The flow behind the jet accelerates beyond the freestream Mach number of 2.92 to 4.3, see Fig. 10. Closeup Mach number and velocity vector plots are shown for plane of symmetry in Figs. 10 and 11. For these plots the field of view is 13 diameters upstream and 10.25 diameters downstream of the jet and 3.9 diameters above the jet. In the plane of symmetry the jet is observed to entrain flow in the boundary layer immediately upstream of the jet. In general, the jet flow expands due to it being underexpanded. The jet is visualized in Fig. 12 by the total temperature contour. Fig. 13 is a 3-D plot of a constant total temperature surface, and shows the jet in 3-D. The jet spread and rapid turning over of the jet is observed in Figs. 12 and 13.

A cross sectional view of the velocity vectors in the cross (Y-Z) plane at 2.7 ft. is shown in Fig. 14. A vortex is present near the floor of the plate, where the flow is entrained. A similar plot was shown for subsonic crossflow. The main difference appears to be the low level of penetration of the contrarotating (primary) vortex in the supersonic flow. Both flowfields have a vortex near the plate.

Conclusions and Recommendations

Computations have been obtained for 90 deg. injected jets in a subsonic crossflow and a supersonic crossflow. Satisfactory agreement with the jet trajectory for the subsonic case has not been obtained. This may be a grid resolution issue, especially in the vicinity of the jet. Reasonable agreement with C_p was obtained for the subsonic and supersonic cases. The vortices for the subsonic case were much more evident than for the supersonic case. Separated flow behind the jet was computed for the 90 deg. subsonic crossflow and ahead of the jet for supersonic crossflow.

Further research is recommended to bring the predicted jet centerline and vortex curves in better agreement with the experimental data. In addition to the grid resolution issues, it is felt that the subsonic jet probably had nonuniform jet properties which may have contributed to the disagreement.

Acknowledgement

Prepared for the NASA Lewis Research Center under Contract NAS 3-24105, project manager Dr. E. McFarland.

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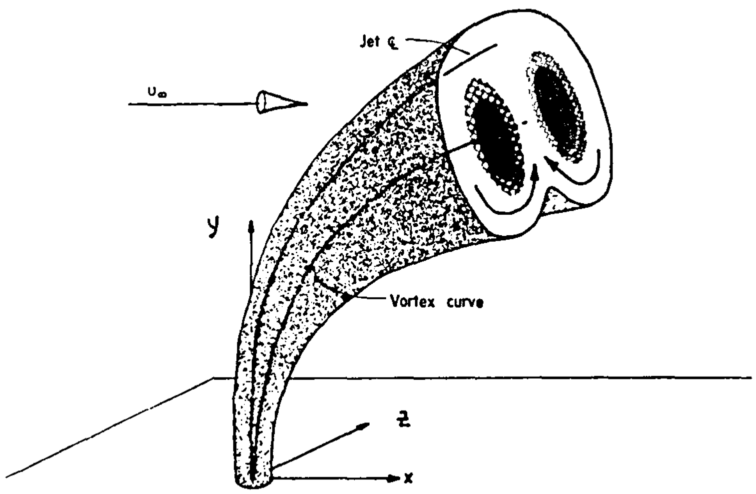

Fig. 1 Sketch of the Jet Plume (after Fearn)

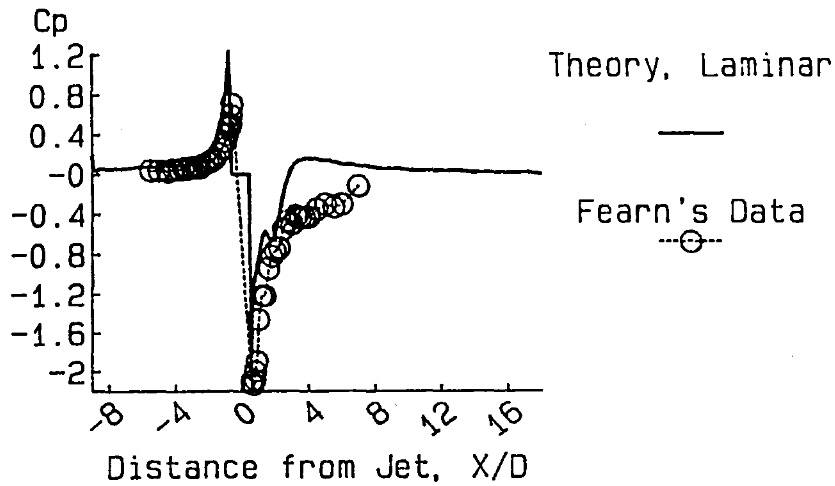

Fig. 2 Comparison of C_p on centerline, Theory and Experiment; Crossflow Mach No.=0.1875

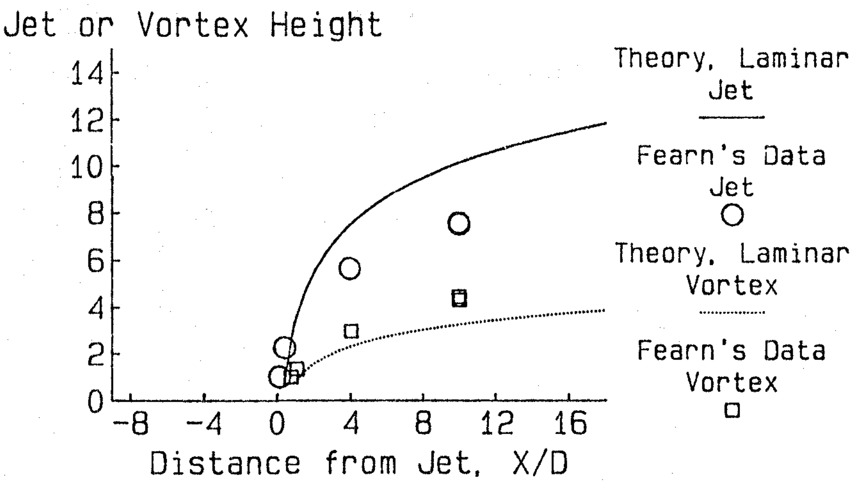

Fig. 3 Jet and Vortex Centerline Trajectories; R=4, 90 deg injection

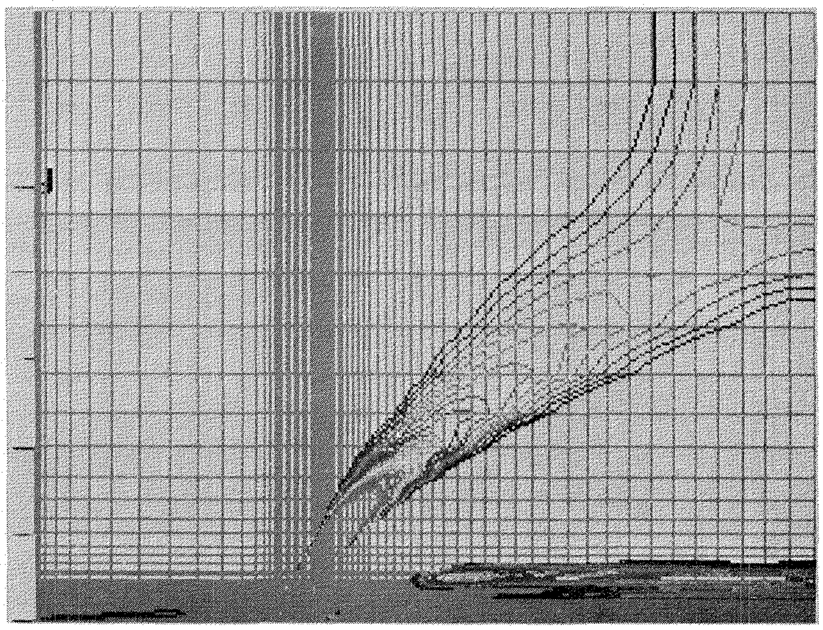

Fig. 4 Mach Number Contours in Jet; R=4, Crossflow Mach No.=0.1875

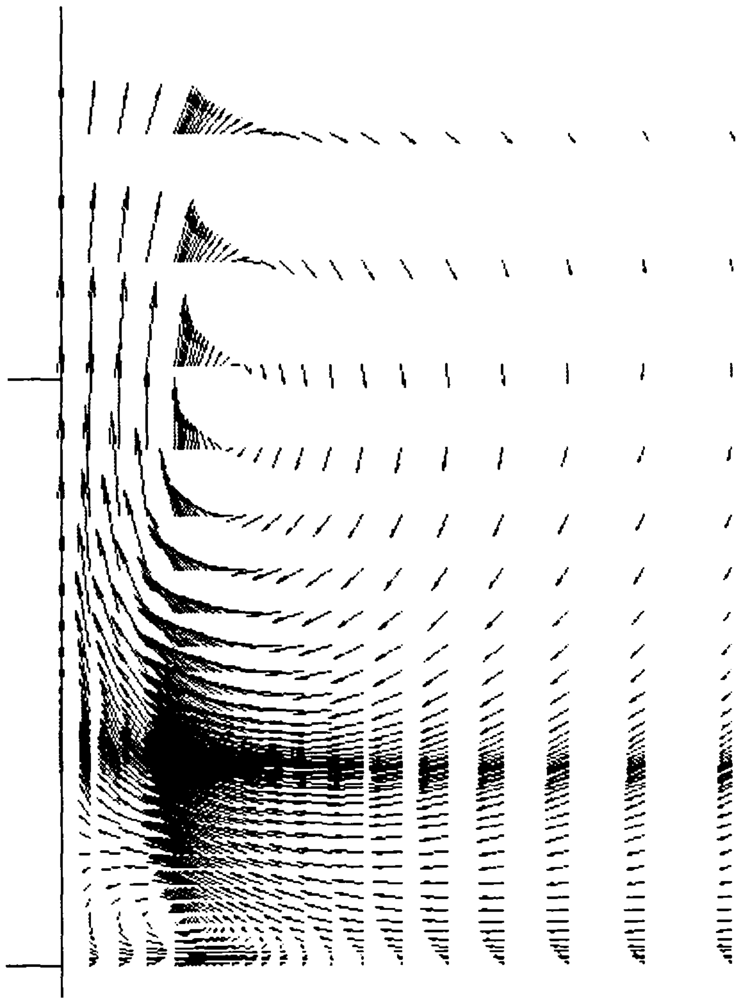

Fig. 5 Velocity Vectors in Y-Z Plane; X/D=7.65, R=4,
Crossflow Mach No.=0.1875

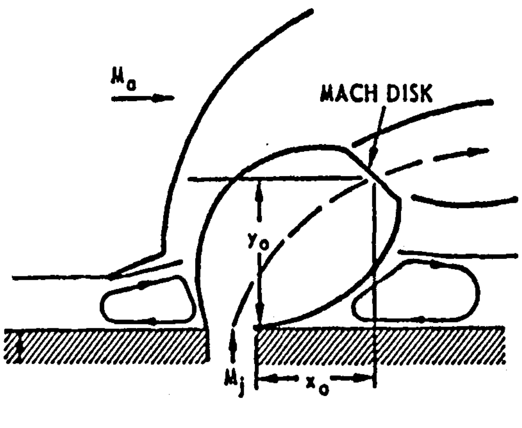

Fig. 6 Sketch of Supersonic Flowfield

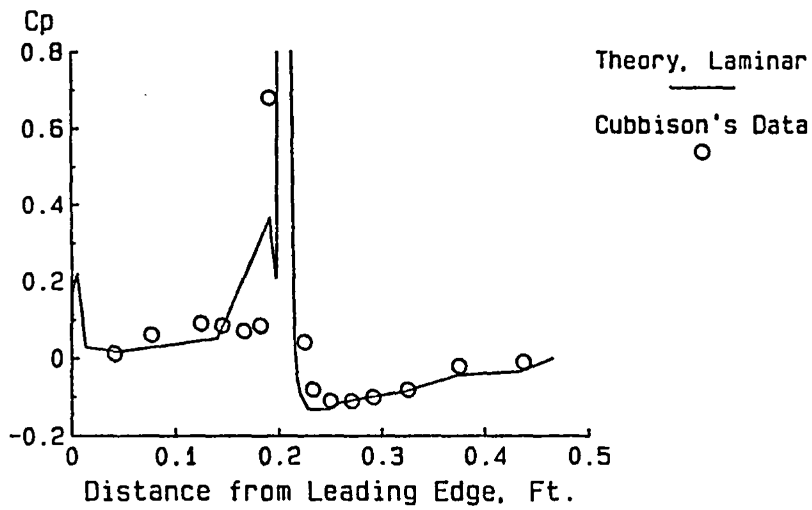

Fig. 7 Cp on Centerline; Crossflow Mach No.=2.92

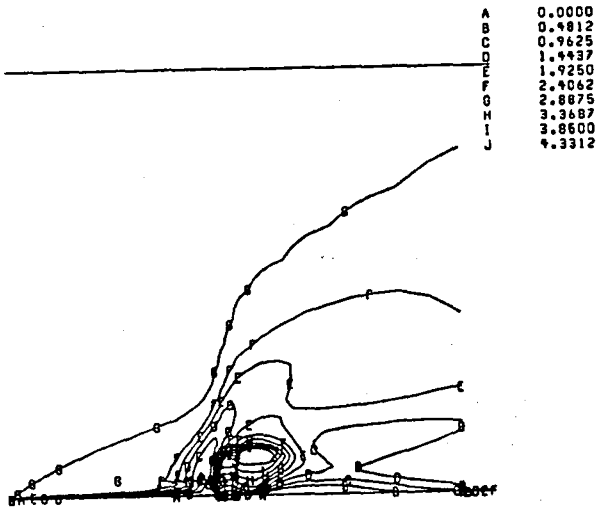

Fig. 8 Mach Number Contours on Plane of Symmetry;
-40 X/D < jet < 50 X/D, 0 < Y/D < 79

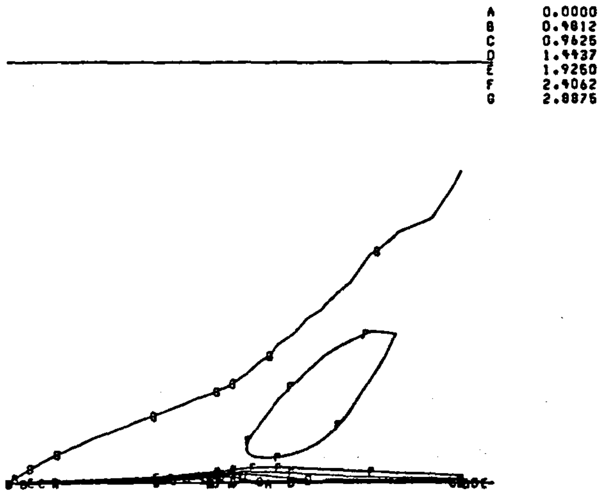

Fig. 9 Mach Number Contours at Z/D= 16.2;
-40 X/D < jet < 50 X/D, 0< Y/D <70

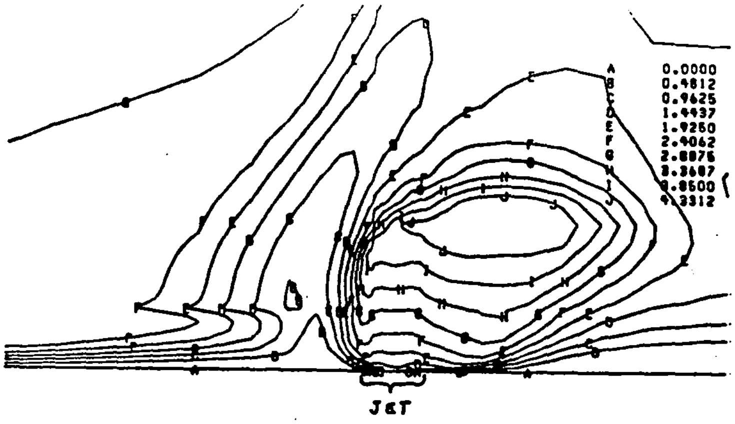

Fig. 10 Mach Number Contours on Plane of Symmetry;
-13 X/D < jet < 10.25 X/D, 0< Y/D <3.9

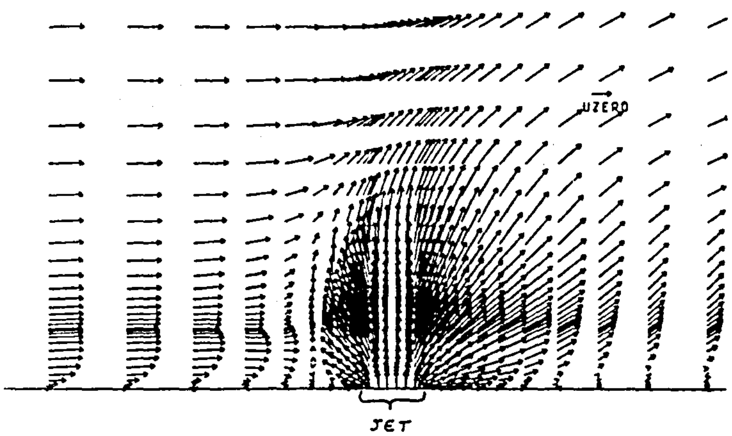

Fig. 11 Velocity Vector Contours on Plane of Symmetry;
-13 X/D < jet < 10.25 X/D, 0< Y/D <3.9

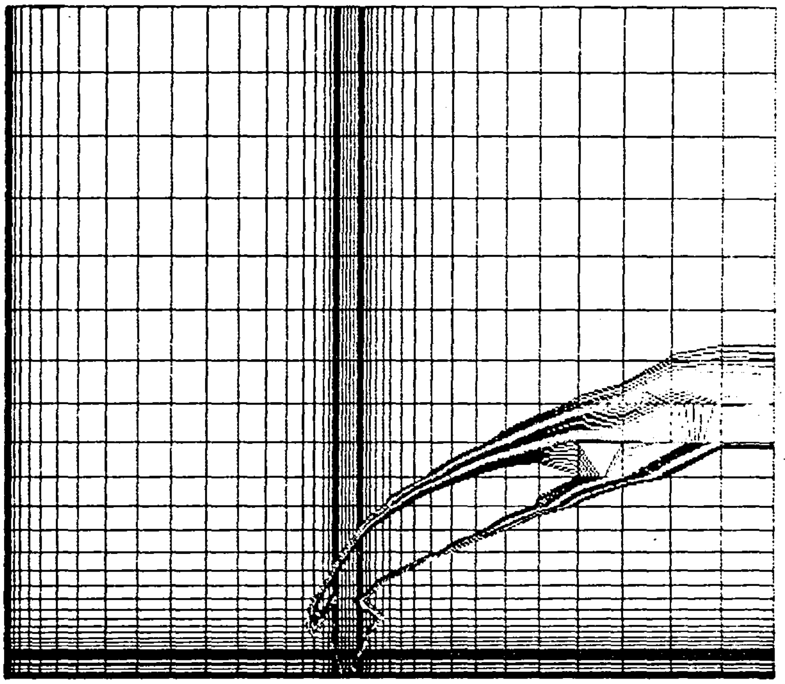

Fig. 12 Total Temperature Contours on Jet Centerline; Crossflow Mach No.=2.92

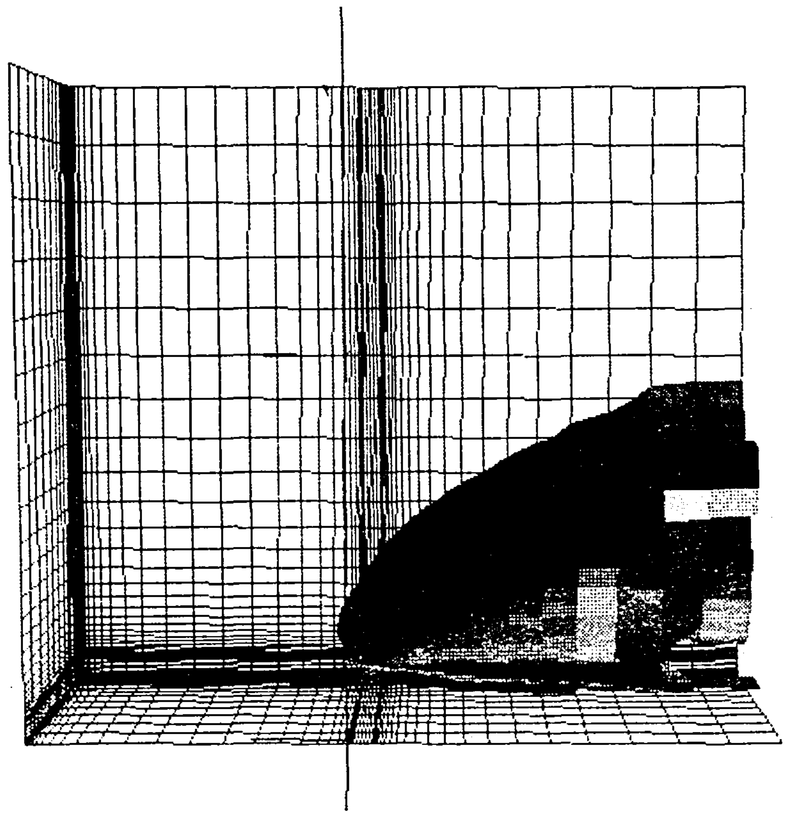

Fig. 13 3-D Total Temperature Contour in Jet;
Crossflow Mach No.=2.92

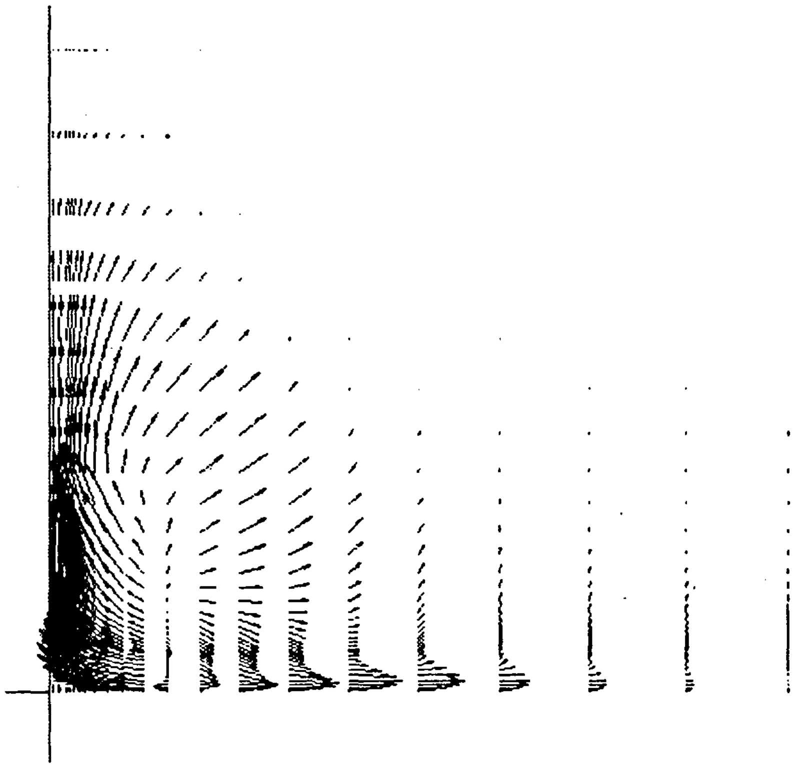

Fig. 14 Velocity Vectors in the Y-Z plane, X=2.7 ft, Crossflow Mach No.=2.92

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Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-182153		

4. Title and Subtitle Three-Dimensional Viscous Flow Computations of a Circular Jet in Subsonic and Supersonic Cross Flow	5. Report Date July 1988 6. Performing Organization Code
7. Author(s) G.J. Harloff and J.K. Lytle	8. Performing Organization Report No. None (E-4223) 10. Work Unit No. 505-62-21
9. Performing Organization Name and Address Sverdrup Technology, Inc. NASA Lewis Research Center Group Cleveland, Ohio 44135-3191	11. Contract or Grant No. NAS3-24105 13. Type of Report and Period Covered Contractor Report Final
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager, Eric McFarland, Internal Fluid Mechanics Division, NASA Lewis Research Center. Prepared for the First National Fluid Dynamics Congress sponsored by the American Society of Mechanical Engineers, Cincinnati, Ohio, July 24-28, 1988.

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Viscous flow computations; 3-D; Subsonic; Supersonic; Jet/Cross flow	Unclassified – Unlimited Subject Category 34

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified	14	A02

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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