ANALYSIS AND TESTING OF TWO-DIMENSIONAL SLOT NOZZLE EJECTORS WITH VARIABLE AREA MIXING SECTIONS

by Gerald B. Gilbert and Philip G. Hill

Prepared by
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Cambridge, Mass.
for Ames Research Center

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Finite difference computer techniques have been used to calculate the detailed performance of air to air two-dimensional ejectors with symmetric variable area mixing sections and co-axial converging primary nozzles. The analysis of the primary nozzle assumed correct expansion of the flow and is suitable for subsonic and slightly supersonic velocity levels. The variation of the mixing section channel walls is assumed to be gradual so that the static pressure can be assumed uniform on planes perpendicular to the axis. An x-y coordinate system is used in the solution of the momentum and energy equations to remove a singularity condition at the wall.

A test program was run to provide two-dimensional ejector test data for verification of the computer analysis. A primary converging nozzle with a discharge geometry of 0.125" x 8.0" was supplied with 600 SCFM of air at about 55 psia and 180°F. This nozzle was combined with two mixing section geometries with throat sizes of 1.25" x 8.0" and 1.875" x 8.0" and was tested at a total of 11 operating points.

The comparisons of wall static pressures, centerline velocity, centerline temperature, and velocity profiles between experimental and analytical results at the same flow rate were generally very good.
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MIXING SECTIONS

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Gerald B. Gilbert, Philip G. Hill

SUMMARY

Finite difference computer techniques have been used to calculate the detailed performance of air to air two dimensional ejectors with symmetric variable area mixing sections and co-axial converging primary nozzles. The successful completion of this program completes a step in the development of a computer program to analyze the ejector of the augmentor wing lift augmentation system for STOL aircraft.

The finite difference computer program analyzes two dimensional mixing in converging-diverging jets. The analysis of the primary nozzle assumes correct expansion of the flow and is suitable for subsonic and slightly supersonic velocity levels. The variation of the mixing section channel walls is assumed to be gradual so that the static pressure can be assumed uniform on planes perpendicular to the axis. An $x-y^2$ coordinate system is used in the solution of the momentum and energy equations to remove a singularity condition at the wall. Different assumptions for eddy viscosity are made for each distinctly different region of the flow based on information available in the literature.

A test program was run to provide two-dimensional ejector test data for verification of the computer analysis. Geometry and primary air operating conditions similar to a typical augmentor wing ejector were selected for the tests. A primary converging nozzle with a discharge geometry of 0.125" x 8.0" was supplied with 600 SCFM of air at about 35 psia and 180°F. This nozzle was combined with two mixing section geometries with throat sizes of 1.25" x 8.0" and 1.875" x 8.0" and was tested at a total of 11 operating points. Secondary flow was varied by adding three steps of increased restriction to the ejector discharge. For each test mass flow rate, wall static pressures and several velocity traverses were recorded for comparison with analytical results.
The comparisons of wall static pressures, centerline velocity, centerline temperature, and velocity profiles between experimental and analytical results at the same flow rate were generally very good. The computer program presented in this report accurately predicts the performance of the simple two-dimensional ejectors and thereby successfully completes the objectives of this program.
Section 1

INTRODUCTION

1.1 Background

The augmentor wing concept under investigation by NASA for STOL aircraft lift augmentation is powered by an air to air ejector. The wing boundary layer is drawn into the deflected double flap augmentor channel at the trailing edge of the wing and is pressurized by a high velocity slot jet which is oriented at an angle to the augmentor channel. To predict the performance and to optimize the design of the complete augmentor wing, an analytical method is needed to predict the performance of the air ejector which powers the augmentor flap section.

Under contract NAS2-5845 a computer analysis was developed for single nozzle axisymmetric ejectors with variable area mixing sections using integral techniques\(^1\). The ejectors of primary interest in that program and earlier programs were high entrainment devices using small amounts of supersonic primary flow to pump large amounts of low pressure secondary flow. Good agreement was achieved between analytical and experimental results.

The integral analytical techniques used to analyze the axisymmetric ejector configurations are also valid for the analysis of two dimensional ejectors. However, the augmentor wing configuration may include asymmetric geometries, inlet flow distortions, wall slots, and primary nozzles that are at large angles to the axis of the augmentor mixing section. The integral techniques are not easily adaptable to these more complex flows. Finite difference techniques can be used to analyze these more complex flow geometries at the expense of increased computer time.
1.2 Objectives of Program

The specific objectives of this investigation are the following:

(1) to develop a finite difference computer program for the analysis of two-dimensional, air ejectors with symmetric variable area mixing sections and with co-axial converging primary nozzles.

(2) to obtain test results with two-dimensional ejector configurations so that the analytical methods can be checked.

By modifying the present analysis additional complicating features of the actual augmentor wing ejector may be incorporated into the computer program until the complete augmentor wing ejector can be successfully analyzed.
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<td>Nozzle discharge area</td>
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<td>Coefficient appearing in the finite difference equations 26 and 36</td>
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<td>$B_{n-1}$</td>
<td>Coefficient appearing in the finite difference equations 26 and 36</td>
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<td>$C_p$</td>
<td>Time average specific heat at constant pressure</td>
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<td>$C_{p_{0}}$</td>
<td>Specific heat at constant pressure evaluated at a reference temperature $T_o$</td>
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<td>Dimensionless constant pressure specific heat, $\frac{C_p}{C_{p_{0}}}$</td>
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<td>$C_L$</td>
<td>Eckert number, $\frac{(\gamma - 1) M_{ir}^2}{T_{wr} - T_0}$</td>
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<td>$C_N$</td>
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<td>$C_{n-1}$</td>
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<td>Dimensionless thermal conductivity, $\frac{k}{k_0}$</td>
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<td>$g_o$</td>
<td>Dimensional Constant, 32.2 lbm-ft/lbf-sec$^2$</td>
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<td>$l_m$</td>
<td>Prandtl mixing length</td>
</tr>
<tr>
<td>$L_m$</td>
<td>Dimensionless mixing length, $\frac{l_m u_o}{\nu_0}$</td>
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<tr>
<td>$m$</td>
<td>Node points along a streamline</td>
</tr>
<tr>
<td>$n$</td>
<td>Streamline designation</td>
</tr>
<tr>
<td>$M_{ir}$</td>
<td>Dimensionless Mach number, $\frac{u_o}{(\gamma R T_o)^{1/2}}$</td>
</tr>
<tr>
<td>$P_b$</td>
<td>Barometric pressure</td>
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NOMENCLATURE
(continued)

\( P_N \)  
Nozzle pressure

\( \bar{p} \)  
Time average static pressure

\( P_{rt} \)  
Turbulent Prandtl number, \( \frac{\eps}{\eps_H} \)

\( P_{ro} \)  
Prandtl number, \( \frac{u_o C_p o}{k_o} \)

\( P \)  
Dimensionless pressure, \( \frac{\bar{p}}{1/2 \rho_o u_o^2} \)

\( q \)  
Heat Transfer

\( q_T \)  
Turbulent heat transfer, \( (\rho v)' \cdot T' \)

\( R \)  
Gas constant

\( T_a \)  
Atmospheric temperature

\( T \)  
Time average temperature

\( T' \)  
Instantaneous fluctuating temperature

\( T_j \)  
Jet temperature at the nozzle exit plane

\( T_o \)  
Flow reference temperature

\( T_N \)  
Nozzle temperature

\( T_{wr} \)  
Wall reference temperature

\( u \)  
Time averaged velocity in x-direction

\( u' \)  
Instantaneous fluctuating x component of velocity

\( u_o \)  
Jet centerline velocity at the nozzle exit plane

\( u_{2,n} \)  
Unknown velocity at the \( n^{th} \) grid point

\( u \)  
Dimensionless velocity in x-direction, \( \frac{\bar{u}}{u_o} \)

\( u^* \)  
Friction velocity, \( \left( \frac{\tau_w}{\rho} \right)^{1/2} \)

\( \bar{v} \)  
Time averaged flow velocity in y-direction
NOMENCLATURE
(continued)

\( v' \)
Instantaneous fluctuating y-component of velocity

\( W_m \)
Mixing section total flow rate

\( W_n \)
Nozzle flow rate

\( W_s \)
Secondary flow rate

\( x \)
Space co-ordinate in the axial direction

\( X \)
Dimensionless space co-ordinate in the axial direction, \( \frac{u_o x}{\nu_o} \)

\( \Delta X \)
Step size in x-direction

\( y \)
Space co-ordinate perpendicular to axial direction

\( Y \)
Dimensionless space co-ordinate perpendicular to axial direction, \( \frac{yu_o}{\nu_o} \)

\( y_w \)
Duct half width or duct radius

\( y^+ \)
Dimensionless wall co-ordinate \( \frac{yu^*}{\nu} \)

\( \alpha \)
Constant, unity for axisymmetric flow and zero for two-dimensional flow

\( \gamma \)
Ratio of specific heat, \( \frac{c_p}{c_v} \)

\( \psi \)
Transformed co-ordinate defined by equation 8

\( \psi_s \)
Regular stream coordinate

\( \psi^* \)
Dimensionless \( \psi \) co-ordinate \( \frac{\psi^2}{\nu o^2} \) for two-dimensional flow

\( \bar{\rho} \)
Time averaged fluid density

\( \rho_o \)
Fluid density evaluated at a reference temperature \( T_o \)

\( \rho^* \)
Dimensionless fluid density

\( \bar{\mu} \)
Time averaged absolute viscosity

\( \mu_o \)
Absolute viscosity evaluated at a reference temperature \( T_o \)

\( \mu^* \)
Dimensionless absolute viscosity, \( \frac{\bar{\mu}}{\mu_o} \)

\( \tau \)
Mean average shear stress
NOMENCLATURE
(continued)

\( \tau_T \)  
Turbulent shear stress, \((\rho v)'u'\)

\( \tau_w \)  
Local wall shear stress

\( \epsilon \)  
Eddy viscosity

\( \epsilon_H \)  
Eddy conductivity

\( \theta \)  
Dimensionless temperature \( \frac{T - T_o}{T_{wr} - T_o} \)

\( \nu \)  
Kinematic viscosity at local temperature

\( \nu_o \)  
Reference kinematic viscosity evaluated at a reference temperature \( T_o \)

\( \delta \)  
Local wall boundary layer thickness or jet half width

\( \Delta \)  
Dimensionless boundary layer thickness, \( \frac{u_o \delta}{\nu_o} \)

\( \kappa \)  
Mixing length constant

\( \Phi \)  
Mean value of dissipation
3.1 Introduction

This section is concerned with the essential physical features of a computation model for plane two-dimensional jet mixing in converging-diverging jets. A finite-difference computer program has been developed for treating the mixing of two parallel and compressible air streams, allowing for at least one of them to be supersonic. In all cases, the nozzle expansion is assumed "correct", i.e. nozzle exit plane pressure is matched to the ambient pressure at that station. Thus, expansion waves and shocks at the nozzle exit plane are assumed to be absent. Even though the correct expansion assumption may not be realized in a practical case, the downstream flow field will not likely be sensitive to small degrees of over- or under-expansion. The flows considered include compound flows of supersonic and subsonic streams; however, no provision is made for compound choking which may occur with an appropriate transverse distribution of Mach number. Such a condition is amenable to analytical treatment under simplified circumstances, but has not been encountered in experimental tests carried out so far.

This development is restricted to symmetric jet mixing in which the high speed jet is located on the axis of the channel and no provision is made for blowing or suction along the channel walls. The variation in channel geometry along the axis is assumed gradual, so that wall curvature is neglected and, on all planes normal to the axis, the pressure is assumed uniform.

In most calculations performed with this method to date, the velocity distribution at the nozzle exit plane was assumed to be rectangular, i.e., the wall boundary layer has been assumed to have zero thickness at that point; the initial thickness of the jet-secondary stream shear layer has also been assumed to be zero. This requirement is not necessary, however, and in general any initial distribution of velocity in the initial plane is permissible, under the assumption that pressure distribution across the plane is uniform.

Although previous work \(^1\) has amply demonstrated that integral methods are capable of predicting symmetric jet mixing of compressible flow in jets, the finite difference method has been chosen for this problem. The finite difference method has
advantages relative to the integral method of much greater flexibility in allowable flow inlet conditions, and wall boundary conditions, e.g., the use of wall jets or wall suction. Further the finite difference method offers the considerable advantage of mathematical precision in determining the overall consequences of any particular physical hypothesis regarding the shear stress distribution. With the integral method, the mathematical approximation due to the formation of integrals may contribute uncertainty in flow prediction in addition to the uncertainty introduced by a lack of precise physical knowledge. Thus, in developing a model to handle a certain class of flows, it is advantageous to have a method which is relatively precise mathematically, so that the effects of physical uncertainties may be assessed relatively clearly. The finite difference method is however, quite costly in its requirement for computer time. Further, as experience has shown, considerable care is required in adjusting the computation grid such that spacings are appropriately small in the region of the wall, and in any part of the flow where velocity gradients are quite large.

3.2 Basic Conservation Equations

In stream-wise coordinates, the momentum and energy equations (2) for the plane two-dimensional flow are:

\[ \frac{\bar{u}}{\partial x} = - \frac{1}{\bar{p}} \frac{d \bar{p}}{d x} + \frac{\bar{u}}{\partial \psi_s} \]

(1)

\[ \frac{\bar{u}}{\partial x} \frac{\partial (\bar{C} \bar{T})}{\partial x} = \frac{\bar{u}}{\bar{p}} \frac{d \bar{p}}{d x} + \frac{\bar{u}}{\partial \psi_s} + \frac{\Phi}{\bar{p}} \]

(2)

\[ \Phi = \frac{\bar{u}}{\bar{p}} (\bar{u}^2) - (\rho v') u' \frac{\partial \bar{u}}{\partial y} = (\bar{u} + \bar{v} \epsilon) \frac{\partial \bar{u}}{\partial y} \]

(3)

in which \( \bar{u} \) is the velocity component in the x or principal flow direction, \( \bar{p} \) is the static pressure, \( \bar{\rho} \) the density and \( \bar{T} \) is the temperature of the fluid. Using the eddy viscosity assumption, the mean average shear stress and heat transfer are defined by:

\[ \tau = \bar{\mu} \frac{\partial \bar{u}}{\partial y} - (\rho v') u' = (\bar{\mu} + \bar{\rho} \epsilon) \frac{\partial \bar{u}}{\partial y} \]

(4)
\[ q = k \frac{\partial T}{\partial y} - C_p \left( \varphi V \right)' T' = \left( k + \frac{\rho C_p \epsilon}{\rho r t} \right) \frac{\partial T}{\partial y} \]  

(5)

in which \( \epsilon \) is the kinematic eddy viscosity.

In developing the finite difference solution to this problem, the stream-wise coordinate system was attractive, not only in terms of the simplicity of the governing equations but also for possible development as a design procedure, in which the flow field pressure distribution could be specified and the required wall geometry determined, non-interactively, once the solution is obtained in stream coordinates. However, the difficulty with the stream-wise coordinate is that it introduces a singularity in the governing equations in the vicinity of the wall. Given the definition of the stream function,

\[ \frac{\partial \psi}{\partial y} = \overline{\rho u} \]  

(6)

it can be seen that the gradient

\[ \frac{\partial \overline{u}}{\partial \psi} = \frac{1}{\overline{\rho u}} \frac{\partial \overline{u}}{\partial y} \]  

(7)

becomes undefined at the wall where the value of \( \overline{u} \) approaches zero. The singularity can be removed as Denny\(^\text{(3)}\) has shown by using the transformation

\[ \frac{\partial \psi^2}{\partial y} = \overline{\rho u} , \quad \frac{\partial \psi}{\partial y} = \frac{\overline{\rho u}}{2\psi} , \quad \text{and} \quad \frac{\partial \overline{u}}{\partial y} = \frac{\overline{\rho u}}{2\psi} \frac{\partial \overline{u}}{\partial \psi} \]  

(8)

instead of conventional stream function definition

in which case the limiting value of the gradient \( \frac{\partial \overline{u}}{\partial \psi} \) is finite and higher derivatives also exist. With this transformation then, the equations of motion may be written.

\[ -\overline{u} \frac{\partial \overline{u}}{\partial x} = -\frac{1}{\overline{\rho}} \frac{d \overline{p}}{dx} + \frac{\overline{u}}{2 \psi} \frac{\partial}{\partial \psi} \left[ \left( \mu + \overline{\rho \epsilon} \right) \frac{\overline{\rho u}}{2 \psi} \frac{\partial \overline{u}}{\partial \psi} \right] \]  

(9)
\[ \bar{u} \frac{\partial}{\partial x} (\bar{C}_p T) = \frac{\bar{u}}{\rho} \frac{d\bar{p}}{dx} + \frac{\bar{u}}{2\psi} \frac{\partial}{\partial \psi} \left[ (k + \frac{\rho \bar{C}_p \epsilon}{\rho_{rt}}) \frac{\partial \bar{u}}{\partial \psi} \frac{\partial T}{\partial \psi} \right] \]

\[ + \left( \frac{\bar{u}}{\rho} + \bar{\rho} \epsilon \right) \left( \frac{\rho \bar{u}}{2\psi} \frac{\partial \bar{u}}{\partial \psi} \right)^2 \]  

(10)

where \( \psi \) is now the transformed quantity according to Denneysup(3)sup. The transformation of these equations is shown in Appendix A.

3.3 Dimensionless Groups

Before solution of the finite-difference method, these equations are made dimensionless by the following steps.

The velocity \( \bar{u} \) is normalized by dividing by the jet centerline velocity \( u_o \). Also a reference Mach number is defined by:

\[ M_{ir} = \frac{u_o}{\sqrt{\gamma RT_o}} \]  

(11)

in which \( T_o \) is a reference temperature and \( \gamma \) is the specific heat ratio. A dimensionless temperature parameter is defined by:

\[ \theta = \frac{T - T_o}{T_{wr} - T_o} \]  

(12)

in which \( T_{wr} \) is a second arbitrary reference temperature.

The fluid properties variables are made dimensionless by defining:

\[ k^* = \frac{\bar{k}}{k_o} \]

\[ \bar{C}_p^* = \frac{\bar{C}_p}{C_{po}} \]

\[ \mu^* = \frac{\bar{\mu}}{\mu_o} \]

\[ \rho^* = \frac{\bar{\rho}}{\rho_o} \]

\[ P_{ro} = \frac{\mu_o C_{po}}{k_o} \]

\[ E = \frac{\epsilon}{\nu_o} \]

(13)
in which \( k_0 \), \( C_{po} \), \( \mu_0 \), and \( \rho_0 \) are fluid properties at reference values of pressure and temperature and \( \mu_0 = \rho_0 \nu_0 \).

In the program the reference values of temperature are
\[
T_0 = 520^\circ R \\
T_{wr} = 560^\circ R
\]
and the reference fluid properties are evaluated at 520\(^\circ\)R and 2115 psf.

The coordinate variables are transformed to:
\[
X = \frac{u_0 x}{\nu_0} \\
\psi^* = \frac{\psi}{\sqrt{\rho_0 \nu_0}}
\]

Then in dimensionless form the equations of motion become:
\[
u \frac{\partial u}{\partial X} = -\frac{1}{2} \rho^* \frac{dP}{dX} + \frac{u}{2 \psi^*} \frac{\partial}{\partial \psi^*} \left[ \left( \frac{\mu^* + E\rho^*}{\rho^*} \right) \frac{\rho^* u}{2 \psi^*} \frac{\partial u}{\partial \psi^*} \right] + C_L \left( \frac{\mu^* + E\rho^*}{\rho^*} \right) \left( \frac{\rho^* u}{2 \psi^*} \frac{\partial u}{\partial \psi^*} \right)^2
\]
in which
\[
C_L = \frac{(\gamma - 1) M_{ir}^2}{T_{wr} - 1} = \frac{u_0^2}{C_{po}(T_{wr} - T_0)}
\]
The turbulent Prandtl number \( Pr_t \) is taken to be 0.9. Neglecting the dependence of the specific heat on temperature, \( C^* = 1.0 \). The derivative of the dimensionless equations of motion is shown in Appendix A.
3.4 Evaluation of the Eddy Viscosity

In general, the eddy viscosity is evaluated by

$$\epsilon = \ell_m \frac{2 \partial \bar{u}}{\partial y}$$  \hspace{1cm} (19)

in which $\ell_m$ is the mixing length. In two-dimensional jet mixing, values of mixing length are not well known especially for the region in which the shear zone extends from wall to wall. In various zones of the flow, the mixing lengths have been evaluated as follows:

In the shear layer adjacent to the potential core zone of the primary jet the mixing length is evaluated from

$$\ell_m = 0.08 \delta$$  \hspace{1cm} (20)

in which $\delta$ is the shear layer width (including the zone between 1% and 99% of the total velocity difference between primary and secondary streams).

For the "fully-rounded" portion of the jet flowing coaxially with a secondary potential stream, the mixing length has been calculated from

$$\ell_m = 0.108 \delta$$  \hspace{1cm} (21)

in which $\delta$ is the half-width of the jet, evaluated from centerline to the point at which the difference between local and secondary velocity is only 1% of the difference between centerline and secondary velocity.

In the wall boundary layer, the mixing length has been evaluated from the lesser of:

$$\ell_m = 0.09\delta \quad \text{(outer part)}$$  \hspace{1cm} (22)

or, using the Van Driest approximation,

$$\ell_m = 0.41 \left[ 1 - e^{-\left(y^+/26\right)} \right] y \quad \text{(inner part)}$$  \hspace{1cm} (23)
in which
\[ y^+ = \sqrt{\frac{\gamma}{\rho}} \frac{y}{\nu} \quad (24) \]

For the region downstream of the point where the jet spreads to intersect the edge of the boundary layer the mixing length is evaluated, as a first approximation only, from
\[ \ell_m = y_w \left[ 0.14 - 0.08 \left( \frac{y}{y_w} \right)^2 - 0.06 \left( \frac{y}{y_w} \right)^4 \right] \quad (25) \]
which is due to Nikuradse and is cited by Schlichting\(^4\) for fully developed flow in round tubes. Near the wall \( y = y_w \) the mixing length is evaluated by the Van Driest approximation cited earlier, provided the local mixing length so calculated is less than that given by the Nikuradse formula.

3.5 Boundary Conditions

With prescribed wall geometry the boundary conditions at the outer wall are:
\[ y = y_w(x) \]
\[ \psi^* = \text{const.} \]
\[ \frac{\partial \theta}{\partial \psi^*} = 0 \]
\[ u = 0 \]

Along the channel axis of symmetry the boundary conditions are:
\[ y = 0 \]
\[ \psi^* = 0 \]
\[ \frac{\partial \theta}{\partial \psi^*} = 0 \]
\[ \frac{\partial u}{\partial \psi^*} = 0 \]
3.6 Finite Difference Procedure

By the finite-difference technique, the derivatives in the differential equations of motion are replaced by differences either along a streamline between two neighboring points \( X \) and \( X + \Delta X \) or normal to it between two neighboring points \( \psi \) and \( \psi + \Delta \psi \).

If one takes the velocity field at plane \( X \) as completely known then the velocity field at \( X + \Delta X \) may be solved, using the implicit method, from the finite-difference form of the momentum equation which is of the form

\[
A_{n-1} u_{2,n} + B_{n-1} u_{2,n+1} + C_{n-1} u_{2,n-1} = D_{n-1}
\]

in which \( u_{2,n} \) is the unknown velocity at the \( n \)th grid point on plane \( X + \Delta X \) and \( A_{n-1}, B_{n-1}, C_{n-1}, D_{n-1} \) are coefficients containing the mean pressure gradient between \( X \) and \( X + \Delta X \) and the velocity and shear stress distributions at plane \( X \).

As shown in the derivation in reference\(^{(5)}\) and Appendix B, the coefficients in the finite difference form of the momentum equation are evaluated from:

\[
A_{n-1} = Y8 + Y9 + \frac{u_{1,n}}{\Delta X}
\]

\[
B_{n-1} = -Y8
\]

\[
C_{n-1} = -Y9
\]

\[
D_{n-1} = -\frac{1}{4} \rho^* \left( \frac{dP}{dX} \right)_{m=2} + \frac{dP}{dX} \left. \right|_{m=1} + \frac{u^2}{\Delta X}
\]

in which,

\[
Y8 = \frac{u_{1,n}}{2 \psi^*_n} \left( \frac{S_{n+1} + S_n}{\Delta \psi_1 S1} \right)
\]

\[
Y9 = \frac{u_{1,n}}{2 \psi^*_n} \left( \frac{S_n + S_{n-1}}{\Delta \psi_2 S1} \right)
\]
\[ S_l = \Delta \psi_1 + \Delta \psi_2 \]  \hspace{1cm} (33)

\[ \Delta \psi_2 = \psi_n^* - \psi_{n-1}^*, \quad \Delta \psi_1 = \psi_n^* + 1 - \psi_n^* \]  \hspace{1cm} (34)

\[ S = \left( \frac{\mu^* + E \rho^*}{2 \psi^*} \right) \rho^* u \]  \hspace{1cm} (35)

In a similar way\(^{(5)}\), the energy equation can be written in the finite difference form:

\[ A_{n-1} \theta_{2,n} + B_{n-1} \theta_{2,n+1} + C_{n-1} \theta_{2,n-1} = D_{n-1} \]  \hspace{1cm} (36)

where,

\[ A_{n-1} = Y_8' + Y_9' + \frac{u_{1,n}}{\Delta X} \]  \hspace{1cm} (37)

\[ B_{n-1} = -Y_8' \]  \hspace{1cm} (38)

\[ C_{n-1} = -Y_9' \]  \hspace{1cm} (39)

\[ D_{n-1} = \frac{u_{1,n} \theta_{1,n}}{\Delta X} + \frac{C_L u_{1,n}}{\rho^* \psi_1,n} \left[ \frac{dP}{dX}_{m=1} + \frac{dP}{dX}_{m=2} \right] \]

\[ + \frac{C_L S_1, u_{1,n}^2}{2 \psi^*} \left[ R_2(u_{2,n+1} - u_{2,n}) + R_1 (u_{2,n} - u_{2,n-1}) \right]^2 \]  \hspace{1cm} (40)

\[ Y_8' = \frac{u_{1,n}}{2 \psi^* n} \left[ \frac{Q_{n+1}}{\Delta \psi_1 S_1} + \frac{Q_n}{\Delta \psi_1 S_1} \right] \]  \hspace{1cm} (41)

\[ Y_9' = \frac{u_{1,n}}{2 \psi^* n} \left[ \frac{Q_n}{\Delta \psi_2 S_1} + \frac{Q_{n-1}}{\Delta \psi_2 S_1} \right] \]  \hspace{1cm} (42)

\[ Q = \left[ \frac{k^*}{P_{ro}} + \frac{E \rho^*}{P_{rt}} \right] \frac{\rho^* u}{2 \psi^*} \]  \hspace{1cm} (43)
\[ R_1 = \frac{\Delta \psi_1}{\Delta \psi_2 (\Delta \psi_2 + \Delta \psi_1)} \]  
\[ R_2 = \frac{\Delta \psi_2}{\Delta \psi_1 (\Delta \psi_2 + \Delta \psi_1)} \]  

The relationship between the x-ψ coordinates, and the physical plane in finite difference form, for any n, becomes,

\[ Y_n = \begin{bmatrix} \frac{\psi_2^* - \psi_{n-1}^*}{(\rho^* u)_n + (\rho^* u)_{n-1}} 
\end{bmatrix} \]  

Finally the property relation becomes:

\[ E_{2,n} = \frac{u_{1,n} \rho_{1,n}^* L^2}{2 \psi^*} \begin{bmatrix} \frac{u_{1,n + 1} - u_{1,n - 1}}{\psi_{n + 1}^* - \psi_{n - 1}^*} 
\end{bmatrix} \]  

For a set of N ψ-lines and known boundary conditions, Equations (26) and (36) each provide a set of N-2 conditions to solve for the unknown velocities and temperatures. Each set of equations can be solved simultaneously if the pressure gradient is known or assumed. For calculation of flow between fixed channel walls, the pressure gradient is assumed and the velocities determined; then the location of the outer boundary is calculated from successive use of equation (46) across all N grid lines. If the calculated value of the outer boundary location does not agree satisfactorily with the actual wall geometry, a new value of the pressure gradient is chosen.

Since each set of equations can be represented by a tridiagonal matrix of coefficients, the Thomas Algorithm\(^5\) is employed for speedy solution as shown in Appendix C which describes the solution procedure.

The structure of the computer program is given in Appendix D.
Section 4

TEST PROGRAM

A two-dimensional experimental rig was designed, fabricated, and installed in our laboratory. The purpose of the experimental work was to obtain test data for verification and adjustment of the computer analysis. The experimental program is described in this section.

4.1 Experimental Apparatus

4.1.1 Two-Dimensional Ejector

The two-dimensional ejector consisted of a slot type primary nozzle and a two-dimensional mixing section. The arrangement of the ejector system is shown on Figure 1.

A picture of the primary nozzle is shown on Figure 2. The discharge slot is 0.1215" + 0.0005" by 8.00" with rounded corners. The side walls are quarter inch carbon steel and four internal supports are included to prevent widening of the discharge slot when the nozzle is pressurized. Dial indicator measurements show that the slot opened up by about 0.0008 inches in the center of the nozzle, about 0.0004" at the quarter width location and zero near the ends of the slot. This is equivalent to an increase in nozzle slot area of 0.33% when pressurized. Stagnation pressure measurements were made with a kiel probe from side to side in the nozzle discharge and were found to be uniform across the 8" width of the slot. The primary nozzle is positioned in the mixing section (see Figure 1 and Figure 3) so that the primary flow is discharged along the centerline of the straight symmetrical mixing section.

The mixing section as shown on Figure 1 consists of a rectangular variable area channel formed by two identically contoured aluminum plates and two flat side plates. The pictures in Figures 3 and 4 show two views of the mixing section. The two contoured plates can be positioned in two symmetrical locations about the centerline to form the two channels tested (throat heights of 1.25" and 1.875"). The width of the mixing section is 8.00" for the full length. The variation of channel height with distance from the nozzle discharge is given on Table 1 for the 1.875 throat mixing
section. The geometry for the 1.25" throat height is obtained by subtracting 0.312"
from each y value. Three plexiglass windows are installed along each side of the
mixing section so the tufts of wool mounted inside can be observed for indications of
flow separations and unsteadiness.

The screened mixing section inlet is shown on Figure 5. Initial tests without the extended inlet showed that highly swirling corner vortices were formed in the four corners of the bellmouth and extended into the test section. The extended inlet eliminated the corner vortices and improved the stability of the ejector flow and static pressures. The extended inlet shown on Figure 5 was used for all ejector tests.

4.1.2 Facilities for Ejector Tests

The schematic of the ejector test facilities on Figure 6 shows the three required subsystems needed for operation, control and measurement of the ejector:

- Primary Flow System
- Mixed Flow System
- Boundary Layer Suction System

The primary air flow is supplied by a 900 SCFM oil free screw compressor at 100 psig and an equilibrium operating temperature between 180°F and 240°F. The primary air flow rate and pressure are controlled by a manual pressure regulator and bleed valve. The mass flow is measured by a standard 3 inch Danial orifice system. The air flow is delivered to the primary nozzle through a flexible hose.

The mixed flow system consists of a plenum chamber, an 8" orifice system and a throttle valve. Four different operating flow rates are achieved by the following equipment combinations.

1. Maximum Flow Rate - Mixed flow discharges directly into laboratory from mixing section.
2. First Reduced Flow Rate - The plenum is connected to the mixing section discharge.
3. Second Reduced Flow Rate - The orifice is connected to the plenum.
4. Lowest Flow Rate - The throttle valve is partially closed.
Orifice flow rates are obtained only for the two lowest flow rate conditions. Figure 7 and 8 show most of the experimental ejector installation. The large rectangular box connected to the mixing section by the large black flexible hose is the main plenum. The 8" orifice is not visible in the picture.

The suction system removes the boundary layer flow from each of the four corners of the mixing section to prevent wall boundary layer separation in the ejector. The pictures in Figures 7 and 8 show three 3/4 inch tubes connected to each corner of the mixing section. These 12 tubes collect the boundary layer flow from the corner suction slots which are 0.060 inches wide and are machined into the sides of the contoured plates (See figures 9 and 10). The four tubes at one X location are connected to a single large tube under the mounting table. The three large tubes are each connected to a large tank plenum through a separate throttle valve. A Roots blower draws the air through the suction system and through a three inch orifice system. The suction system is capable of removing about 1% to 2% of the mixing section flow rate. During the operation of the ejector rig, the boundary layer suction system was necessary to prevent flow separation in the mixing section diffuser. The presence of separation was easily observed from the violently flopping tufts, the large fluctuation in wall static pressures and audible pulsations. The operation of the suction system drastically reduced these symptoms.

The ejector system was operated by starting the primary air flow at low pressure and flow rate. The suction was turned on and then the primary pressure was increased to the desired test conditions. The large mixing section (1.875" throat height) was operated at 21 psig without separation in the mixing section. The small mixing section (1.25" throat height) could not be operated over 20 psig without separation for the high flow condition. The tests with the small mixing were therefore run at 17 psig.

4.2 Instrumentation and Data Reduction

4.2.1 Instrumentation

The following instrumentation was included on the test rig.
Primary Flow System

Flow Rate - Standard 3" orifice system
Nozzle Pressure - Pressure gage accurate to ± 0.25 psig
Nozzle Temperature - Thermocouple with digital readout

Mixed Flow System

Flow Rate - 8" orifice system for two lowest flow rate conditions
Static Pressures - Wall static pressures down the center of the mixing section and some at other locations (see Figures 9 and 10). Manometers were used for measurement.
Traverse Data - Stagnation pressure and temperature profiles were measured at up to 9 axial locations using a kiel temperature probe, a pressure transducer and direct digital readout, and a temperature direct digital readout (see Figure 8).

Suction Flow System

Flow Rate - 3" orifice system
Suction Pressure - a mercury manometer

4.2.2 Data Reduction Procedures

Three types of data reduction calculations were needed in this program:

- Standard orifice calculations
- velocity profile calculations
- integration of velocity profiles to calculate flow rate

The orifice calculations were carried out using standard orifice equations and ASME orifice coefficients. The velocity profiles were calculated from the well known compressible flow relationships between Mach number and the ratio of stagnation pressure to static pressure that can be found in most fluid mechanics text books. The local velocity is calculated from the Mach number and the local speed of sound which
is dependent on the local static temperature. The static temperature is calculated from
the measured stagnation temperature profiles and the compressible flow relation be-
tween temperature ratio and Mach number.

To calculate an integrated mass flow rate for each traverse location a time
sharing data reduction computer program was written to integrate the product of local
velocity and local density over a two-dimensional section of unit width. The program
also calculated the "mass-momentum" stagnation pressure at each traverse section
using the equations presented on page 52 and 53 of reference 6. The mass-momentum
method determines the flow conditions for a uniform velocity profile which has the same
integrated values of mass flow rate, momentum, and energy as the non-uniform velocity
profile actually present.

4.2.3 Experimental Uncertainty

Orifice Calculations

The techniques presented in reference 7 were applied to the primary flow
orifice calculations and the mixed flow orifice calculations. The following uncertainty
results were obtained:

<table>
<thead>
<tr>
<th>Orifice</th>
<th>Nozzle Pressure</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>17.0 and 21 psig</td>
<td>± 0.8%</td>
</tr>
<tr>
<td>Mixed</td>
<td>slightly above</td>
<td>± 1.3%</td>
</tr>
<tr>
<td></td>
<td>atmospheric</td>
<td></td>
</tr>
</tbody>
</table>

Static Pressures

Uncertainty in the wall static pressures mainly occurs because of un-
steadiness in the manometer liquid columns caused by unsteadiness in the flow. The
lowest flow rate condition which had the most system resistance downstream of the
mixing section had a wall static pressure unsteadiness of about ±3/8 inches of water.
The amount of unsteadiness increased as the flow rate was increased by removing
system resistance. For the unrestricted maximum flow rate condition the wall static
pressure unsteadiness was ± 2.0 inches of water. These values are also a measure
of the uncertainty.
Integrated Mass Flow Rate

The mass flow rate calculated by integrating the results of the stagnation pressure and temperature traverses is influenced by many items and is therefore very difficult to estimate. The following items all contribute to the uncertainty in integrated mass flow rate:

1. unsteady wall static pressures
2. unsteady traverse stagnation pressures
3. instrument accuracy of the pressure transducer and digital readout
4. inaccuracies due to the effect of steep velocity gradients on sensed pressure
5. inaccuracies due to probe effect near the mixing section walls
6. inaccuracy in probe position
7. assumptions and inaccuracies associated with the data reduction computer program
8. data recording errors or computer data input errors
9. errors caused by loose connections in the pneumatic sensing tube between the probe and the transducer
10. Non-two-dimensional flow distribution across the width of the 8 inch mixing section.

All of these effects could combine to give both a $\pm$ uncertainty band and a fixed error shift.

One measure of the uncertainty due to these effects is obtained from the limits of individual integrated mass flows for each test run. These values are listed on Table 2 for all of the test runs with traverse data. The results presented on Table 2 show an average variation of $+3.6\%$ and $-2.8\%$ or a total spread of $6.4\%$. These values only include the effect of variable uncertainty and exclude the uncertainty due to probe errors in steep gradients and near walls and integration assumptions. Both of the excluded errors probably cause the integrated mass flows to be too large because the probe tends to measure too high near the wall and the integration program neglects wall boundary layers.
From the above discussion it is concluded that the average integrated mass flow rates may have a fixed error of +1% to 2% and an uncertainty of about +3% to +4%.

4.3 Test Results

A total of eleven ejector tests were carried out on two mixing section configurations (1.25" and 1.875" throat height). The data presented in this report falls into the following categories:

- Test Conditions and Mass Flows
- Static Pressures
- Centerline Velocities and Temperatures
- Velocity Profiles
- Temperature Profiles
- Eddy viscosity Sensitivity
- Flow Rate Sensitivity

Table 3 shows which figures and tables show the data for each test run. Most of the figures and tables present both test data and comparative analytical results. The comparisons will be discussed in section 5.0.
Section 5

COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS

5.1 Test Conditions and Mass Flows

Table 4 presents a tabulation of the measured nozzle conditions, the integrated mass flow rate from the measured pressure and temperature profiles, and the integrated "mass momentum" stagnation pressure.

The nozzle mass flow rate was calculated from standard orifice readings which were shown in section 4.2.3 to have an uncertainty of about +0.8%. Using the orifice flow rate, the nozzle pressure, the nozzle temperature, and the nozzle discharge area, a nozzle discharge coefficient ($C_N$) was calculated for each test run. These values all fall within a range of +0.007 and -0.0085 around an average of 0.973 which is consistent with the calculated uncertainty. If there were no error in the nozzle calculations all of the $C_N$ values would be identical. From these results it is safe to assume that the listed nozzle flow rates are accurate to at least +1%.

The tabulated mixing section flow rates were calculated as described in section 4.2.2 by integrating the measured pressure and temperature profiles. As described in section 4.2.3, these results probably have a fixed error of between +1% and +2% and an uncertainty of between +3% and +4%. Table 5 presents a comparison between three separate mass flow determinations:

- integrated from traverse data
- measured by orifice
- computer mass flow giving the best wall static pressure comparison

Only 4 of the tests could be measured with the large orifice, but all of these four tests agree with the computer mass flow within +0.9% as shown on table 5. Section 4.2.3 shows that the expected uncertainty in orifice mass flow is about +1.3% making it much more accurate than the integrated traverse values. The wall static pressures are in fact a function of the average mass flow represented by the orifice value rather than a local velocity profile down the center of the two-dimensional mixing section. This is
true because the mixing section flow patterns can not support a side-to-side pressure gradient along the 8 inch width of the mixing section which was verified by test measurements. Therefore it is concluded that the measured orifice mass flows and the computer mass flow for best match of wall static pressures are the correct mass flow values. The integrated mass flows are in error and in some cases inconsistent. Table 5 shows that the integrated mass flow values spread over a range of -2.9% to +6.4% around the computer determined value. Figures 11 and 12 show all of the mass flow values on Table 5 plotted versus the mixing section throat static pressure. Figure 11 for Runs 1-5 shows the good agreement between computer analytical mass flows and orifice mass flows and shows the wide scatter of integrated traverse mass flows. Figure 12 for Runs 6-10 again shows good agreement between analytical and orifice values and this time shows a consistent trend of integrated traverse mass flows which are now offset by about +3.2% on a line parallel to the other more accurate mass flow values.

The "mass-momentum" stagnation pressure listed on table 4 suffers from the same inaccuracies as the integrated mass flow rate discussed above. The plotting of mass-momentum stagnation pressure versus mass flow will therefore show some discrepancies.

5.2 Mixing Section Wall Static Pressure Variation

The wall static pressure distributions are shown on Figures 13 and 14 and Table 6 as specified on Table 3. Runs 4, 8, and 11 on Table 6 were extra tests for which no analytical solutions were obtained. Test Run 11 was a repeat of test Run 9 and gives results that are essentially the same.

Figures 13 and 14 show there is a good comparison between experimental wall static pressures (shown as data points) and the analytical static pressures (solid lines) at essentially the same mass flow (see discussion in section 5.1). The analytical results have assumed that the mixing length constant in equation 20 is 0.08 and in equation 21 is 0.108. These values influence the mixing process through the eddy viscosity. The influence on wall pressures is relatively minor as will be discussed in section 5.5 where these values are varied over a reasonable range. The comparison between test and analytical values is generally excellent. Both the data and analytical
results show changes in shape at points where the geometry changes. The two areas where some disagreement occurs is in the entrance region and in the last half of the diffuser.

The difference in the bellmouth section occurs because the analytical program calculates a centerline static pressure and assumes the static pressure constant at each x distance from the nozzle discharge whereas the experimental data are wall static pressures and can be influenced by curving streamlines. At x = 0 the bellmouth walls still have a significant curvature which causes flow streamline curvature in this region. The result is a reduced wall static pressure and an elevated centerline static pressure. Between 1 and 2 inches downstream of the nozzle discharge the wall curvature is reduced to very small values and the data and analytical results agree very closely.

The second area where minor differences occur is in the last half of the diffuser for the higher flow rate test runs. The reason for this difference could be an underestimation of the pressure losses due to wall friction, mixing, and diffusion. Substantiation of this can be seen by comparing the slope of the pressure data to the analytical results in the constant area throat section between 8 and 11 inches. For the low flow rate Runs 2, 6 and 7 where the slopes are essentially equal, the test and analytical diffuser wall pressures are almost identical. For the other runs the test data slope between 8 and 11 inches is always more negative than the analytical results. For frictionless uniform flow in a short constant area duct, the static pressures would be equal all along the duct. For frictionless non-uniform flow in a short constant area duct the static pressure can increase as mixing takes place. For non-uniform flow in a constant area duct with friction, the static pressure will tend to decrease along the duct and the slope will become less positive or more negative as flow rate (and therefore losses) increases. From these observations, it would appear that the flow dependent losses for the analytical solution may be underestimated in the constant area and diffusing sections. This may be the cause of the difference between the test and analytical wall static pressures in the diffuser section.
5.3 Centerline Velocity and Temperature Variations

Figures 15 and 16 present the variation of maximum velocity and maximum temperature as a function of distance from the nozzle discharge. The temperature comparison is generally good for all test runs. The velocity comparison is also good. However, the experimental maximum velocities tend to be higher than the analytical values in the first 4 inches downstream of the nozzle discharge. In the throat section and diffuser, the experimental values tend to be lower than the analytical values. In general, the comparisons are very good. Differences may occur due to the eddy viscosity and mixing length distributions assumed (see section 3.4) or due to measurement inaccuracies.

5.4 Velocity Profiles and Temperature Profiles

A total of 45 sets of traverse measurements were taken during the experimental test program. Table 3 shows the figure numbers that present the comparison of the test data and analytical results for each test run. These results are presented on Figures 17 through 26.

In general, the comparison of profile shape and velocity magnitude is very good between the analytical and experimental profiles. The comparisons for Runs 6 through 10 (Figures 21-24) match very closely. The only differences that are noticeable are that the experimental velocity profiles within 5.0 inches of the nozzle discharge are off center by about 0.025'' and slightly higher in maximum velocity than the corresponding analytical velocities. The nonsymmetry has disappeared for all traverses at distances greater than 5 inches. The good match of velocity profiles for Runs 6 through 10 goes along with the good comparison of static pressures and the consistent trend in integrated traverse mass flow rate discussed previously.

The comparison of experimental and analytical velocity and temperatures is not as good for Runs 1 through 5 as it was for Runs 6 through 10. The comparisons are also not as consistent from run to run which also coincides with some of the static pressure and mass flow differences noted previously for these runs. The following observations apply only to Runs 1 through 5.
1. The experimental jet is off center by about 0.057" but the non-symmetry has disappeared for profiles at distances of greater than 5.0".

2. For x of 3.0" or less the peak experimental velocities are greater than the analytical values for Run 3 and Run 2 and are slightly less for Runs 1 and 5.

3. The spread width of the velocity profiles compares very well at distances from the nozzle of 7.0 inches or less. For distances between 7 inches and 16 inches, the experimental profiles tend to spread faster and have a flatter profile.

4. The experimental temperature profiles in Figure 25 are spread significantly more than the analytical values at x = 3.0" and x = 10.5", the only two profiles plotted.

5. The comparisons for Run 1 are better than for the other runs for the 1.25" throat mixing section.

Both sets of data (for the 1.25" and 1.875" throat height) were calculated using the same eddy viscosity assumptions for mixing (0.08 for eq. 20, 0.108 for eq. 21). The test Runs 6 through 10 have lower average throat Mach numbers (.39 to .52), slightly higher primary nozzle velocities, higher wall static pressures, and larger mixing section dimensions. The eddy viscosity assumptions may be more suitable for these operating conditions than for those of test Runs 1 through 5. In any event, the agreement between experimental and analytical results is better for the Runs 6 through 10.

5.5 Sensitivity of Computer Analysis

The sensitivity of the computer analysis to changes in eddy viscosity and flow rate were investigated to obtain a measure of the amount of performance change that can result from small changes in assumed values.
5.5.1 Eddy Viscosity

The results for the eddy viscosity changes are shown on Figures 27, 28, and 29. The eddy viscosity is directly proportional to the square of the mixing length according to equation 19. The changes in mixing length were confined to the mixing region prior to the point where the jet mixing reaches the developing wall boundary layer. In this region the mixing length is defined by equations 20 and 21 as a constant times a mixing zone dimension (see section 3.4).

Equation 20 is used to calculate the mixing length in the region close to the nozzle discharge where the primary jet still has a flat potential core (probably confined to the first 0.5" to 1.0" of mixing). Most of the calculations have been carried out using a constant of 0.08 in equation 20. For the results presented in this section the comparative runs were made with the constant equal to 0.094 which gives about a 38% increase in eddy viscosity in this small region.

Equation 21 is used to calculate the mixing length in the region where the primary jet is "fully rounded" but has not intersected with the wall boundary layer. This region extends for about 4" to 6" into the mixing section for the 1.25" throat configuration and extends for about 6" to 8" for the 1.875" throat configuration. Most of the calculations have been carried out using a constant of 0.108 in equation 21. For the results presented in this section, the comparative runs were made with a constant equal to 0.120 which gives about a 23% increase in eddy viscosity.

The velocity and temperature results shown on Figures 28 and 29 for Runs 3 and 6 show that the amount of mixing increases with eddy viscosity. This results in reduced centerline velocities, increased velocities near the walls and increased wall static pressures (see Figure 27). All of the changes are small.

The effect of mixing length changes in the rest of the mixing section as defined by equation 25 was not investigated but it is expected that the results would be similar. Section 3.4 points out that equation 25 was obtained by Nikuradse for fully developed flow in round tubes and should be considered to give only approximate results. Changes in this equation could provide a better match of static pressures for some of the high flow test runs as discussed in Section 5.2.
5.5.2 Flow Rate

Figure 27 shows the effect on wall static pressures of a 2.2% change in total mass flow for Runs 3 and 6. The wall pressure decrease as flow rate is increased is about double for Run 3 as compared to Run 6. The reason for this is that the average Mach number for Run 3 (1.25" throat) is larger than for Run 6 (1.875" throat) even though the Run 6 mass flow is larger. Figure 30 shows the influence of throat Mach number on throat static pressure level. The local slope of this line indicates the rate of change of throat pressure with Mach number. Run 6 happens to be the lowest Mach number test run and Run 3 has one of the largest Mach numbers. A comparison of the local slopes for Run 3 and Run 6 on Figure 30 gives results consistent with Figure 27.
Section 6

CONCLUSIONS

(1) The finite difference computer analysis developed to analyze two-dimensional co-axial slot ejectors with variable area mixing sections predicts the performance of the experimental configurations tested under this program very closely.

(2) The analytical and experimental results compared are at essentially the same flow rate within the accuracy of our measurements. The correct mixing section mass flow rates for each test are best represented by the orifice measured values and the computer analytical mass flow for best comparison of measured wall static pressures. These two values agree within \( \pm 0.9\% \). The integrated traverse mass flows are less accurate and range between \(-2.9\%\) and \(6.4\%\) of the other values.

(3) The experimental and analytical wall static pressure distributions agree within 1 or 2 inches of water over most of the mixing section for most of the test runs.

(4) The experimental and analytical velocity profiles compare very well in both velocity level and amount of jet spread due to mixing.
Appendix A

BASIC EQUATIONS OF MOTION

The momentum and energy equations as shown in equations 1 and 2 in the main text can be transformed to the \( x-\psi^2 \) coordinates according to Denny\(^{(3)}\) by the following steps.

**Momentum Equation:**

The stream function transformation is defined by:

\[
\frac{\partial \psi^2}{\partial y} = -\frac{\rho}{u} \frac{\partial u}{\partial y} = \frac{\rho u}{2\psi} \quad \text{(A-1)}
\]

then:

\[
\frac{\partial \bar{u}}{\partial y} = \frac{\partial \psi}{\partial y} \frac{\partial \bar{u}}{\partial \psi} = \frac{\rho \bar{u}}{2\psi} \quad \frac{\partial \bar{u}}{\partial \psi} \quad \text{(A-2)}
\]

The third term of the momentum equation becomes:

\[
\frac{\bar{u}}{\partial \psi_s} \frac{\partial \tau}{\partial \psi} = \frac{\bar{u}}{2\psi} \frac{\partial \tau}{\partial \psi} = \frac{\bar{u}}{2\psi} \quad \frac{\partial}{\partial \psi} \left[ \frac{\rho}{\partial \psi} \left( \mu + \rho \epsilon \right) \frac{\partial \bar{u}}{\partial \psi} \right] \quad \text{(A-3)}
\]

\[
\frac{\bar{u}}{\partial \psi_s} \frac{\partial \tau}{\partial \psi} = \frac{\bar{u}}{2\psi} \quad \frac{\partial}{\partial \psi} \left( \mu + \rho \epsilon \right) \frac{\rho \bar{u}}{2\psi} \quad \frac{\partial \bar{u}}{\partial \psi} \quad \text{(A-4)}
\]

The substitution of equation A-4 into equation 1 of the main text results in equation 9 of the main text.

**Energy Equation**

The third term of the energy equation (equation 2) is transformed as follows:

\[
\frac{\bar{u}}{\partial \psi_s} \frac{\partial q}{\partial \psi} = \frac{\bar{u}}{2\psi} \quad \frac{\partial q}{\partial \psi} = \frac{\bar{u}}{2\psi} \quad \frac{\partial}{\partial \psi} \left[ \frac{\rho C_p \epsilon}{Pr} \right] \quad \text{(A-5)}
\]

\[
\frac{\partial \bar{T}}{\partial y} = \frac{\partial \psi}{\partial y} \frac{\partial \bar{T}}{\partial \psi} = \frac{\rho \bar{u}}{2\psi} \quad \frac{\partial \bar{T}}{\partial \psi} \quad \text{(A-6)}
\]
The substitution of equation A-6 into A-5 completes the transformation of the third term of the energy equation as shown in equation A-7.

\[
\bar{u} \frac{\partial \bar{g}}{\partial \bar{\psi}} = \bar{u} \frac{\partial}{2\psi} \left[ \bar{F} + \bar{\rho} \frac{C_p}{P} \frac{\partial}{Pr} \left( \frac{\bar{\rho} \bar{u}}{2\psi} \frac{\partial}{\partial \psi} \right) \right] \tag{A-7}
\]

The fourth term of the energy equation (equation 2 and 3) is transformed by substituting equation A-2 into equation 3 as follows:

\[
\frac{\bar{\Phi}}{\bar{\rho}} = \left( \frac{\bar{\mu} + \bar{\rho} \bar{\varepsilon}}{\bar{\rho}} \right) \left( \frac{\bar{\rho} \bar{u}}{2\psi} \frac{\partial}{\partial \psi} \right)^2 \tag{A-8}
\]

The substitution of equations (A-7) and (A-8) into equation 2 of the main text results in equation 10 of the main text.

**Dimensionless Momentum Equation**

The equations 11 through 15 of the main text define the dimensionless groups used to non-dimensionalize both the momentum and energy equations.

The first term of the momentum equation (equation 9) is non-dimensionalized as follows:

\[
\bar{u} \frac{\partial \bar{u}}{\partial \bar{x}} = \left( \frac{u_o}{\nu_o} \right)^3 \bar{u} \frac{\partial \bar{u}}{\partial \bar{x}} \tag{A-9}
\]

The second term of the momentum equation is non-dimensionalized as follows:

\[
- \frac{1}{\bar{\rho}} \frac{d \bar{p}}{d \bar{x}} = - \frac{1}{\rho_o} \left( \frac{\rho_o}{2} \right)^{u_o^2} \frac{u_o}{\nu_o} \frac{1}{\rho^*} \frac{d \bar{P}}{d \bar{X}} \tag{A-10}
\]

\[
- \frac{1}{\bar{\rho}} \frac{d \bar{p}}{d \bar{x}} = - \left( \frac{u_o}{\nu_o} \right)^3 \frac{1}{2\rho^*} \frac{d \bar{P}}{d \bar{X}} \tag{A-11}
\]

The third term of the momentum equation is non-dimensionalized as follows:
The non-dimensionalized form of the momentum equation (equation 16) is obtained by substituting equations A-9, A-11, and A-12 into equation 9 of the main text and eliminating the factor \((u_o \nu_o)\) from each term.

**Dimensionless Energy Equation**

The first term of the energy equation (equation 10) is non-dimensionalized as follows:

\[
\frac{\bar{u}}{\bar{\rho}} \frac{\partial \left( \bar{C}_p \bar{T} \right)}{\partial \bar{x}} = \frac{u_o}{\nu} \frac{C_p (T_{wr} - T_o)}{\nu_o} \frac{\partial (C^* \theta)}{\partial X}
\]

\[
= \left[ \frac{u_o^2 C_p (T_{wr} - T_o)}{\nu} \right] \frac{\partial (C^* \theta)}{\partial X}
\]  \hspace{1cm} (A-13)

The second term of the energy equation is non-dimensionalized as follows:

\[
\frac{\bar{u}}{\bar{\rho}} \frac{d \bar{p}}{d \bar{x}} = \frac{u_o u}{\rho_o \nu_o} \frac{u_o^2 u}{2 \nu_o} \frac{d \bar{p}}{d X}
\]

\[
= \left( \frac{u_o}{\nu_o} \right) \frac{u}{2 \rho_o} \frac{d \bar{p}}{d X}
\]  \hspace{1cm} (A-14)
The third term of the energy equation is non-dimensionalized as follows:

\[
\frac{\bar{u}}{2\psi} \left[ \frac{\bar{k}}{\epsilon} + \frac{\rho \bar{C}_p}{\frac{P_{rt}}{P}} \right] \frac{\partial \bar{u}}{\partial \psi} \frac{\partial \bar{T}}{\partial \psi}
\]

\[
= \frac{u^0 u}{2\rho^0 \nu^0 \phi^*} \frac{\partial}{\partial \psi^*} \left[ k^* + \frac{\rho^0 \rho^* C_p^o C^E}{\frac{P_{rt}}{P} \rho^0 \nu^0 \phi^*} \right] \frac{\rho^0 \rho^* u^0 u}{2\rho^0 \nu^0 \phi^*}
\]

\[
\left( T_{wr} - T^o \right) \frac{\partial \theta}{\partial \psi^*}
\]

\[
= \frac{u^2_o C_p^o (T_{wr} - T^o)}{\nu^o} \frac{\partial}{\partial \psi^*} \left[ \frac{k^*}{\frac{P_{ro}}{P}} \frac{\rho^* C^E}{\frac{P_{rt}}{P}} \rho^* u \frac{\partial \theta}{\partial \psi^*} \right]
\]

\[
(A-15)
\]

The fourth term of the energy equation is non-dimensionalized as follows:

\[
\left( \frac{\bar{\mu} + \rho \bar{C}}{\bar{\rho}} \right) \left( \frac{\bar{u}}{2\psi} \frac{\partial \bar{u}}{\partial \psi} \right)^2
\]

\[
= \frac{\mu^*}{\rho^*} + \frac{\rho^* u}{\rho^*} \frac{\partial u}{\partial \psi^*}
\]

\[
= \frac{\rho^* u}{\rho^*} \frac{\partial u}{\partial \psi^*}
\]

\[
(A-16)
\]

Each of the four terms of the energy equation is then divided by the quantity:

\[
\frac{u^2_o C_p^o (T_{wr} - T^o)}{\nu^o}
\]

\[
(A-17)
\]

which results in the following combination of quantities in the second and fourth terms of the energy equation:
\[ \frac{u_o^2}{C_{p0}(T_{wr} - T_o)} \quad \text{which equals } C_L. \]

The substitution of equations A-13, A-14, A-15, and A-16 into equation 10, the division by the quantity in (A-17) and the substitution of \( C_L \) into the second and fourth terms results in equation 17 of the main text.
Appendix B

FINITE DIFFERENCE EQUATIONS

This Appendix provides the detailed derivations of the finite difference equivalents of the momentum and energy conservation equations, (16) and (17) respectively. For convenience the following definitions are introduced:

\[
Q = \left[ \frac{k^*}{\rho_o} + \frac{E \rho^* C_p^*}{P_{rt}} \right] \frac{\rho^* u}{2 \psi^*}
\]

and

\[
S = \left[ \frac{\mu^* + E \rho^*}{2 \psi^*} \right] \rho^* u
\]

These definitions and the assumption that \( C_p^* = 1.0 \) permit the momentum and energy equations to be expressed as

\[
u \frac{\partial u}{\partial x} = -\frac{1}{2 \rho^*} \frac{dP}{dx} + \frac{u}{2 \psi^*} \frac{\partial}{\partial \psi^*} \left[ S \frac{\partial}{\partial \psi^*} \right]
\]

(B-1)

\[
u \frac{\partial \theta}{\partial x} = \frac{C_L}{2 \rho^*} \frac{dP}{dx} + \frac{C_L u S}{2 \psi^*} \left[ \frac{\partial u}{\partial \psi^*} \right]^2 + \frac{u}{2 \psi^*} \frac{\partial}{\partial \psi^*} \left[ Q \frac{\partial}{\partial \psi^*} \right]
\]

(B-2)

Before approximating these equations with finite difference relations a system of grid lines parallel to the \( X \) and \( \psi^* \) axes must be introduced. As illustrated in figure B-1, a nodal point coincides with each intersection of these lines. Lines parallel to the \( \psi^* \) axis are termed m-lines and those parallel to \( X \) axis n-lines. Each node is given a double subscript, the first being the number of the m-line passing through it, and the second the n-line number.

![Figure B-1 Definition of Grid Lines for Finite Difference Solution](image-url)
The values of the variables on the \( m=1 \) line are the known initial conditions. The conservation equations express for each node on the \( m=2 \) line its inter-relation with other nodes on the \( m=2 \) line and nodes on the \( m=1 \) line. If \( m=2 \) line nodes are only related to nodes which lie on the \( m=1 \) line, the finite difference scheme is termed explicit. If an \( m=2 \) node is also related to a number of other \( m=2 \) nodes, the scheme is termed implicit (See figure B-2).

![Figure B-2](image)

Diagrams of Explicit and Implicit Solutions

The implicit form of finite difference schemes leads to a series of \( N \) simultaneous algebraic equations relating the known initial conditions on the \( m=1 \) line and the unknown variables on each of the \( N \) nodes on the \( m=2 \) line. After solution of these simultaneous equations, the variables on the \( m=3 \) line are expressed in terms of the known values on the \( m=2 \) line. Proceeding in this manner, a solution to the complete flow field is marched out. Although simpler to program, the explicit scheme shows unstable characteristics if the \( m \)-lines are widely spaced relative to the \( n \)-line spacing. Implicit schemes show much more stable characteristics and therefore allow much larger \( m \)-line spacings, thus reducing computation times. The computer procedure presented in this report employs a system of implicit finite difference approximations which are defined using the notation described in figure B-3.
The velocity at nodes \( n+1 \) and \( n-1 \) can be expressed in terms of a Taylor series expanded about node \( n \), on the same \( m \)-line, 

\[
\begin{align*}
\frac{u_{n+1} - u_n}{\Delta x} &= \Delta \psi_1 \frac{\partial}{\partial \psi^*} + \frac{1}{2} \left( \frac{\partial \psi}{\partial \psi^*} \right)^2 + \frac{1}{2} \frac{\partial^2 u}{\partial \psi^2} + \frac{1}{2} \frac{\partial^2 u}{\partial \psi^2} + \text{higher order terms} \\
\frac{u_{n-1} - u_n}{\Delta x} &= -\Delta \psi_2 \frac{\partial}{\partial \psi^*} + \frac{1}{2} \left( \frac{\partial \psi}{\partial \psi^*} \right)^2 + \frac{1}{2} \frac{\partial^2 u}{\partial \psi^2} + \frac{1}{2} \frac{\partial^2 u}{\partial \psi^2} + \text{higher order terms}
\end{align*}
\]

Combining these equations to eliminate \( \frac{\partial^2 u}{\partial \psi^2} \) yields,

\[
\frac{(\Delta \psi_2)^2}{2} u_{n+1} - \frac{(\Delta \psi_1)^2}{2} u_{n-1} = \frac{u_n}{2} \left( \Delta \psi_2^2 - \Delta \psi_1^2 \right) + \left( \frac{\partial}{\partial \psi^*} \right) \left[ \frac{1}{2} (\Delta \psi_1 \Delta \psi_2 + \Delta \psi_2 \Delta \psi_1) \right] + \text{higher order terms}
\]
Neglecting terms of the order \((\Delta \psi)^3\) and higher, yields

\[
\frac{\partial u}{\partial \psi^*} \bigg|_n = \frac{\left(\frac{\Delta \psi_2}{\Delta \psi_1}\right) u_{n+1} - \left(\frac{\Delta \psi_1}{\Delta \psi_2}\right) u_{n-1} - \left(\frac{\Delta \psi_2}{\Delta \psi_1} - \frac{\Delta \psi_1}{\Delta \psi_2}\right) u_n}{\Delta \psi_2 + \Delta \psi_1}
\]

Defining

\[R_1 = \frac{\Delta \psi_1}{\Delta \psi_2 (\Delta \psi_2 + \Delta \psi_1)}\]

and

\[R_2 = \frac{\Delta \psi_2}{\Delta \psi_1 (\Delta \psi_2 + \Delta \psi_1)}\]

yields,

\[
\frac{\partial u}{\partial \psi^*} \bigg|_n = R_2 (u_{n+1} - u_n) + R_1 (u_n - u_{n-1}) \quad (B-5)
\]

Similarly

\[
\frac{\partial \theta}{\partial \psi^*} \bigg|_n = R_2 (\theta_{n+1} - \theta_n) + R_1 (\theta_n - \theta_{n-1}) \quad (B-6)
\]

The second derivative term in the momentum equation is approximated using the following Taylor series expansions,
\[ \left( \frac{s_{u}}{\psi} \right)_{n+\frac{1}{2}} = \left( \frac{s_{u}}{\psi} \right)_{n} + \frac{\Delta\psi}{2} \frac{\partial}{\partial \psi} \left[ \left( \frac{s_{u}}{\psi} \right)_{n} \right] + \frac{\Delta\psi^2}{4} \frac{\partial^2}{\partial \psi^2} \left[ \left( \frac{s_{u}}{\psi} \right)_{n} \right] \]

+ higher order terms \hspace{1cm} \text{(B-7)}

\[ \left( \frac{s_{u}}{\psi} \right)_{n-\frac{1}{2}} = \left( \frac{s_{u}}{\psi} \right)_{n} - \frac{\Delta\psi}{2} \frac{\partial}{\partial \psi} \left[ \left( \frac{s_{u}}{\psi} \right)_{n} \right] \]

+ \frac{\Delta\psi^2}{4} \frac{\partial^2}{\partial \psi^2} \left[ \left( \frac{s_{u}}{\psi} \right)_{n} \right] + \text{higher order terms} \hspace{1cm} \text{(B-8)}

Neglecting terms of the order of \( \frac{\Delta\psi^2}{4} \) and higher yields,

\[ \frac{\partial}{\partial \psi} \left( \frac{s_{u}}{\psi} \right)_{n} = \left\{ \left( \frac{s_{u}}{\psi} \right)_{n+\frac{1}{2}} - \left( \frac{s_{u}}{\psi} \right)_{n-\frac{1}{2}} \right\} \left\{ \frac{2}{\Delta\psi_1 + \Delta\psi_2} \right\} \]

\[ = \frac{1}{\Delta\psi_1 + \Delta\psi_2} \left[ \frac{(S_{n+1} + S_n)(u_{n+1} - u_n)}{\Delta\psi_1} - \frac{(S_n + S_{n-1})(u_n - u_{n-1})}{\Delta\psi_2} \right] \hspace{1cm} \text{(B-9)} \]
Similarly,

\[
\frac{\partial}{\partial \psi} \left[ \frac{Q \partial \theta}{\partial \psi} \right]_n = \frac{1}{\Delta \psi_1 + \Delta \psi_2} \left[ \frac{(Q_{n+1} + Q_n) (\theta_{n+1} - \theta_n)}{\Delta \psi_1} \right] + \frac{(Q_n + Q_{n-1}) (\theta_n - \theta_{n-1})}{\Delta \psi_2} \right]
\]

(B-10)

The velocity at a node located at the intersection of the downstream m-line and any n-line \( u_{2,n} \) can be expressed in terms of the following Taylor series,

\[
u_{2,n} = u_{1,n} + \frac{\partial u}{\partial X} \bigg|_n \Delta X + \frac{\partial^2 u}{\partial X^2} \bigg|_n (\Delta X)^2 + \text{higher order terms}
\]

(B-11)

Use of the boundary layer equations implies that gradients in the X-direction are much smaller than those in the \( \psi^* \)-direction. Therefore it is permissible to use a simpler approximation of the X-direction derivatives.

Neglecting terms of \((\Delta X)^2\) and higher yields,

\[
\frac{\partial u}{\partial X} \bigg|_n = \frac{u_{2,n} - u_{1,n}}{\Delta X}
\]

(B-12)

This approximation is termed "backward-difference".

Similarly,

\[
\frac{\partial \theta}{\partial X} \bigg|_n = \frac{\theta_{2,n} - \theta_{1,n}}{\Delta X}
\]

(B-13)
The only terms in the energy and momentum equations which cannot be approximated using the preceding equations are those containing the pressure gradient \( \frac{dP}{dx} \).
Assuming this gradient varies linearly throughout the \( \Delta X \) interval yields,

\[
\frac{dP}{dx} = \frac{1}{2} \left( \frac{dP}{dx} \bigg|_{m=1} + \frac{dP}{dx} \bigg|_{m=2} \right)
\]  

(Momentum Equation)

Combining equations (B-1), (B-9), (B-12) and (B-14) yields

\[
u_{1,n} \left( \frac{u_{2,n} - u_{1,n}}{\Delta X} \right) = -\frac{1}{4\rho^*_1,n} \left[ \frac{dP}{dx} \bigg|_{m=1} + \frac{dP}{dx} \bigg|_{m=2} \right] + \frac{u_{1,n}}{2\psi^*_n} \left( \frac{1}{\Delta \psi_1 + \Delta \psi_2} \right) \left[ \frac{(S_{n+1} + S_n)(u_{2,n+1} - u_{2,n})}{\Delta \psi_1} - \frac{(S_n + S_{n-1})(u_{2,n} - u_{2,n-1})}{\Delta \psi_2} \right]
\]  

This equation can be expressed in the form

\[A_{n-1} u_{2,n} + B_{n-1} u_{2,n+1} + C_{n-1} u_{2,n-1} = D_{n-1}\]  

in which the coefficients are defined by equations 27 through 34 of the main text.

(Energy Equation)

Combining equations (B-2), (B-5), (B-10), (B-13) and (B-14) yields

\[
u_{1,n} \left( \frac{\theta_{2,n} - \theta_{1,n}}{\Delta X} \right) = \frac{C_L}{2\psi^*_n} \left[ R_2 \left( u_{2,n+1} - u_{2,n} \right) + R_1 \left( u_{2,n} - u_{2,n-1} \right) \right] - \frac{u_{1,n}}{2\psi^*_n} \left[ \frac{1}{\Delta \psi_1} \frac{(Q_{n+1} + Q_n)(\theta_{2,n+1} - \theta_{2,n})}{\Delta \psi_1} \right] - \frac{(Q_n + Q_{n-1})(\theta_{2,n} - \theta_{2,n-1})}{\Delta \psi_2} + \left( \frac{C_L}{4\rho^*_1,n} \right) \left[ \frac{dP}{dx} \bigg|_{m=1} + \frac{dP}{dx} \bigg|_{m=2} \right]
\]  

(B-17)
This equation can be expressed in the form

\[ A_{n-1} \cdot \theta_{2,n} + B_{n-1} \cdot \theta_{2,n+1} + C_{n-1} \cdot \theta_{2,n-1} = D_{n-1} \]  \hspace{1cm} (B-18)

in which the coefficients are defined by equations 37 through 45 of the main text.
Appendix C

Solution Procedure

The calculation procedure starts at the upstream flow boundary, where the values of all flow variables must be known or assumed. Specification of the velocity and temperature distribution, dimensionless eddy viscosity, duct and nozzle inlet dimensions, and working fluid, defines all initial conditions.

The known initial conditions, m=1 line, are related to the unknown conditions, m=2 line, by the previously derived equations, and assumed boundary conditions. These inter-relations form a set of N-2 simultaneous algebraic equations, where N is the number of n-lines, and the equations are shown in Appendix B. The resultant matrix of coefficients is tridiagonal in form except for the initial and final rows which only contain two terms. Rapid, exact solutions to this type of matrix are obtained using the Thomas Algorithm, a successive elimination technique, which is described in this Appendix.

The solution for the variables on the m=2 line is iterative, because of the presence of the unknown pressure in the momentum equation. The procedure adopted was to estimate the pressure gradient, and solve the equations, using the algorithm. The equations automatically satisfy conservation of mass, momentum, and energy, but only one pressure gradient yields the correct wall geometry. The duct dimension corresponding to the estimated pressure gradient was calculated from the m=2 line variables. The pressure gradient was then incremented by a small percentage of its initial estimated value, and the calculation process repeated for a new duct dimension. A third estimate of the pressure gradient was obtained by interpolation between the two calculated, and the actual duct dimension. In almost all the calculations performed to date, this value has been acceptably close, within 0.001%, to the actual duct dimension. If this criterion is not met, a further iteration is applied, and a fourth solution obtained.

The now known variables on the m=2 line become the new m=1 line variables and the procedure is repeated for another set of m=2 line variables. Thus a solution to the complete flow field is marched out.
The difference form of the momentum and energy equation is:

\[ A_{n-1} X_n + B_{n-1} X_{n+1} + C_{n-1} X_{n-1} = D_{n-1} \]  

where \( X \) is either \( u \) or \( \theta \). If the number of \( n \)-lines is \( N \), there are \( N-2 \) equations of the form (1) and two equations expressing the boundary conditions. The first and the last equations represent the boundary conditions, which in difference form along the axis of symmetry are:

\[ \frac{\partial u}{\partial \psi^*} = 0 \text{ or } u_{2,2} = u_{2,1} \]  

\( \text{(C-2)} \)

and

\[ \frac{\partial \theta}{\partial \psi^*} = 0 \text{ or } \theta_{2,2} = \theta_{2,1} \]  

\( \text{(C-3)} \)

Equations (C-2) and (C-3) can be written in terms of \( X \) as follows:

\[ X_1 = X_2 \]  

\( \text{(C-4)} \)

At the duct wall the boundary conditions are

\[ u_N = 0 \]  

\( \text{(C-5)} \)
\[ \theta_{2,N} = \theta_{2,N-1} \]  
\[ \text{(C-6)} \]

Equations (C-5) and (C-6) can be written in terms of \( X \) as follows:

\[ X_N = K X_{N-1} \]  
\[ \text{(C-7)} \]

where \( K \) is 0 for the momentum equation and unity for the energy equation. Thus, the matrix form of the equation (C-1) is shown on the following page (Table C-1).

The second equation is

\[ C_1X_1 + A_1X_2 + B_1X_3 = D_1 \]  
\[ \text{(C-9)} \]

Substituting equation (C-4) into this equation yields:

\[ A'_1X_2 + B_1X_3 = D_1 \]  
\[ \text{(C-10)} \]

where \( A'_1 = C_1 + A_1 \)

The \( N^{th} \) equation is

\[ C_{n-2}X_{n-2} + A_{n-2}X_{n-1} + B_{n-2}X_N = D_{n-2} \]  
\[ \text{(C-11)} \]

Substituting equation (C-7) into this equation yields:

\[ C_{N-2}X_{N-2} + A'_{N-2}X_{N-1} = D_{N-2} \]  
\[ \text{(C-12)} \]

where \( A'_{N-2} = A_{N-2} + K \cdot B_{N-2} \)

Thus the \( N \) equations (C-8) can be reduced to the \( N-2 \) equations shown on Table C-2.
Matrix Form of Equation C-1 Designated As Equation C-8

\[
\begin{bmatrix}
0 & D_1 & D_2 & D_3 & \ldots & D_{n-1} & D_n & 0 \\
X_1 & X_2 & X_3 & X_4 & \ldots & X_{n-1} & X_n & X_{n+1} & \ldots & X_N
\end{bmatrix}
= \begin{bmatrix}
1 & A_1 & A_2 & A_3 & \ldots & A_{n-1} & A_n & 0 & 0 & \ldots & 0 & \ldots & 0 & -k & 1 \\
C_1 & C_2 & C_3 & C_4 & \ldots & C_{n-1} & C_n & 0 & 0 & \ldots & 0 & \ldots & 0 & 0 & 0
\end{bmatrix}
\]
Table C-2
Matrix Form of Equation C-8 with Simplified Terms Designated as Equation C-13

\[
\begin{bmatrix}
A_1' & B_1 & 0 & 0 & - & 0 & 0 & 0 & - & 0 & 0 & 0 \\
C_2 & A_2 & B_2 & 0 & - & 0 & 0 & 0 & - & 0 & 0 & 0 \\
0 & C_3 & A_3 & B_3 & - & 0 & 0 & 0 & - & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & - & C_{n-1} & A_{n-1} & B_{n-1} & - & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & - & 0 & 0 & 0 & - & C_{N-3} & A_{N-3} & B_{N-3} \\
0 & 0 & 0 & 0 & - & 0 & 0 & 0 & - & 0 & C_{N-2} & A_{N-2} \\
\end{bmatrix}
= \begin{bmatrix}
x_2 \\
x_3 \\
x_4 \\
x_{n-1} \\
x_n \\
x_{n+1} \\
x_{N-2} \\
x_{N-1} \\
\end{bmatrix} = \begin{bmatrix}
D_1 \\
D_2 \\
D_3 \\
D_{n-2} \\
D_{n-1} \\
D_n \\
D_{N-3} \\
D_{N-2} \\
\end{bmatrix}
\]
The Thomas Algorithm

Starting with the first equation, \(X_2\) can be expressed in terms of \(X_3\). The second equation gives \(X_3\) in terms of \(X_4\). Continuing through all the equations until the \(N^{th}\) - 3 equation gives \(X_{N-2}\) in terms of \(X_{N-1}\). Combining this with the last equation gives \(X_{N-1}\). Working backwards through the equations then allows the remaining unknowns to be found. This procedure is most easily applied by defining the following:

\[
W_1 = A_1
\]
\[
g_1 = \frac{D_1}{W_1}
\]
\[
Q_{n-1} = \frac{B_{n-1}}{W_{n-1}} \quad n = 2, 3, \ldots (N-2) \quad (C-14)
\]
\[
W_n = A_n - C_n Q_{n-1} \quad n = 2, 3, \ldots (N-2)
\]
\[
g_n = D_n - \frac{C_n g_{n-1}}{W_n} \quad n = 2, 3, \ldots (N-2)
\]

Equations (C-13) then reduce to:

\[
X_{N-1} = g_{N-2} \quad \text{and} \quad X_n = g_{n-1} - Q_{n-1} \quad X_{n+1} \quad n = (N-2), (N-3), \ldots 2 \quad (C-15)
\]

If the values of \(W\), \(Q\) and \(g\) are calculated in order of increasing \(n\) using equations (C-14), then equations (C-15) can be used to calculate the values of \(X\) in order of decreasing \(X\) starting with \(X_{N-1}^\text{-.}\) To clarify this procedure, the method is now used to solve the following four simultaneous equations:
\[
\begin{bmatrix}
A' & B_1 & 0 & 0 \\
C_2 & A_2 & B_2 & 0 \\
0 & C_3 & A_3 & B_3 \\
0 & 0 & C_4 & A_4'
\end{bmatrix}
\begin{bmatrix}
X_2 \\
X_3 \\
X_4 \\
X_5
\end{bmatrix}
= 
\begin{bmatrix}
D_1 \\
D_2 \\
D_3 \\
D_4
\end{bmatrix}
\]

\[A_1 X_2 + B_1 X_3 = D_1\]

\[W_1 = A_1\]

\[Q_1 = \frac{B_1}{W_1}\]

\[g_1 = \frac{D_1}{W_1}\]

hence \[X_2 = g_1 - Q_1 X_3\]

\[A_2 X_3 + B_2 X_4 + C_2 X_2 = D_2\]

\[W_2 = A_2 - C_2 Q_1\]

\[Q_2 = \frac{B_2}{W_2}\]

\[g_2 = \frac{D_2 - C_2 g_1}{W_1}\]

hence \[X_3 = g_2 - X_4 Q_2\] \hspace{1cm} (C-16)
\[ A_3 \, x_4 + B_3 \, x_5 + C_3 \, x_3 = D_3 \]

\[ w_2 = A_3 - C_3 \, q_2 \]

\[ q_3 = \frac{B_3}{w_3} \]

\[ g_3 = \frac{D_3 - C_3 \, q_2}{w_3} \]

hence \( x_4 = g_3 - q_3 \, x_5 \) \hspace{1cm} (C-17)

\[ A_4 \, x_5 + C_4 \, x_4 = D_4 \]

\[ w_4 = A_4 - C_4 \, q_3 \]

\[ g_4 = \frac{D_4 - C_4 \, g_3}{w_4} \]

hence \( x_5 = g_4 \) \hspace{1cm} (C-18)

Substituting in equation (C-16) yields \( x_3 \). Equations (C-17) and (C-18) are special forms of equations (C-15) for \( N=6 \) and \( n=4 \).
Appendix D

COMPUTER PROGRAM

The computational procedure consists of a main program, which is divided into ten sections, and six subroutines. The program Flow Chart is shown on Figure D-1. The functions of each section of the main program are as follows:

Section (1): Input and Initialization

(a) Constants which have single, initial value for most applications are defined with data statements.

(b) The parameters which specify the test conditions are inputted from data cards.

(c) Dimensional parts of the data are non-dimensionalized.

Section (2): Initial Profiles Generated

(a) The initial u, \( \theta \), \( \mu^* \), \( \rho^* \), E, Y, and \( \psi^* \) distributions are calculated.

(b) The shear layer and wall boundary layer thickness are calculated using a search technique applied to the \( m = 1 \) line velocity profile.

Section (3): Turbulence Model

(a) The dimensionless eddy viscosity, which will subsequently be used in calculating the variables on the \( m = 2 \) line, is calculated from \( m = 1 \) velocity profile and one of the turbulence models detailed in the main text.

Section (4): Choice of X-Step

(a) The distance between the \( m = 1 \) and \( m = 2 \) lines is chosen. Initially, this distance is related to the shear layer width but after this layer impinges on the wall boundary layer, it becomes a constant fraction of the duct radius or width.
Figure D-1

Computer Program Flow Chart
FLOW CHART - INNER LOOP

FROM MAIN PROGRAM

SPECIFY THE BOUNDARY CONDITIONS

ITER=1; ICIX=0

EVALUATES THE COEFFICIENTS IN THE MOMENTUM EQUATION, i.e. A's, B's, C's & D's

CALL CALC

EVALUATES THE COEFFICIENTS IN THE ENERGY EQUATION

CALL CALC

CALL CALC

CALL YD1S

YES

ITER>9

NO

ITER = ITER+1

YES

DOES PRESSURE GRADIENT YIELD AN ACCEPTABLE YOUT

IS ICIX=0

YES

INCREMENT ΔP

ICIX=2

NO

CALCULATE NEW ΔP

NO

P = P+ΔP

TO MAIN PROGRAMME

Figure D-1 (continued)
Section (5): Calculation of Velocity on \( m = 2 \) Line

(a) The duct radius or width at the \( m = 2 \) line, is interpolated from the input data.

(b) Initially, the \( m = 2 \) line pressure gradient is set equal to the average of the pressure gradients at the previous two \( m \) lines.

(c) The distribution of velocity on the \( m = 2 \) line is calculated.

Section (6): Calculation of Temperature on \( m = 2 \) Line

(a) The distribution of temperature on the \( m = 2 \) line, is calculated, and from it the distributions of density and molecular viscosity.

Section (7): Pressure Gradient Modification

(a) The position of the \( n \)th node, in the \( y \)-plane, is calculated from the \( m = 2 \) line profiles. If this value is acceptably close to the duct wall, the pressure is incremented by \( dp \).

(b) Alternatively if this requirement is not satisfied, then an improved estimate of the pressure gradient is made.

(c) Using this estimate, section 5(c) and section (6) are repeated.

Section (8): Transference

(a) The values of \( u \) and \( \theta \) calculated on the \( m = 2 \) line are transferred to the storage space previously used for conditions on the \( m = 1 \) line, in preparation for the advance to the next \( m \)-line.

Section (9): Output

(a) The velocity and temperature profiles are printed out at defined intervals, and several flow variables are printed at every step.
Section (10): Termination Test

(a) If the maximum x-value has not been reached, execution is returned to Section (3), in order to advance to the next m-line. The functions of each sub-routine are as follows:

CALC: This evaluates \( u \) and \( \theta \) using the Thomas algorithm.

RADIUS: The duct shape is inputed to the calculation procedure, through this routine. It interpolates this data and calculates the local duct radius at every m-line.

TEMP: If the dimensionless temperature variation is a known boundary condition, it is specified in the routine. This routine is redundant with the present boundary conditions.

YDIS: The position of the grid nodes in the y-plane is calculated with this routine.

PSI: The position of the grid nodes in the \( \psi \)-plane is assigned in this routine. The initial flow conditions determine the form of this routine, i.e. single stream flow, two-stream and mass ratio.

LOOK: The shear layer and boundary layer width are calculated using a search technique applied to the \( m = 1 \) line velocity profile.

CHECK: This routine checks the conservation of mass and energy.

MCHECK: This routine checks the conservation of momentum between adjacent m-lines.

PROF: Calculates the initial velocity and temperature profiles.
<table>
<thead>
<tr>
<th>FORTRAN SYMBOLS</th>
<th>MEANING</th>
</tr>
</thead>
<tbody>
<tr>
<td>A(I)</td>
<td>$A_{n-1}$</td>
</tr>
<tr>
<td>B(I)</td>
<td>$B_{n-1}$</td>
</tr>
<tr>
<td>BB</td>
<td>Minimum value of step size $\Delta X$</td>
</tr>
<tr>
<td>BE</td>
<td>Dimensionless jet shear layer inner edge</td>
</tr>
<tr>
<td>BH</td>
<td>Dimensionless jet shear layer width,</td>
</tr>
<tr>
<td>BY</td>
<td>Dimensionless jet shear layer outer</td>
</tr>
<tr>
<td></td>
<td>edge</td>
</tr>
<tr>
<td>CC</td>
<td>$\kappa$</td>
</tr>
<tr>
<td>C(I)</td>
<td>$C_{n-1}$</td>
</tr>
<tr>
<td>D(I)</td>
<td>$D_{n-1}$</td>
</tr>
<tr>
<td>DELTA</td>
<td>$\Delta$</td>
</tr>
<tr>
<td>DP1</td>
<td>$\frac{dP}{dX}$ at $m = 1$ line</td>
</tr>
<tr>
<td>DP2</td>
<td>$\frac{dP}{dX}$ at $m = 2$ line</td>
</tr>
<tr>
<td>DP11</td>
<td>$\frac{dP}{dX}$ at $m = 0$ line</td>
</tr>
<tr>
<td>DX</td>
<td>$\Delta X$</td>
</tr>
<tr>
<td>E(I)</td>
<td>$E$</td>
</tr>
<tr>
<td>ENERG</td>
<td>$\sum_{i=1}^{N} \theta u \rho \Delta Y$</td>
</tr>
<tr>
<td>FDUCT</td>
<td>Mass flow in duct</td>
</tr>
<tr>
<td>FPRIM</td>
<td>Mass flow in nozzle</td>
</tr>
<tr>
<td>GAMMA</td>
<td>$\gamma$</td>
</tr>
<tr>
<td>IFLOW</td>
<td>Control variable (zero upstream of point</td>
</tr>
<tr>
<td></td>
<td>where wall boundary layer and shear layer</td>
</tr>
<tr>
<td></td>
<td>meet, otherwise one)</td>
</tr>
<tr>
<td>ITER</td>
<td>Iteration counter for inner loop</td>
</tr>
<tr>
<td>JFLOW</td>
<td>Control variable with the value one for single-</td>
</tr>
<tr>
<td></td>
<td>stream flow and two for two-stream flow</td>
</tr>
<tr>
<td>SYMBOLS</td>
<td>MEANING</td>
</tr>
<tr>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>LVH</td>
<td>Dimensional local velocity head, $\bar{v}u^2/2g_o$</td>
</tr>
<tr>
<td>LZ</td>
<td>$L_m$</td>
</tr>
<tr>
<td>N</td>
<td>Total number of node points on each $m$-line</td>
</tr>
<tr>
<td>NL, NP, NPP, SQP</td>
<td>Control variables for axisymmetric flow $NL=1$, $NP=2$, $NPP=0$ and $SQP=0.5$; and for plane flow $NL=0$, $NP=0$, $NPP=1$ and $SQP=1$</td>
</tr>
<tr>
<td>NJ</td>
<td>Number of node points in jet</td>
</tr>
<tr>
<td>NSTEP</td>
<td>Number of downstream steps</td>
</tr>
<tr>
<td>NTEST</td>
<td>Test number</td>
</tr>
<tr>
<td>PAMB</td>
<td>Ambient pressure</td>
</tr>
<tr>
<td>PCUM</td>
<td>Local dimensionless pressure</td>
</tr>
<tr>
<td>PE</td>
<td>Pressure at nozzle exit plane</td>
</tr>
<tr>
<td>PH2O</td>
<td>Local dimensional pressure</td>
</tr>
<tr>
<td>PS(I)</td>
<td>$\psi_n$</td>
</tr>
<tr>
<td>PR</td>
<td>$p_r$</td>
</tr>
<tr>
<td>PRT</td>
<td>$p_{rt}$</td>
</tr>
<tr>
<td>PSN</td>
<td>Total $\psi^*$ in the duct</td>
</tr>
<tr>
<td>PSNJ</td>
<td>Total $\psi^*$ in the jet</td>
</tr>
<tr>
<td>RHO(m, I)</td>
<td>$\rho^*$ in the jet</td>
</tr>
<tr>
<td>RM</td>
<td>$M_{lr}$</td>
</tr>
<tr>
<td>RNU</td>
<td>$\mu_o$</td>
</tr>
<tr>
<td>ROREF</td>
<td>$\rho_o$</td>
</tr>
<tr>
<td>RR(I)</td>
<td>Duct width or diameter</td>
</tr>
<tr>
<td>T(m, I)</td>
<td>$\theta$</td>
</tr>
<tr>
<td>TCLI</td>
<td>$T_j$</td>
</tr>
<tr>
<td>TFLOW</td>
<td>Total mass, flow rate, $\sum_{i=1}^{N} \rho^* u \Delta Y$</td>
</tr>
</tbody>
</table>
TREF
TSEC
TTP(J)
TTT(J)
TWREF
U(m, I)
UCLI
UPOT
URR
USE
UUU(I)
VHEAD
VIS(I)
X
XX
XX(I)
XRO
Y(I)
YJ
YS

\[ T_o \]

Temperature of secondary flow at nozzle exit plane

\[ \bar{T} \]

Dimensional stagnation temperature at each node,

\[ \bar{T} + \frac{-\rho u^2}{2g_o} \]

\[ T_{wr} \]

Secondary velocity at nozzle exit

\[ u \]

Reference velocity head, \( \rho_o u_o^2 / 2g_o \)

\[ \mu^* \]

Distance from duct inlet at which calculation ends

Distance from duct inlet at which duct width, \( RR(I) \) are provided

Non-dimensional downstream distance with respect to the initial duct half width or radius

Half nozzle width or radius at nozzle exit

\( y^+ \)
### Definition of the Input and Output Parameters

#### Part (a) Input data

The input data to the program must be prepared according to the following sequence:

<table>
<thead>
<tr>
<th>Card No.</th>
<th>Parameters</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SQP, NP, NPP, NL</td>
<td>F5.0, 3I5</td>
</tr>
<tr>
<td>2</td>
<td>DP1, DP2, DP11</td>
<td>3E13.6</td>
</tr>
<tr>
<td>3</td>
<td>X, xx</td>
<td>8F10.0</td>
</tr>
<tr>
<td>4</td>
<td>MK</td>
<td>I5</td>
</tr>
<tr>
<td>5</td>
<td>{PROFE(I), I = 1, MK}</td>
<td>8F10.0</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>NTEST</td>
<td>I5</td>
</tr>
<tr>
<td>8</td>
<td>PO1, TO1, PAMB, TOO, AMASS1, AMASS0, RD, YJ</td>
<td>8F10.0</td>
</tr>
<tr>
<td>9</td>
<td>{(PS(I), I = 53, 70)}</td>
<td>6E13.6</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>NS</td>
<td>I2</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>{(RR(I), I = 1, NS)}</td>
<td>8F10.0</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>{(XX(I), I = 1, NS)}</td>
<td>8F10.0</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>SQP, NP, NPP, NL</td>
<td>F5.0, 3I5</td>
</tr>
</tbody>
</table>

Card 19 is the last card to end the calculation of the Program, on which NPP must be set a value larger than 1.

Cards 1 through 18 are required for each set of data. For data more than one set, cards 1 through 18 must be repeated in the same sequence.
An example of input data for two sets of data are shown on Table A-1. The input parameters are:

**SQP, NP, NPP, NL**  
Control Card for axisymmetric flow  
SQP = 0.5, NP = 2, NPP = 0, NL = 1, for plane flow  
SQP = 1.0, NP = 0, NPP = 1, NL = 0.

**DPI, DP2, DPII**  
Initial guessed dimensionless pressure gradients on m=1, 2 and zero lines respectively. The initial guesses of the values of DPI, DP2, DPII at the initial plane may be assumed equal at any plus or minus dimensionless value of the order of $10^{-7}$ to $10^{-8}$.

**X**  
Distance from duct inlet to nozzle exit plane at which calculation begins, inches.

**XX**  
Distance from duct inlet at which calculation stops

**MK**  
A number which indicates the number of velocity and temperature detail being printed out.

**PROFE(I)**  
An array contains MK value of downstream positions in inches where the velocity and temperature detail are required to be printed out.

**NTEST**  
Test or Run number identity

**POI**  
Stagnation pressure of the primary flow, psia

**TOI**  
Stagnation temperature of the primary flow, °R

**PAMB**  
Ambient pressure (i.e., stagnation pressure of the secondary flow), psia

**TOO**  
Stagnation temperature of the secondary flow, °R

**AMASS1**  
Primary mass flow rate.

**AMASS0**  
Secondary Mass flow rate.  
For axisymmetric flow, lbm/sec.  
For plane flow, lbm/sec-in.

**RD**  
Half duct width at nozzle discharge plane, inches

**YJ**  
Full jet width, inches, (Outside dimension of nozzle exit)
<table>
<thead>
<tr>
<th>Card No.</th>
<th>1</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.100000E-03</td>
<td>-0.100000E-03</td>
<td>-0.100000E-03</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>23.5</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0.99</td>
<td>1.98</td>
<td>2.98</td>
</tr>
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<td>0.081500E08</td>
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<td>0.967500E08</td>
<td>0.968500E08</td>
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<td>0.995500E08</td>
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**Table D-1**

Input Data Example for Runs 3 and 6
To take care of the boundary layer problem, the last 18 values to the wall are required to be specified in the SUBROUTINE PSI. SUBROUTINE PS(I) already includes the values needed for the computer calculation. The computer values were selected to satisfy the following:

1. grid spacing of the wall should not correspond to a value of $y^+$ greater than 3.
2. neighboring grid spacings should not differ in size by more than 50%.
3. close spacing is also required in any region away from the wall where the velocity gradient is large.

Indicates the total number of duct geometry to be read in the SUBROUTINE RADIUS

An array contains the total number (NS) of duct width, inches

An array contains the total number (NS) of axial downstream distance, where RR(I) are provided, inches

The first section of the output repeats the most important input data for different test or run number.

**Velocity ratio** = \( \frac{\text{initial velocity of secondary flow}}{\text{initial velocity of primary flow}} \)

**Width ratio** = \( \frac{\text{initial duct width}}{\text{nozzle width}} \)

**Mass flow ratio** = \( \frac{\text{secondary mass flow}}{\text{primary mass flow}} \)

**J** - Indicates node point counting from centerline to wall

**Y(J)** - Dimensionless Y coordinate with respect to the local half duct width.

**U(J)** - Dimensional velocity on Jth node, ft/sec
TO(J) - Dimensional stagnation temperature on Jth node, °F

I - Print step counter at approximately XIN increases 0.25 inches

XIN - downstream distance from nozzle exit plane where calculation begins, inches

X/BO - ratio of downstream distance with respect to initial half duct width.

B/BO - ratio of the local duct width with respect to initial duct width.

PH2O - Local wall static pressure, 9 inches of water

UCENT - velocity of the flow at centerline, ft/sec

TOCENT - centerline stagnation temperature of the flow, °F

AUGMENT - Local momentum flux, \( 2 \int_{0}^{y_{w}} \frac{\rho}{\rho} u^{2} dy \), divided by initial jet momentum

USTER - Local friction velocity, ft/sec

The selection of intervals at which calculations are made is determined by a subroutine in the computer program. The data is printed out at approximately quarter inch intervals. The locations where temperature and velocity profiles are printed out are specified by the user in PROFE(I) described in the input data.
PROGRAM LISTING

The program listing included in this report is for the program as run on a CDC/6600. The program was initially developed on an IBM 360/50. The deck is the one successfully run on the CDC/6600.

The essential changes to the program necessary to recover the IBM 360/50 deck are:

1. Certain variables should be in a real*8 mode

Add

Card
JMX40       REAL*8 Y, DABS, DLOG, YB1, YB2
YIS20       REAL*8 ZY, Y
CHE20       REAL*8 Y
BLC20       REAL*8 Y
LEF20       REAL*8 Y

Change

Functions ABS(), and ALOG(), should be changed to DABS(), and DLOG(). These occur in cards

JMX2710     JMX3750     JMX4450
JMX3030     JMX4340     JMX4460

Card YIS50 should be Y(1) = 0.0D0

Output Hollerith symbols should be changed from * to These occur in cards

JMX460     JMX660     JMX730     JMX2120     JMX5640
JMX470     JMX700     JMX740     JMX5190     JMX5650
JMX520     JMX710     JMX2090    JMX5200     JMX5660
JMX530     JMX720     JMX2110    JMX5590     JMX5670
GEM110     CHE330     BLC190
GEM120     CHE340     BLC200

Deck characters are BCD.
RUN VERSION 2.1 --PSK LEVEL 29A--

PROGRAM NAS(INPUT,OUTPUT,TAPES=INPUT,TAPE6=OUTPUT)

REAL A, Z, --PSR LEVEL
ZG --

COMMON NP, NP, NPP, NL
DI)'EHSION
I}(ZeTn )_TTT(?_)_ T(2_70 ),SI(70 )_S2(70 )_S3(70 ),
LPS(70 ),R2(70 ),EIt70 )_PI(70 )_ Y(70 ),E(70 )t
QH_(?t70)*VIS(Tr),TTR(?0}tAA(70)t
O(70)
I,A(70 ),R(70 )_C(70 )_H(70 )tRBB(70)
4
,TnLO(2),AUGM(?0)tPROFE(P_)_UJ(70)
TYRL(70)
FtX1,Y1)=(2,/_=4)*(|,**_Xt**_))*e3-YI*XI

SECTION 1

KJ IS A CONTROL VARIABLE, 1 FOR SINGLE STREAM FLOW WITH INITIAL WAJMX
RUNDINARY LAYER, 2 FOR SINGLE STREAM FLOW WITHOUT W,8,L, oR
TWO STRJHX
X =oISTANcE Fg_ THE DUct INLET TO NOZZLE EXIT INCHES
_/S_=
SECONOA_Y (FT/SEC)
XW=DISTANCE FROM THE
DUCT INLET AT wHICH
CALCULATIONS
TOP
(INCMJHX
R_t_=
REFERENCE
VISCOSITY
FT/SEC
PF_=_PRozzle EXIT PLANE PRESSURE LBF/FT2 GAUGE
FNICT=TOTAL MASS FLOW RATE (LBM/SEC )
P=PRANTL NUMBER
P= TURBILIENT PRANTL NUMBER
TW_EF =540.
CC=
BPR
= EFFECTIVE nozzzle EXIT RADIUS(INCHES)
UEF = JET VELOCITY AT NOZZLE EXIT FT/SEC
GAM=GEAS CONSTANT= 1,4 FOR AIR
CT CLI= JET TEMPFRATURE AT NOZZLE EXIT DEG#R
YJ= EFFECTIVE nozzzle EXIT RADIUS(INCHES)
TCLI =JET VELOCITY AT NOZZLE EXIT FT/SEC
NC=reference temperature (DEG#R)
PNFF=REFERENCE PRESSUq_ LRFIFT_ A
PP_=_LNM _PRESSURE LBF/FT_
CR=REFERENCE TEMPERATURE (DEG#R)
CR=REFERENCE RADIUS I_ INCHES
RUN VERSION 2.7 -PSR LEVEL 29A-

**NAS**

```
000N54 AHEAD(S,S7417) DP1,OP1,OP11
000N5A 7817 FORMAT(3E13.6) JMX 580
000N8A HFA1,S,S74) XX,XX JMX 590
00007A HFA(S,37) MX JMX 600
000N9A HFA(S,37) PROFE(1)=1,MK JMX 610
000117 HFA(S,37) NTEST JMX 620
00012E 37 FORMAT(15) JMX 630
000125 APIT6E(40) NTEST JMX 640
000131 90 FORMAT(15) INPUT DATA RUN NO. = 153/15
000137 HFA(S,37) PO1,TO1,PAMH,T00,AMASS1,AMASSO,RO,YJ JMX 660
000157 73 FORMAT(7F10.7) JMX 670
000203 -7 FNAME(15x,RO) = *FR,4* PSIA*/15x*TO1 = *FR,4* DEG A* JMX 690
1/15x*PSIA*115%%15x*TO1 = *FR,4* DEG A* JMX 700
7/15x*AMASS1 = *FR,4* LAM*/15x*/IN*15x*AMASS0 = *FR,4* LAMJMX 710
3/15x*/15x*RO(HALF NUC WT) = *FR,4* IN*,*/15x*YJ(FULL) JMX 720
4 JFT WT) = *FR,4* IN*,*/ JMX 730
000209 IF(INP =E 2) G0 TO 201
00020E A2 = 2.*RO =YJ JMX 740
000210 G0 TO 1201
000211 2001 AP = 3./1416/="*((2.*RO)**2-YJ)**2) JMX 750
000216 1D01 CONTINUE JMX 760
000216 1D01 CONTINUE JMX 770
00022A A2 = PAMH(AMASSO,PAMB)*SQRT(100*(53,3/1.4*32,2))**1.2**3 JMX 780
000230 Y1 = A2I4ST4G JMX 790
000231 X11 = 1.* JMX 800
000231 X22 = -03 JMX 810
000231 X22 = -03 JMX 820
000233 TOL = 0.0001 JMX 830
000234 TEST1=F(X11,Y1) JMX 840
000237 TEST2=F(X22+Y1) JMX 850
000241 77 HALF = (X11+X22)/2 JMX 860
000241 77 HALF = (X11+X22)/2 JMX 870
000247 CF(LF=CHFK1,LF,TL0) GO TO 23 JMX 880
000252 IF(ARS(=CHFK1)=ABS(ARS(=TEST1)) 19,23,19 JMX 890
000255 X22 = HALF JMX 900
000260 TEST2=CHK1 JMX 910
000261 G0 TO 22 JMX 920
000265 19 X11 = HALF JMX 930
000265 19 X11 = HALF JMX 940
000269 TEST1=CHK1 JMX 950
00026A G0 TO 22 JMX 960
00026A G0 TO 22 JMX 970
000269 X22 = HALF JMX 980
00026A X22 = HALF JMX 990
000274 P1 = PAMH((1.**2** RHO**2**)**3.5) JMX 1000
000274 P1 = PAMH((1.**2** RHO**2**)**3.5) JMX 1010
000295 PM = SQRT(P11-1.)**((GAMA-1.)/GAMA) JMX 1020
000295 PM = SQRT(P11-1.)**((GAMA-1.)/GAMA) JMX 1030
00029A TSEC = PO1/PA1 JMX 1040
000314 TSEC = PO1/PA1 JMX 1050
000314 TSEC = PO1/PA1 JMX 1060
00031A USEC = SQRT(1.+32.*+32,2+(-TSEC))/100 JMX 1070
00031A USEC = SQRT(1.+32.*+32,2+(-TSEC))/100 JMX 1080
00031A USEC = SQRT(1.+32.*+32,2+(-TSEC))/100 JMX 1090
00031A USEC = SQRT(1.+32.*+32,2+(-TSEC))/100 JMX 1100
00031A USEC = SQRT(1.+32.*+32,2+(-TSEC))/100 JMX 1110
00031A USEC = SQRT(1.+32.*+32,2+(-TSEC))/100 JMX 1120
```
RUN VERSION 2.3 --PSR LEVEL 29A--

JMM 1130
000456  NIN = N-1
JMM 1140
000457  PUFF = 2115
JMM 1150
000460  PT = 0
JMM 1160
000471  Trn (0) = 0
JMM 1170
000472  IFER = n
JMM 1180
000347  REN
JMM 1190
000344  ILE = 0
JMM 1200
000346  UPLNW = 2
JMM 1210
000467  TURFS = 0
JMM 1220
000370  BREV
JMM 1230
000371  RMP = 2
JMM 1240
000377  NSTEP = 0
JMM 1250
000373  IFLOW = 0
JMM 1260
000374  URR = 1
JMM 1270
000375  ICONF = 0
JMM 1280
000377  TOLD(2) = 0
JMM 1290
0000377  DFLTA = 0
JMM 1300
0000400  KJ = 2
JMM 1310

NAS

UJRN SECONDARY / U PRIMARY

JMM 1320
000401  DE:ICL/J(24*#RNU)
JMM 1330
000404  IF (NP > EQ. 21) GO TO 118
JMM 1340
000406  AMASS1 = AMASS1*12.
JMM 1350
000407  FFICT = AMASS1*12.*AMASS1
JMM 1360
000412  PSN = FFICT/(2.*RNU*RREF)
JMM 1370
000415  PSN = AMASS1/(2.*RNU*RREF)
JMM 1380
000417  DICT = PSN
JMM 1390
000420  GO TO 117
JMM 1400

JMM 1410
000421  117 CONTINUE

JMM 1420
000427  YNUT = RD2*REN
JMM 1425
000428  IC = AMASS1*AMASS1
JMM 1430
000429  PSN = FFICT/(6.284*#RNU*#RREF)
JMM 1435
000430  PSN = AMASS1/(6.284*#RNU*#RREF)
JMM 1440
000432  FICT = FFICT/(#RNU*#RREF)
JMM 1445
000433  FICT = FICT/(#RNU*#RREF)
JMM 1450

JMM 1455
000444  117 CONTINUE

JMM 1460
000445  C SPECIFY STREAM FUNCTION DISTRIBUTION

JMM 1465
000446  CALL PSI( N, PSN=NJ, PS=PSNJ)

JMM 1470
000447  C DO 9 J=2+NN

JMM 1475
000451  J=1+J

JMM 1480
000452  J=J+1

JMM 1485
000453  JM=J-1

JMM 1490
000454  S(I,J)=PS(J+I-PS(J)

JMM 1495
000455  S2(I,J)=PS(I-PS(J)

JMM 1500
000456  S3(I,J)=PS(J+I)-PS(J)

JMM 1505
000457  R1(I,J)=S1(I,J)/S2(I,J)

JMM 1510
000458  R2(I,J)=S2(I,J)/S3(I,J)

JMM 1515
000459  R CONTINUE

JMM 1520
000463  OD 9 I=1+IN

JMM 1525
000464  C F(I) = 0

JMM 1530
000469  X = X * UCL1/(1RNU*12)

JMM 1535
000470  XX = XX * UCL1/(1RNU*12)

JMM 1540
000471  YJ = YJ * UCL1/(1RNU*12)

JMM 1545

71
RUN VERSION 2.7 --PSR LEVEL 29--

000514 CALL RADIUS(XIYOUT, XI, JEN)
000616 Y^YOUT
000217 NP=1
000051 X:FWNO=0
000051 X:NG=XTVOUT
000051 X:ND=4.5

C  FLFINDING LENGTH IN RADIUS
000051 TF(1:1.4, GT.990), FLOW=1
000051 TF(1:KLOW, 1:11, JEN)
000051 TF(1:KLOW, 4, 1:CCRD.09)

C  INITIALISATION OF DP/DX VARIABLES
000051 VMEFN=UCLI*2*PREF/A4.4
000051 JU=ITSEC*TCLI/(TWREF-TCLI)
000051 PHFF=PHFE /VMHEAD
000051 PAMF=PAMF /VMHEAD
000051 PCHM=PCHM /VMHEAD
000051 UNJ=1

C  URP = 1.

C  * * SECTION 2  * * *

C  * * INITIAL FLOW CHARACTERISTICS AT M=1 LINE.
000051 CALL PHOF(U1, NJ, UJR, JR, KJ, UCLI)

C  VELOCITY AND TEMPERATURE ON M=1 LINE
000051 CONA=(TWREF-TCLI)/TREF
000051 CONR=T CLI/TREF
000051 CON=CONB, CONE
000051 CTIM=PE/VNEAD
000051 NNP=N-1
000051 UPJ=1

C  INITIALISATION ENDS +OUTER LOOP BEGINS

000670 CONTINUE
RUN VERSION 2.3 --PSR LEVL 29A--

000670 NSTEP=NSTEP+1
000672 IF(NSTEP.EQ.1)GO TO 631
000673 IF(IFLOW.EQ.1)GO TO 88
000674 CALL LOOK(JK,JN,YN,DELTA,BH,AY,NN,CC,IFLOW,XBLEND,YJ,BE)
000675 EVALUATES SHEAR LAYER WIDTH ECT.
000671 88 CONTINUE
000676 SECTION 3 INSERTED HERE
000677 • • • SECTION 3 • • •
000678 • EVALUATE TURBULENT VISCOITY USING MIXING LENGTH •
000679 • VERSION FOR PIPE FLOW (AS PER APRIL 17, 1972 )
000671 IF(IFLOW.EQ.1)GO TO 77A
000673 IF(JFLOW.EQ.1)GO TO 77A
000675 JFLOW=1 INDICATES A PIPE FLOW
000677 INM=0
000679 AZ1 = 0.9*DELTA
000681 DO 4 I=1,NN
000683 IF(ILZ.LT.A/|)INM=INM*I
000685 IF(ILZ,GT,AZI}LZ=AZI
000687 E(I)=O*
000689 Th
000691 JET VISCOSITY
000693 LZ=CC
000695 765 E(I)= AS(Y(I)-Y(IM))+(U(I+1)-U(I))/((Y(I))2-Y(IM))2
000697 45 CONTINUE
000699 GO TO 48
000700 PIPEFLOW MIXING LENGTH

NAS

000720 LZ=O,4*EXP(-YSI26.0)*(Y(N)-Y(I))
000722 DO 45 I=1,NN
000724 IF(OELTS.LE.OO10)GO TO 1360
000726 IF(Y(I),LT.BE)GO TO 1360
000728 A(I,J) = 0.0*DELTA
000730 IF(Y(I),GT.BE)GO TO 1360
000732 IF(Y(I).GE.OELTA)GO TO 1360
000734 IF(Y(I).LT.GE)GO TO 1360
000736 CONTINUE
000738 YSU(Y(N)-Y(I))*I;REF
000740 LZ=O,4*(I.0-EXP(-YSI26.0))*(Y(N)-Y(I))
000742 IF(LZ.LT.A/|)INM=INM*I
000744 IF(LZ,GT,AZI}LZ=AZI
000746 E(I)=O*
000748 Th
000750 JET VISCOSITY
000752 LZ=CC
000754 767 E(I)= AS((Y(I)-Y(IM))+(U(I+1)-U(I))/((Y(I))2-Y(IM))2
000756 45 CONTINUE
000758 GO TO 48
000760 PIPEFLOW MIXING LENGTH

JMX 2220
JMX 2230
JMX 2240
JMX 2250
JMX 2260
JMX 2270
JMX 2280
JMX 2290
JMX 2300
JMX 2310
JMX 2320
JMX 2330
JMX 2340
JMX 2350
JMX 2360
JMX 2370
JMX 2380
JMX 2390
JMX 2400
JMX 2410
JMX 2420
JMX 2430
JMX 2440
JMX 2450
JMX 2460
JMX 2470
JMX 2480
JMX 2490
JMX 2500
JMX 2510
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JMX 2580
JMX 2590
JMX 2600
JMX 2610
JMX 2620
JMX 2630
JMX 2640
JMX 2650
JMX 2660
JMX 2670
JMX 2680
JMX 2690
JMX 2700
JMX 2710
JMX 2720
JMX 2730
JMX 2740
JMX 2750
JMX 2760

73
C  Version 7.1  --PSR LEVEL 29A--

C
CFINAL CARD OF SECTION 3

CEND

C EVALUATE nx STF P (FOR EJECTOR FLOW AS PER FEB. 19)

C

C

C

C

C

C

R hostile

R hostile

R hostile

R hostile

R hostile

R hostile

R hostile
**SECTION 5**

Determine boundary conditions on M=1 line.

**C**

001370  
U(2,N) = 0.

001377  
CALL RADIUS(X,YOUT,2,REM).

00137A  
NP*(DP1+NP1)/2.

00137D  
IF(R) = 0.

**C**

Calculate velocity U on M=1 line.

**C**

Iteration starts.

001303  
E(I) = 0.

001304  
DN 7347 J = 2,N.

001305  
7347 E(I,J)*Y(J)*NP = U(I,J)*RHO(1+J)/(2+PS(J)).

001326  
IF(NTT = -1).

**C**

Iteration continues.

001330  
NO 13 J = 2,NTT.

001339  
JP1 = J + 1.

00133A  
JMJ = J - 1.

00133B  
Y1 = E(I,JP1) = (VIS(JP1) + RHO(I,JP1) * E(JP1)).

0013A2  
Y2 = E(I,JM1) = (VIS(JM1) + RHO(I,JM1) * E(JM1)).

001347  
Y3 = E(I,J) = (VIS(I,J) + RHO(I,J) * E(I,J)).

001354  
Y4 = (Y3 + Y2) / S2(J).

001367  
Y6 = Y4 / (S3(J) * Y2 + Y3).

001368  
Y7 = Y5 / (S3(J) * Y2).

001367  
Y8 = Y4 / (U(I,J) / PS(I,J)).

001372  
Y9 = Y7 * Y1 / PS(J).

00137S  
A(JM1) = U(I,J) / DX + Y6 + Y9.

001407  
A(JM1) = Y6.

001408  
13 (JMJ) = (U(I,J) * DP2 / (2 * RHO(1+J))).

001417  
A(I) = A(I) + C(I).

001427  
IF(NP < 20) GO TO 119.

00142B  
P1 = (Y(NN) - Y(N)) / (Y(NTT) - Y(N)).

001432  
NBAR = DP1 * (Y(NN) ** 2 - Y(N) ** 2 - (Y(NTT) ** 2 - Y(N) ** 2) * DP1) / VIS(NN).

001444  
GO TO 219.

**C**

CONTINUE.

001447  
IF(N1) = LOG(Y(NN) / (Y(N))/LOG(Y(NNT) / Y(N)).

001457  
NBAR = DP1 * (Y(NN) ** 2 - Y(N) ** 2 - (Y(NTT) ** 2 - Y(N) ** 2) * DP1) / VIS(NN).

001477  
CONTINUE.

001477  
IF(N1) = DP1 * LOG(NTK) / (NTK) = DP1 * LOG(NTK).

001477  
D(NTK) = DP1 * LOG(NTK).

001477  
IF (U(2,J) = 0.1) URES = 1.

001514  
1934 CONTINUE.

001514  
U(2,J) = U(2,J).

001527  
IF (U(2,J) = 0.1) U(2,J) = 0.1.

001527  
CONTINUE.

001532  
U(2,J) = U(2,J).
**SECTION 6**

EVALUATE TEMPERATURE, VISCOSITY, AND DENSITY FIELDS

**SECTION 7**

FOR INCOMPRESSIBLE FLOW

**SECTION 8**

**CALCULATE PRESSURE GRADIENT**

**SECTION 10**

CALL VOIS(Y, PS, RHO, u, N)
00240       WRITE(6,752)  
00241       DO 706 J=1,N  
00242       T(J)=T(J)  
00243       IF(IF(DP1)) GO TO 4311  
00244       WRITE(6,61) J,YRL(J),U(J),T(J),TTT(J)  
00245       IF(J=1) GO TO 1213  
00246       WRITE(6,61) J,YRL(J),U(J),T(J),TTT(J)  
00247       GO TO 1213  
C THE FOLLOWING CARD IS INSERTED IF A MASS ENERGY CHECK REQUIRED  
00248       CALL CHECK(Y,EX,EXM,YT,FOUCT,TTP,TTT,UCLI,UJR)  
00249       CALL CHECK(Y,EX,EXM,YT,FOUCT,TTP,TTT,UCLI,UJR)  
00250       GO TO 1213  
C SECTION 10  
C TERMINATION TEST  
00255       IF (X,GT, XX) GO TO 1A  
00256       END
RUN VERSION 2.1 --PSR LEVEL 29A--

00251 GO TO 100
C RETURN TO START OF OUTER LOOP
C
00251 1A CONTINUE
00251 GO TO 0000
00252 1A WRITE(6,7717)
00256 7717 FORMAT(/,*, END OF CALCULATION*,*)
C ОРMAT STATEMENTS,
C
00256 41 FORMAT(25X,6X,F10.6,A14.5,2X,8E5)
00256 76 FORMAT(/,4X,I3,5X,4X,F15.6,F14.5,2X,F14.5)
  1U20 UCENT(F/S) TOCENT(DEC/R) AUGMENT USTAR(F/S)*
00256 752 FORMAT(25X,*, J Y(J) U(J))
  1 T(J) *)
00256 STOP
00256 END
### Run Version 2.7 -- PSR Level 29 --

#### NA5

**Program Length Including I/O Buffers**

013414

**Function Assignments**

| F | 000006 |  |

#### Statement Assignments

| 7 | 002644 9 | 005000 10 | 001216 11 | 001165 |
| 12 | 007273 16 | 001752 18 | 002561 19 | 000262 |
| 22 | 002241 23 | 000266 29 | 000256 37 | 002633 |
| 39 | 002635 45 | 001044 48 | 001221 61 | 003044 |
| 63 | 003113 73 | 002643 88 | 005711 100 | 000670 |
| 117 | 000444 118 | 000421 119 | 001447 162 | 000726 |
| 219 | 001477 235 | 002064 236 | 002070 279 | 002603 |
| 351 | 003220 458 | 002327 631 | 001221 737 | 000045 |
| 740 | 002243 752 | 003067 757 | 003051 762 | 001013 |
| 778 | 001477 796 | 001011 829 | 002616 832 | 001163 |
| 837 | 000075 883 | 002252 902 | 002246 904 | 002215 |
| 1621 | 000854 1051 | 002744 1201 | 000216 1213 | 002473 |
| 1360 | 001077 1373 | 000760 1744 | 002263 1934 | 001527 |
| 2001 | 000711 4172 | 001237 4173 | 001116 4311 | 002457 |
| 4775 | 002246 6000 | 002245 6001 | 001330 6732 | 002101 |
| 7142 | 002270 7232 | 002752 7347 | 001305 7717 | 003035 |
| 7817 | 002261 8019 | 002577 8140 | 001132 8888 | 000016 |

#### Block Names and Lengths

| - | 000004 |  |

VARIABLE ASSIGNMENTS

| A | 006635 | AA | 005621 | AMASSO | 001771 | AMASS1 | 001710 |
| AMR | 007221 | ASTR | 007175 | ASTRG | 005755 | ASTRG | 005747 |
| A2 | 007214 | A2 | 007277 | A2 | 007274 | A2 | 007243 |
| BB | 007322 | BB | 006465 | BDELTA | 007275 | BHE | 007274 |
| BH | 007324 | BLEN | 007267 | BLEN | 007270 | BLEN | 007270 |
| 97 | 007341 | C | 006251 | CF | 007153 | CF | 007205 |
| CONA | 007265 | CONA | 007266 | CONA | 007270 | CONA | 007267 |
| CONL | 007271 | D | 005727 | DBAR | 007327 | DBAR | 007350 |
| DELTA | 007367 | DELU | 007362 | DFLY | 007342 | DFLY | 007326 |
| DJR | 007221 | DPRI | 007333 | DPAC | 007340 | DPAC | 007154 |
| DP11 | 007162 | DP2 | 007155 | DX | 007311 | DX | 005063 |
| E1 | 004541 | E | 007245 | GAMA | 007146 | GAMA | 006357 |
| MF | 007204 | I | 007152 | ICHX | 007314 | ICHX | 007241 |
| IFLOW | 007237 | IL | 007230 | INM | 007301 | INM | 007276 |
| IP1 | 007300 | IT | 007304 | ITER | 007226 | ITER | 007233 |
| J | 007292 | JFLOW | 007231 | JK | 007273 | JK | 007254 |
| JP1 | 007253 | KJ | 007263 | LVH | 007351 | LVH | 003244 |
| NK | 007141 | K | 007222 | NJ | 007251 | NJ | 00003001 |
| NN | 007224 | NP | 000000C01 | NPP | 000002G01 | NSTEP | 007236 |
| NTEST | 007163 | NTK | 007315 | NTP | 007256 | NTP | 007223 |
| PNR | 007166 | PA1 | 007210 | PA2 | 007214 | PA2 | 007264 |
| PE | 007217 | PH20 | 007235 | PI | 007225 | PI | 007164 |

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START OF CONSTANTS
002562

START OF TEMPORARIES
003100

START OF INDIRECTS
003166

UNUSED COMPILER SPACE
002200
RUN VERSION 2.1 --PSR LEVEL 29A--

SUBROUTINE YD3(Y,PS,RH0,UP,N)
FUNCTION Y(70),PS(70),RH0(2,70),U(2,70)
COMMON NP,SP,NPP,ML
Y(1)=0.0
M=5U0=1=2,N
Z=(2.*FLOAT(NP))/(RH0(2,1)-U(2,1)+RH0(2,1)-U(2,1))
Y=Y(1)**(NP+PP)*Z*(PS(1)+PS(1)+PS(1)+PS(1)-1)
RETURN
END

RUN VERSION 2.1 --PSR LEVEL 29A--

YD3

SUBPROGRAM LENGTH
000010A

FUNCTION ASSIGNMENTS

STATEMENT ASSIGNMENTS

BLOCK NAMER AND LENGTHS
  = 000004

VARIABLE ASSIGNMENTS
  I = 000103  NP = 000000C01  NPP = 000002C01  SQP = 00001C01
  Z = 000104  ZY = 000105

START OF CONSTANTS
000052

START OF TEMPORARIES
000054

START OF INDIRECTS
000073

UNUSED COMPILER SPACE
073330

82
RUN VERSION 2.1 --PSR LEVEL 29a--

SURROUNTE CALC (A+R+C+D+H+J)  

AS PER MAY 19 1971

* * * THIS EVALUATES RESULTS USING THOMAS ALGORITHM * * *

000010 DIMENSION A(70),B(70),C(70),D(70),H(70),G(70)  

000011 CAL 10  

000012 N2=J-2  

000015 N3=J-1  

000016 N1=A(1)  

000017 W(1)=D(1)/W(1)  

000020 K1=W-1  

000021 G(W)=G(K1)/W(K1)  

000022 G(K1)=A(K1)+C(K1)*G(K1)  

000030 G(K1)=G(K1)-C(K1)*G(K1))/W(K1)  

000040 RETURN  

RUN VERSION 2.2 --PSR LEVEL 29a--

CALC

SURROUNTE LENGTH 00437

FUNCTION ASSIGNMENTS

STATEMENT ASSIGNMENTS

BLOCK NAMES AND LENGTHS

VARIABLE ASSIGNMENTS

G = 0006433 K = 000433 N1 = 000432 N2 = 000431 N3 = 000435 0 = 000434

W = 000147

START OF CONSTANTS 00064

START OF TEMPORARIES 00065

START OF INDIRECT 00071

UNUSED COMPILER SPACE 07320

83
RUN VERSION 2.3 --PSR LEVEL 29--

SUBROUTINE PROF(U,T,NJ,N,JR,TJ,K,UCLI)

C VERSION FOR SINGLE STREAM FLOW WITH A WALL BOUNDARY LAYER IF KJ=1

C VERSION FOR TWO STREAM FLOW (TOP-HAT PROFILE) OR SINGLE

C STREAM FLOW WITHOUT A BOUNDARY LAYER IF KJ=2

NDFUSION(U(3,7)+U(Z,7))

10 IF(KJ.EQ.1)GO TO 12

0 IF(I,G.EQ.1)GO TO 5

1 U(I,1)=1.0

T(I,1)=0.0

GO TO 10

5 U(I,1)=UJR

10 CONTINUE

GO TO 8

12 READ(5,13)(U(I,1),I=1,N)

13 FORMAT(6E13.6)

NO 15 I=1,N

15 T(I,1)=0.0

NO 20 I=1,N

20 T(P,1)=U(I,1)

RETURN

END

RUN VERSION 2.3 --PSR LEVEL 29--

PROF

FUNCTION ASSIGNMENTS

STATEMENT ASSIGNMENTS

5 = 000025 10 = 000065 12 = 000031

13 = 000177 15 = 000061

BLOCK NAMES AND LENGTHS

VARIABLE ASSIGNMENTS

I = 000123 KJ = 000000 UCLI = 000001

START OF CONSTANTS

START OF TEMPORARIES

START OF INDIRECTS

UNUSED COMPILER SPACE

84
RUN VERSION 2.3 ==PSR LEVEL 29==

SUBROUTINE PSI(N, PSHNJ, PSNJ)

NJ = 1
PST = PSHNJ/NJ
NJ = NJ+1
CONTINUE

PSI(1) = PSHNJ*1.0 + PSI(1)*COS(3.1416/FLOAT(JN)*FLOAT(I-1))
CONTINUE

CONTINUE

/乃是(PSN-PSNJ)/FLOAT(N-K-|81
J = K-1
PST = (PSN-PSNJ)/FLOAT(N-K-1)
CONTINUE

CONTINUE

PSI = SQRT(PSI)
CONTINUE

CONTINUE

PSI

SUBPROGRAM LENGTH
000224

FUNCTION ASSIGNMENTS
STATEMENT ASSIGNMENTS
200 - 000174

BLOCK NAMES AND LENGTHS

VARIABLE ASSIGNMENTS
DELPS = 000224 FS = 000221 FSA = 000225 I = 000220
J = 000222 JN = 000271 K = 000223

START OF CONSTANTS
001162

START OF TEMPORARIES
000176

START OF INDIRECTS
000715

UNUSED COMPILER SPACE
072708
SUBROUTINE RADIUS(X,YOUT,XZ,REN)
C
DIMENSION RR(25),XX(25)
000007 C
000007 DO Tn(i+2)+XZ
000014 1 RRn(i)+NS
000022 6 FORMAT(12)
000027 READ(ns,3)(RR[i]*XZ=NS)
000035 READ(ns,3)(XX[i]*XZ=NS)
000050 2 FORMAT(8F10.0)
000055 WRITE(i,20)
000054 FORMAT(25,S54,D25)*DUCT GEOMETRY*,//5K*DUCT DIAMETER OR HEIGHT
000054 D 25 = 1 + NS
C
DO 25 = 1 + NS
000060 RR(i) = RR(i)*XZ
000067 WRITE(i,7) RR(i),XX(i)
000072 7 FORMAT(10xF10.5,25x,f10.5)
000075 CONTINUE
1 DISTANCE FROM NOZZLE EXIT (IN)/
000077
000077 4 6 4 IM=NS
000101 IF(RR(i)NRR(I)*REN)
000108 4 XX(I)XX(I)*REN=2.
000107 I = I
000110 7 IF(X,<GT.XXXNS)GO TO 5
000114 IF(XGT.XX(I+1)=I=1
000114 RETURN GOTO(RR(i)+XX-XX(I))*RR(I+1)+XX(1)+XX(I))/
000120 YOUT=RR(I)+XX(I)*RR(I+1)+XX(1)+XX(I))
000125 RETURN
000130 END

RETURN
END

RUN VERSION 2.9 --PSR LEVEL 29A--

RADIUS

SUBPROGRAM LENGTH
00026A
FUNCTION ASSIGNMENTS

STATEMENT ASSIGNMENTS
<table>
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BLOCK NAMES AND LENGTHS

VARIABLE ASSIGNMENTS
| 1 | 00026A | NS | 00026A | RR | 000262 | XX | 000233 |

START OF CONSTANTS
000134

START OF TEMPORARIES
000164

START OF INDIRECTS
00017A

UNUSED COMPILER SPACE
073800

86
RUN VERSION 2.3 --PSR LEVEL 29A--

SUPERQUITINE CHECK(Y,E,U,RHO,UP,TDAT,T,TT,T,TNT,NN,UQ,UL,UL)

COMMON NP,UP,NNP,NNL

000014
DIMENSION Y(70),E(70),U(70),RHO(2,70),UP(70),TT(70)

000014
ENFUG=0.0

000017
TFLOW=0.0

000020
VISCIN=0.0

000021
DEL2=0.0

000022
N0=0.0

000024
JPI=1.0

000024
TFLOW=TFLOW*(Y(JPI)*E(JPI)-Y(J)*E(J))

000024
+TFLOW*(U(2,JPI)-U(2,J))

000024
*2*(U(2,JPI)+U(2,J))/4.0

000024
VISCN=VISCN*(Y(JPI)*E(JPI)-Y(J)*E(J))*U(2,JPI)-U(2,J)

000024
+DEL2*(U(2,JPI)+U(2,J))

000024
+DEL2*(Y(JPI)*E(JPI)-Y(J)*E(J))*U(2,JPI)-U(2,J)

000024
ENFUG=ENFUG*(Y(JPI)*E(JPI)-Y(J)*E(J))

000024
+DEL2*(U(2,JPI)+U(2,J))

000024
*U(2,JPI)+U(2,J))

000024
VISCN=VISCN*(Y(JPI)*E(JPI)-Y(J)*E(J))

000024
+DEL2*(U(2,JPI)+U(2,J))

000024
*U(2,JPI)+U(2,J))

000024
TFLOW=TFLOW*(Y(JPI)*E(JPI)-Y(J)*E(J))

000024
+DEL2*(U(2,JPI)+U(2,J))

000024
*U(2,JPI)+U(2,J))

000024
ENFUG=ENFUG*(Y(JPI)*E(JPI)-Y(J)*E(J))

000024
+DEL2*(U(2,JPI)+U(2,J))

000024
*U(2,JPI)+U(2,J))

000024
RETURN

RUN VERSION 2.3 --PSR LEVEL 29A--

CHECK

SUBPROGRAM LENGTH

FUNCTION ASSIGNMENTS

STATEMENT ASSIGNMENTS

BLOCK NAMES AND LENGTHS

VARIABLE ASSIGNMENTS

DEL2 = N0+401
ENERG = 000376
J = 000402
JPI = 000403

NY = 00002
NP = 000000C0
NPP = 000000C0
PSN = 00000404

TFLOW = 000377
TTT = 000000
UCL = 000003

UQ = 00004
VISCIN = 00004

START OF CONSTANTS

START OF TEMPORARIES

START OF INDIRECTS

UNISFN COMPILERS SPACE

01000100
### RUN VERSION 2.3 --PSH LEVEL 29A--

**SUBROUTINE HLCHK**

```
000175 40 FORMAT(10E13.6) \text{, \texttt{RC,RRB(N),RRM}}
000176 40 \text{WRITE(6,40) RC,RRB(N)\text{, RRM}}
```

**FUNCTION ASSIGNMENTS**

**STATEMENT ASSIGNMENTS**

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run version 2.1 --psr level 29--

```
SUBROUTINE LOOK(IJK,NN,U,Y,DELTA,RH,AY,N,CC,IFLOW,XRLEND,YJ,RE)

C FOR JECTOR FLOW AS PER FER, 19
C
0000a
C DENSION II(2771),Y(70)

0000b
C SIMPLIES FOR INFLECTION POINT

0000c
NX=1

0000d
NX=2

0002e
NZ=(U(I+1,J)+U(I+1,J+1)-U(I,J)-U(I+1,J))/(Y(I+1,J)-Y(I,J))

0002f
IF(NZGT.0)GO TO 771

0002g
RETURN

0002h

C IFLOYEE FLOWER IS NO INFLECTION POINT

0002i
N=1

0002j
UP=U(I+1,J)

0002k
IF(Y(I+1,J).LE.Y(I,J))GO TO 776

0002l
DELTA=Y(N)-DELTA

C SEARCH FOR SHEAR LAYER OUTER EDGE

0002m
HYM=1

0002n
NO 1319 HM,MY

00020
HYM=1

00021
UP=U(I+1,J)+U(I+1,J+1)

00022
IF(Y(I+1,J).LE.Y(I,J))GO TO 776

00023
IF(NZLT.0)GO TO 776

C SEARCH FOR SHEAR LAYER INNER BLUE

00024
N=1

00025
<i>CONTINUE</i>

00026
FOR SHEAR LAYER INNER EDGE

00027
NO 772 IF=I

00028
U(I+1,J)+U(I,J)

00029
IF(NZLT.0)GO TO 773

C SEARCH FOR EDGE OF WALL BOUNDARY LAYER

0002a
NO 773 IF=I

0002b
UKK=UP+U(I+1,J)+U(I,J)

0002c
FOR(KK,GT=.003)GO TO 776

0002d
RETURN

RUN VERSION 2.3 --PSR LEVEL 29--

0002e
776 IFLOW=1

0002f
XRLEND=0

0002g
777 RETURN

0002h
END
```

89
RUN VERSION 2.7 ---PSA LEVEL 26---

LOOK

SUBPROGRAM LENGTH
00032K

FUNCTION ASSIGNMENTS

STATEMENT ASSIGNMENTS
771 - 000040 773 - 000146 775 - 000216 776 - 000250
777 - 000297 1320 - 000110

BLOCK NAME AND LENGTHS

VARIABLE ASSIGNMENTS
BE - 00008A DELTA - 000313 BFRAC - 000232 BYY - 000000
CC - 000002 UE - 000310 I - 000315 IFLOW - 000003
J - 000104 JJ - 000311 K - 000027 KI - 000323
M - 000104 MP - 000317 MY - 000314 MZ - 000024
N - 000101 UKK - 000322 UPOT - 000312 UTT - 000320
UTV - 000316 XBLNQ - 000004 VJ - 000005

START OF CONSTANTS
00025A

START OF TEMPORARIES
00034A

START OF INDIRECTS
000777

UNUSED COMPILER SPACE
072400
REFERENCES


Table 1
Mixing Section Dimensions for 1.875" Throat Size

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*Nozzle discharge plane at x = 0.000*
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Variation of Individual Integrated Traverse Mass Flows For Each Test Run

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### Table 3

Location of Test Data for Each Test Run

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T Stands for Table
F Stands for Figure
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Table 5
Comparison of Experimental and Analytical Mass Flow Rates

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<th>Mixing Section Mass Flow Rate From Orifice Data lb/sec.in.</th>
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<th>Analytical Mass Flow For Best Static Match lb/sec.in.</th>
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<th>Comparison Of Orifice To Analytical Mass Flow</th>
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<tr>
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<td>0.485</td>
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<td>0.525</td>
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<td>0.508</td>
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</table>

* Transducer Battery May Have Been Going Bad During This Test
### Table 6

**Tabulation of Static Pressures For Runs 4, 8, and 11**

<table>
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<tr>
<th>Distance From Nozzle Discharge inches</th>
<th>Run No.</th>
<th>4</th>
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<th>11</th>
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<td>35.61</td>
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<td>Nozzle Pressure psia</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>1.25&quot;</td>
<td>1.875&quot;</td>
<td>1.875&quot;</td>
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<tr>
<td>Throat Height</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Wall Static Pressure in Inches of Water Gage</td>
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<td>-14.2</td>
<td>-21.5</td>
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<td>+13.2</td>
<td>+10.9</td>
<td>+3.7</td>
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</table>
Figure 2

Picture of Primary Nozzle
Figure 3

Picture of Nozzle Positioned in the Mixing Section
Figure 4

Picture of Mixing Section Discharge
Figure 5
Extended Inlet on Ejector Test Rig
Figure 7

Picture of Right Side of Ejector Rig
Figure 8

Picture of Left Side of Ejector Rig
Figure 11 Comparison of Experimental and Analytical Mass Flow Rates for Runs 1, 2, 3 and 5
Figure 12 Comparison of Experimental and Analytical Mass Flow Rates for Runs 6, 7, 9, and 10
Solid Lines are Analytical Results

<table>
<thead>
<tr>
<th>Data</th>
<th>Analytical</th>
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<td>$W_m$ lb/sec</td>
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<td>2</td>
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<tr>
<td>3</td>
<td>0.351</td>
</tr>
<tr>
<td>1</td>
<td>0.382</td>
</tr>
<tr>
<td>5</td>
<td>0.395</td>
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</table>

Figure 13 Wall Static Pressure Distribution for Mixing Section with 1.25" Throat
Solid Lines are Analytical Results

<table>
<thead>
<tr>
<th>Data Run</th>
<th>$W_m$ lb/sec</th>
<th>$W/W_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 △</td>
<td>0.420</td>
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</tr>
<tr>
<td>7 □</td>
<td>0.443</td>
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<tr>
<td>9 ○</td>
<td>0.485</td>
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<tr>
<td>10 ▽</td>
<td>0.508</td>
<td>4.81</td>
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</table>

Figure 14 Wall Static Pressure Distributions for Mixing Section with 1.875" Throat
Figure 15 Maximum Velocities for 1.25" Throat Mixing Section

\[ p_N = 17.0 \text{ psig} \]
Figure 16 Maximum Velocities for 1.875" Throat Mixing Section

\[ p_N = 21.0 \text{ psig} \]
Analytical $W_m = 0.382 \text{ lb/sec} \cdot \text{in.}$

Figure 17 Velocity Profiles for Run 1 for 1.25" Throat Mixing Section

$p_N = 17.0 \text{ psig}, T_N = 181^\circ \text{F}, W_N = 0.0780 \text{ lb/ sec} \cdot \text{in.}$
Analytical $W_m = 0.322$ lb/sec. in.

Figure 18 Velocity Profiles for Run 2 for 1.25" Throat Mixing Section
$P_N = 17.0$ psig $T_N = 177^\circ F$, $W_N = 0.0782$ lb/sec. in.
Analytical $W_m = 0.351 \text{ lb/sec. in.}$

Figure 19a Velocity Profiles for Run 3 for 1.25" Throat Mixing Section

$p_N = 17.0 \text{ psig, } T_N = 246^\circ \text{ F, } W_N = 0.075 \text{ lb/sec. in.}$
Analytical $W_m = 0.351$ lb/sec in.

Figure 19b Velocity Profiles for Run 3 for 1.25" Throat Mixing Section

$p_N = 17.0$ psig, $T_N = 246^\circ F$, $W_N = 0.075$ lb/sec in.
Figure 20 Velocity Profiles for Run 5 for 1.25" Throat Mixing Section

\( p_N = 17.0 \) psig, \( T_N = 188^\circ \) F, \( W_N = 0.0787 \) lb/sec. in.
Analytical $W_m = 0.420$ lb/sec, in.

$P_N = 21.0$ psig, $T_N = 189$° F, $W_N = 0.0882$ lb/sec, in.

Figure 21 Velocity Profiles for Run 6 for 1.875" Throat Mixing Section
Analytical $W_m = 0.443$ lb/sec in.

Figure 22 Velocity Profiles for Run 7 for 1.875" Throat Mixing Section

$P_N = 21.0$ psig, $T_N = 187^\circ F$, $W_N = 0.0884$ lb/sec in.
Analytical $W_M = 0.485$ lb/sec in.

Figure 23a Velocity Profiles for Run 9 for 1.875" Width Mixing Section

$p_N = 21.0$ psig, $T_N = 184^\circ F$, $W_N = .0884$ lb/sec in.
Analytical \( W_m = 0.485 \text{ lb/sec in.} \)

Figure 23b Velocity Profiles for Run 9 for 1.875" Throat Mixing Section

\( P_N = 21.0 \text{ psig}, T_N = 184^\circ F, W_N = 0.0884 \text{ lb/sec in.} \)
Analytical $W_m = 0.508 \text{ lb/sec.in.}$

Figure 24  Velocity Profiles for Run 10 for 1.875" Throat Mixing Section

$p_N = 21.0 \text{ psig}, T_N = 200^\circ F, W_N = .0874 \text{ lb/sec.in.}$
Figure 25 Temperature Profiles for Run 3 for 1.25" Throat Mixing Section
Figure 26 Temperature Profiles for Run 9 for 1.875" Throat Mixing Section
Figure 27 Wall Static Pressure Sensitivity to Flow Rate and Eddy Viscosity for Run 3 and Run 6
Figure 28  Centerline Velocity and Temperature Sensitivity to Eddy Viscosity for Run 3 and Run 6
Figure 29 Velocity Profile Sensitivity to Eddy Viscosity
For Run 3 and Run 6 at $x = 7.0''$
Figure 30  Mixing Section Throat Static Pressure
As A Function of Throat Mach Number