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USER'S MANUAL FOR A TEACH COMPUTER PROGRAM
FOR THE ANALYSIS OF TURBULENT, SWIRLING
REACTING FLOW IN A RESEARCH COMBUSTOR

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Described herein is a computer program for the analysis of the subsonic, swirling, reacting turbulent flow in an axisymmetric, bluff-body research combustor. The program features an improved finite-difference procedure designed to reduce the effects of numerical diffusion and a new algorithm for predicting the pressure distribution within the combustor.

A research version of the computer program described in the report was supplied to United Technologies Research Center by Professor A. D. Gosman and his students, R. Benodeker and R. I. Issa, of Imperial College London. The Imperial College staff also supplied much of the program documentation contained in this report.

This report presents a description of the mathematical model for flow within an axisymmetric bluff-body combustor, the development of the finite-difference procedure used to represent the system of equations, an outline of the algorithm for determining the static pressure distribution within the combustor, a description of the computer program including its input format, and the results for representative test cases.

This report constitutes the final report for Task VII of NASA Lewis Research Center Contract NAS3-22771.
User's Manual for a TEACH Computer Program
For the Analysis of Turbulent, Swirling
Reacting Flow in a Research Combustor

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1.0 SUMMARY

Described herein is a computer program for the analysis of the subsonic, swirling, reacting turbulent flow in an axisymmetric, bluff-body research combustor. The program features an improved finite-difference procedure designed to reduce the effects of numerical diffusion and a new algorithm for predicting the pressure distribution within the combustor.

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This report constitutes the final report for Task VII of NASA Lewis Research Center Contract NAS3-22771. Funding for this effort was provided by the Air Force Aero Propulsion Laboratory under contract FY1455-82-N0633. The AFAPL program manager was Dr. W. M. Roquemore.

The NASA project monitor is Dr. C. J. Marek.
2.0 INTRODUCTION

This report presents a description of the mathematical basis for and operation of a new version of the TEACH computer program developed originally by workers at Imperial College, London. The program is intended for use in the analysis of the subsonic, swirling, reacting, turbulent flow in a cylindrical bluff-body research combustor (Fig. 1). This combustor has been developed by W. M. Rocquemore and colleagues of AFAPL as a research tool for gas turbine combustor modelling and for diagnostic instrumentation development (Ref. 1). The flowfield of interest is that which is developed in the open-ended, cylindrical chamber downstream of the base of the bluff-body which houses the fuel injector (Fig. 1). Such flows can be described by the fully-elliptic, steady-state equations of motion. The present version of TEACH solves these equations using an improved finite-difference procedure—the Bounded Skew-Upwind Differencing (BSUD) method. The axisymmetric pressure distribution is estimated by means of a new algorithm—the Pressure-Implicit Split Operation (PISO) predictor-corrector technique.

Sections of the computer program have been reorganized by UTRC in an attempt to minimize the changes necessary to install the program on different computer systems. The input format has been extensively revised to permit more flexibility in setting up and running cases. In the program that was supplied to UTRC, Imperial College included a number of additional options. These include switches that permit (1) the analysis of two-dimensional (planar) flows and (2) the selection of the more conventional hybrid differencing scheme. Verification of the operational status of these optional features was beyond the scope of the present contract and would have required additional documentation from Imperial College. These options have been retained in the present version of TEACH for the convenience of the user.

In Section 3, the system of equations describing the flow within the research combustor is presented. In Section 4, the finite-difference forms of these equations, the special numerical treatment for certain source terms, and the PISO algorithm are described. In Section 5, the input format, source language listings, and other documentation for the computer program are presented. In Section 6, three representative sample cases are used to illustrate the results obtained with the computer program.

References are listed in Section 7 and the nomenclature is presented in Section 8.
3.0 MATHEMATICAL MODEL

In this section, the governing equations describing the subsonic, swirling, reacting turbulent flow in an axisymmetric research combustor are presented. The two-equation turbulence model is then described. Finally, a combustion model for the turbulent reaction of propane with air is outlined.

3.1 Governing Equations

The governing conservation equations for the mean motion of a two-dimensional (axisymmetric), steady-state turbulent flow are presented below using cylindrical coordinates. Closure of this set of equations is provided by using the turbulent kinetic energy \( k \) and energy dissipation rate \( \varepsilon \) which are derived from additional transport equations (see Sect. 3.2 and Launder and Spalding (Ref. 2)) to obtain an effective eddy viscosity such that the unknown turbulence diffusional fluxes can be expressed as the product of the eddy viscosity and the gradient of the appropriate dependent variable; i.e., from the "gradient transport hypothesis" (Hinze, Ref. 3).

The governing equations are:

**Continuity**

\[
\frac{\partial}{\partial x} (r:u) + \frac{\partial}{\partial r} (r:v) = 0
\]  
(3.1.1)

**Axial Momentum**

\[
\frac{1}{r} \left[ \frac{\partial}{\partial x} (r:uu) + \frac{\partial}{\partial r} (r:uv) \right] = -\frac{\partial p}{\partial x} + \frac{1}{r} \left[ \frac{\partial}{\partial x} \left( r_k \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial r} \left( r_{\varepsilon} \frac{\partial u}{\partial r} \right) \right] + S_u
\]  
(3.1.2)

**Radial Momentum**

\[
\frac{1}{r} \left[ \frac{\partial}{\partial x} (r:uv) + \frac{\partial}{\partial r} (r:vv) \right] = -\frac{\partial p}{\partial y} + \frac{1}{r} \left[ \frac{\partial}{\partial x} \left( r_k \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial r} \left( r_{\varepsilon} \frac{\partial v}{\partial r} \right) \right] - \frac{\varepsilon}{r^2} + S_v
\]  
(3.1.3)

**Tangential Momentum**

\[
\frac{1}{r} \left\{ \frac{\partial}{\partial x} (r:urw) + \frac{\partial}{\partial r} (r:ovw) \right\} = \frac{1}{r} \left\{ \frac{\partial}{\partial x} \left( r_k \frac{\partial w}{\partial x} \right) + \frac{\partial}{\partial r} \left( r_{\varepsilon} \frac{\partial w}{\partial r} \right) \right\} + S_w
\]  
(3.1.4)

**Scalar Transport**

\[
\frac{1}{r} \left[ \frac{\partial}{\partial x} (r:uc) + \frac{\partial}{\partial r} (r:vc) \right] = \frac{1}{r} \left[ \frac{\partial}{\partial x} \left( r_k \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial r} \left( r_{\varepsilon} \frac{\partial c}{\partial r} \right) \right] + S_c
\]  
(3.1.5)
where $\phi$ represents such scalars as temperature, mass fraction, turbulent kinetic energy, etc. The quantities $\nu_{\text{eff}}$ and $\Gamma_{\text{eff}}$ are the effective exchange coefficients and are the sum of both the laminar and turbulent transport coefficients.

$$\nu_{\text{eff}} = \nu_l + \nu_t; \Gamma_{\text{eff}} = \Gamma_l + \Gamma_t$$  \hspace{1cm} (3.1.6)

The sources $S_u$, $S_v$, and $S_w$ in the momentum equations represent additional terms associated with non-uniform viscosity. Their influence is generally small except where changes in fluid properties have considerable effects. These terms are given by:

$$S_u = \frac{\partial}{\partial x} \left( \nu_{\text{eff}} \frac{\partial u}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \Gamma_{\text{eff}} \frac{\partial v}{\partial r} \right)$$ \hspace{1cm} (3.1.7)

$$S_v = \frac{\partial}{\partial x} \left( \nu_{\text{eff}} \frac{\partial u}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \Gamma_{\text{eff}} \frac{\partial v}{\partial r} \right) - 2 \nu_{\text{eff}} \frac{v}{r} - \frac{\partial}{\partial r} \left[ \frac{2}{3} \nu_{\text{eff}} \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial r} \right) \right]$$ \hspace{1cm} (3.1.8)

$$S_w = -\frac{2}{r} \frac{\partial}{\partial r} \left( \Gamma_{\text{eff}} \frac{w}{r} \right)$$ \hspace{1cm} (3.1.9)

The governing equations (3.1.1) to (3.1.5) can be represented by the following general equation:

$$\frac{1}{r} \left[ \frac{\partial}{\partial x} (cr + \mu \frac{\partial u}{\partial r}) + \frac{\partial}{\partial r} (cr \frac{\partial v}{\partial r}) - \frac{\partial}{\partial x} \left( r \frac{\partial u}{\partial x} \right) - \frac{\partial}{\partial r} \left( r \frac{\partial v}{\partial r} \right) \right] - S_t = 0$$ \hspace{1cm} (3.1.10)

where it is now assumed that the axial and radial pressure gradients have been incorporated into $S_u$ and $S_v$, respectively.

### 3.2 Turbulence Model

The two equation $(k-\epsilon)$ turbulence model, developed by Launder and Spalding (Ref. 2), is used in the computer program. In the model, the turbulent viscosity is determined from the time-mean values of the kinetic energy of turbulence ($k$) and the volumetric turbulent kinetic energy dissipation rate ($\epsilon$) by the relationship:

$$\nu_t = C_{\nu} \rho \frac{k^2}{\epsilon}$$ \hspace{1cm} (3.2.1)

where $C_{\nu}$ is a constant. The quantities $k$ and $\epsilon$ are determined from transport-equations of the same form as Eq. (3.1.10) where for the $k$ equation:
\[ \frac{\epsilon}{\epsilon_t} = 1 + 0.5 \frac{k^2}{\epsilon_t} \]  
\[ \frac{S}{S_t} = 1 + \frac{k^2}{\epsilon_t} \]  
and for the \( \epsilon \) equation

\[ \frac{\epsilon}{\epsilon_t} = 1 + \frac{k^2}{\epsilon_t} \]

where

\[ \frac{\epsilon}{\epsilon_t} = 1 + \frac{k^2}{\epsilon_t} \]

The quantity \( G \) represents the production of turbulent kinetic energy by the mean motion. Turbulent kinetic energy is dissipated at a rate proportional to \( \epsilon \) which, in turn, is also generated and dissipated at rates that depend on \( k \) and \( \epsilon \) as can be seen from Eq. (3.2.3). Thus, the equations for \( k \) and \( \epsilon \) are strongly coupled. In the vicinity of the walls, the determination of both \( k \) and \( \epsilon \) requires special consideration as noted in Section 4.3. The constants appearing in the turbulence model are listed in Table 1.

### 3.3 Combustion Model

The model proposed by Magnussen and Hjertager (Ref. 4) is used in the computer program. This model relates the rate of combustion of the fuel (restricted to propane in the present analysis) to the rate of dissipation of turbulent eddies and expresses the rate of reaction in terms of the mean concentration of the reacting species, the turbulent kinetic energy, and the rate of dissipation of turbulent kinetic energy.

For propane, the stoichiometric relationship is:

\[ C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O + 5.006 \times 10^7 \text{J/kg} \]  

In the combustion model, the species concentrations are determined from the governing partial differential equations for the fuel mass fraction and the mixture fraction defined below. The enthalpy is defined as:

\[ h = m_f H_R + C_{p,m} T \]  

The mean specific heat is obtained from

\[ C_{p,m} = \sum_i m_i C_{p,i} \]

with the summation over all species. The specific heats of individual species are obtained using polynomials of the form:

\[ C_{p,i} = \frac{R}{N_i} (C_{1i} + C_{2i}T + C_{3i}T^2 + C_{4i}T^3 + C_{5i}T^4) \]

where \( R \) is the universal gas constant, 8314.3 J/kg-molK).

The constants of the polynomials are obtained from standard thermochemical tables and are listed in Table 2.
The mixture fraction \( f \), enthalpy \( h \) and fuel mass fraction \( m_f \) are governed by equations identical in form to Eq. (3.1.10). For both the mixture fraction and enthalpy, the source term is zero. For the fuel mass fraction, the source term is calculated in accordance with the Magnussen-Hjertager model:

\[
S_{mf} = -c \frac{f}{k} \min \left[ A m_f, A \frac{m_o2}{i}, AB \frac{m_{pr}}{i+1} \right]
\]  
(3.3.5)

for which the constants are \( A = 4 \), \( B = 0.5 \); for propane, the stoichiometric oxygen to fuel mass ratio is 3.635. The rate of combustion is then,

\[ R_f = -S_{mf} \]  
(3.3.6)

The fuel mass fraction is defined by the sum of the unburned and burned fuel:

\[ f = m_f + \frac{1}{3} m_{CO2} \]  
(3.3.7)

where, from (Eq. 3.3.1) and the fact that propane and carbon dioxide have nearly identical molecular weights, the mass fraction of burned fuel equals one-third of the mass fraction of \( CO_2 \). Since both the mixture fraction and fuel mass fraction are determined by the solution of the respective transport equation, Eq. (3.3.7) can be used to determine the mass fraction for \( CO_2 \):

\[ m_{CO2} = 3 (f - m_f) \]  
(3.3.8)

Similarly, for the remaining species:

\[ m_{H2O} = 0.545 m_{CO2} = 1.635 (f - m_f) \]  
(3.3.9)

\[ m_{pr} = m_{CO2} + m_{H2O} = 4.635 (f - m_f) = (i+1)(f - m_f) \]  
(3.3.10)

\[ m_{N2} = 0.767 (1-f) \]  
(3.3.11)

\[ m_{O2} = 1 - (m_{N2} + m_f + m_{CO2} + m_{H2O}) = 0.233 - 3.868f + 3.635 m_f \]  
(3.3.12)

\[ = 0.233 - (i+0.233)f + i m_f \]

The average density is given by

\[ \rho = \frac{P}{RT} \sum_{i} m_i \]  
(3.3.13)

and the temperature is calculated from Eq. (3.3.2).
In this section, the finite-difference approximations used in the computer program are discussed. In Section 4.1, the Bounded Skew-Upwind Differencing (BSUD) scheme is presented. In Section 4.2, the special treatment given to certain source terms in the equations of motion are discussed briefly. In Section 4.3, the boundary condition formulations are outlined. Finally, in Section 4.4, the predictor-corrector algorithm for determining the static pressure distribution is presented.

4.1 The Bounded Skew-Upwind Differencing Scheme

In this section, the Bounded Skew-Upwind Differencing (BSUD) scheme is described. First, a brief review of the flux form of the equations of motion is presented. Second, a detailed description of the finite-difference form of the flux contribution to a representative face of a typical control volume is given; the derivation of the flux contributions to the other faces is then outlined. Third, the resulting coefficients for the finite-difference equations representing the total flux (and sources) are presented. Finally, the bounding scheme for the coefficients is detailed.

4.1.1 Flux Form of the Equations of Motion

Further generalization of Eq. (3.1.10) leads to the conclusion that the equations of motion for both laminar flow and (time-averaged) turbulent flow can be written in similar fashion for all of the dependent variables:

\[
\frac{\partial}{\partial x} (pu\xi) + \frac{1}{r} \frac{\partial}{\partial r} (r \xi \rho v \xi) = \frac{\partial}{\partial x} \left( \tau \xi \frac{\partial \xi}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \tau \xi \frac{\partial \xi}{\partial r} \right) + S_{\xi}
\]

(4.1.1.1)

where \( \xi = 0 \) for two-dimensional (planar) flow and \( \xi = 1 \) for axisymmetric flow. The variable \( \xi \) represents any of the dependent variables (e.g., the velocity components \( u, v, w \), mixture fraction, turbulent kinetic energy and turbulent energy dissipation rate, etc.). The exchange coefficient, \( \tau \xi \), represents the sum of both laminar and turbulent contributions and is interpreted as the effective viscosity for \( \xi = u, v, w \), the effective diffusivity for \( \xi = \) mixture fraction, etc. \( S_{\xi} \) is a generalized source term.

Eq. (4.1.1.1) is integrated over a control volume appropriate for each dependent variable \( \xi \) and, after some manipulation, the finite-difference equivalent form of Eq. (4.1.1.1) is obtained. The control volumes are defined using an orthogonal grid formed by the intersection of co-ordinate lines in the axial and radial co-ordinate directions. The intersection of the grid lines, Fig. 2, form the grid nodes at which all flow properties except the axial (u) and radial (v) velocities are calculated; i.e., all scalars and the tangential velocity component (w) for swirling flows. The axial velocity is calculated using a second grid with grid lines such that the grid nodes of the scalars in the axial direction are midway between the axial velocity grid nodes, Fig. 3. The axial velocity and scalar grid nodes are co-incident in radial position. The radial velocity is
calculated using a third grid such that the grid nodes of the scalars in
the radial direction are midway between the radial velocity grid nodes,
Fig. 3. The radial velocity and scalar grid nodes are co-incident in axial
position. Directions in the grids are identified as north, south, east and
west. It should be noted that it is the axial grid line locations for the
axial velocity and the radial grid line locations for the radial velocity
which are input to the present version of the computer program.

Control volumes for each scalar and the tangential velocity are
defined such that (1) the east and west faces of the control volume are co-
incident with the axial velocity axial grid line locations and (2) the
north and south faces are co-incident with the radial velocity radial grid
line locations as shown in Fig. 4. The control volumes for the u velocity
are shifted relative to the scalar control volumes such that the east and
west faces are co-incident with the scalar grid node axial locations;
similarly, the v velocity control volumes are shifted such that the north
and south faces are co-incident with the scalar grid node radial positions.

The finite-difference form of Eq. (4.1.1.1) is derived by integrating
this equation over the appropriate control volume. In performing the inte-
gration over the control volume for each term in Eq. (4.1.1.1), the mean-
value theorem is employed and the source term is linearized in the vicinity
of the center of the control volume (point P). After some manipulation,
the finite-difference form of Eq. (4.1.1.1) is obtained
\[
C_E \epsilon_e - C_{W} \epsilon_w + C_N \epsilon_n - C_S \epsilon_s = D_E (\epsilon_E - \epsilon_P) - D_W (\epsilon_P - \epsilon_W)
\]
\[
+ D_N (\epsilon_N - \epsilon_P) - D_S (\epsilon_P - \epsilon_S) + (S_u + S_w \epsilon_P)
\]
where \( C_E, C_W, \) etc. are "convective coefficients" as defined below
\[
C_E = (\epsilon u) e a_e
\]
\[
C_N = (\epsilon v) n a_n
\]
\[
C_W = (\epsilon u) w a_w
\]
\[
C_S = (\epsilon v) s a_s
\]
and \( a_e = a_n, a_w = a_s \) are the areas of the faces of the control volume. The
"diffusion" coefficients are given by
\[
D_E = \left( \frac{\epsilon k}{\Delta x} \right) e a_e
\]
\[
D_N = \left( \frac{\epsilon k}{\Delta y} \right) n a_n
\]
\[
D_W = \left( \frac{\epsilon k}{\Delta x} \right) w a_w
\]
\[
D_S = \left( \frac{\epsilon k}{\Delta y} \right) s a_s
\]
and \( (\cdot x) e \) is the distance between points P and E, etc. (e.g., see Fig. 4).
It is important to note that Eq. (4.1.1.2) applies to all of the dependent variables although the appropriate grid must be used in each case to define the geometric parameters used in the calculation. Also, Eq. (4.1.1.2) applies to both the hybrid and bounded skew-upwind differencing procedures used in the computer program since each scheme is simply an alternative method for defining (interpolating for) the fluxes at the faces of the control volume (e.g., \( \psi_e, \psi_w, \psi_n, \psi_s \)). However, the diffusion terms are always represented by central differences.

It is convenient to define a total flux for each face of the control volume as the sum of a convective flux and a diffusive flux such that

\[ F_e - F_w + F_n - F_s = S_u + S_p \psi_p \tag{4.1.1.5} \]

where

\[ F_e = C_E \psi_e - D_E (\psi_e - \psi_p) \]
\[ F_w = C_w \psi_w - D_w (\psi_w - \psi_p) \]
\[ F_n = C_n \psi_n - D_n (\psi_n - \psi_p) \]
\[ F_s = C_s \psi_s - D_s (\psi_s - \psi_p) \tag{4.1.1.6} \]

In the following section, the skew upwind differencing procedure will be used to calculate the values of the dependent variables at the faces of the control volume. As a result, Eq. (4.1.1.5) will include not only the values of \( \psi \) at the "normal", or main, grid node locations (E, W, N, S and P) but also at the corner locations (NE, SE, NW, and SW). The finite-difference form for Eq. (4.1.1.5) will be shown to be

\[ A_p \psi_p = A_e \psi_e + A_w \psi_w + A_n \psi_n + A_s \psi_s + A_{NE} \psi_{NE} + A_{SE} \psi_{SE} \]
\[ + A_{NW} \psi_{NW} + A_{SW} \psi_{SW} + S_u + S_p \psi_p \tag{4.1.1.7} \]

4.1.2 - Calculation of the Fluxes

Recall that the equation of motion, Eq. (4.1.1.1), can be written in terms of fluxes to each face of the control volume, Eq. (4.1.1.5). In this section, a procedure will be described to calculate fluxes, \( F_e, F_w, F_n, \) and \( F_s \). The derivation of \( F_e \), the flux to the west face, of a typical scalar control volume is given in detail. The derivation of the fluxes for the other faces or the fluxes for the u and v velocity components are outlined.

Consider the control volume shown in Fig. 5. For this case, it has been assumed that the velocity vector is oriented as shown; i.e., the u and v components are non-negative. The flux to the west face is given by:

\[ F_w = C_w \psi_w - D_w (\psi_w - \psi_\psi) \tag{4.1.2.1} \]
For central-differencing (CD), the value of the dependent variable at the west face, $\phi_w$, is given by linear interpolation between $\phi$ at the W and P grid nodes:

$$\phi_w = (1 - a_w) \phi_W + a_w \phi_P$$  \hspace{1cm} (4.1.2.2)

where the interpolating factor is

$$a_w = \frac{x_w - x_P}{x_P - x_W}$$  \hspace{1cm} (4.1.2.3)

The central difference form of the flux at the west face is then:

$$\frac{F_{wCD}}{D_w} = \left[ F_{e_w} (1 - a_w) + 1 \right] \phi_w + \left( a_w F_{e_w} - 1 \right) \phi_P$$  \hspace{1cm} (4.1.2.4)

where the Peclet number at this face is given by:

$$F_{e_w} = c_w/D_w$$  \hspace{1cm} (4.1.2.5)

The upwind difference (UD) form for the flux at the west face is obtained by setting $a_w$ to zero and neglecting the diffusion term:

$$\frac{F_{wUD}}{D_w} = F_{e_w} \phi_w$$  \hspace{1cm} (4.1.2.6)

Equation (4.1.2.1) is also the starting point for the skew upwind differencing (SUD) scheme. The value of $\phi$ at the west face of the control volume, $\phi_w$, is determined by extrapolating the velocity vector upstream to the point $w'$ which lies along the grid line connecting the west and southwest nodes (see Fig. 5) to give:

$$\phi_w = (1 - k_w) \phi_W + k_w \phi_{SW}$$  \hspace{1cm} (4.1.2.7)

where the skew interpolation factor is the ratio of the vertical distance between $w'$ and SW to the vertical distance between W and SW:

$$k_w = \frac{1}{2} \frac{V_w}{U_w} \frac{Ax}{Ay}$$  \hspace{1cm} (4.1.2.8)

For very large flow angles (skewing) relative to the co-ordinate directions, $k_w$ will exceed unity and $\phi_w$ will be defined in terms of $\phi$ at the SW and S nodes; however, it is known that this approach can yield negative coefficients at the corner nodes (NW, SW, NE, SE) which can in turn produce oscillations in the solution. To assure that the coefficients for the corner nodes are non-negative, then:
\[ l_w = \min \left( 1.0, \frac{1}{2} \frac{|v_w|}{u_w} \Delta \right) \quad (4.1.2.9) \]

The use of absolute value in Eq. (4.1.2.9) permits this equation to be used to define \( k \) for all velocity components at the west face.

In his original development of the skew upwind differencing approximation, Raithby (Ref. 5) assumed that \( c_w = c_w' \). Thus,

\[ \frac{F_w}{D_w} = \frac{1}{a_w} \quad (4.1.2.10) \]

It is desirable to use the central-difference procedure for small values of the grid Peclet number and the skew upwind differencing method for large values of the grid Peclet number. It is also desirable that these two formulations produce a continuous transition at the transition Peclet number which in the present case is:

\[ c_w = \frac{1}{a_w} \quad (4.1.2.11) \]

At the transition Peclet number, the central difference result (Eq. 4.1.2.4) is:

\[ \frac{F_w}{D_w} = c_w \quad (4.1.2.12) \]

while the skew upwind differencing method (Eq. 4.1.2.10) yields:

\[ \frac{F_w}{D_w} = c_w' - (\phi - \phi_w) \quad (4.1.2.13) \]

Noting the definition given by Eq. (4.1.2.7), it is clear that these two results are not equal.

The fluxes at the transition Peclet number can be made equal by noting (contrary to the assumption made by Raithby) that \( c_w \) and \( c_w' \) are related by:

\[ c_w' = c_w - \left( \frac{\partial c_w}{\partial s} \right)_w \Delta s + \ldots \quad (4.1.2.14) \]

so that Eq. (4.1.2.10) becomes

\[ \frac{F_w}{D_w} = \frac{1}{a_w} \left( \frac{\partial c_w}{\partial s} \right)_w \Delta s - (\phi - \phi_w) \quad (4.1.2.15) \]

Writing the central difference result in terms of the flux definition, Eq. (4.1.2.1) then:
Clearly, these two fluxes will be equal at the transition Peclet number if a correction $\text{Pe}^* (\partial \phi / \partial s) \Delta s$ is added to the skew upwind differencing flux, Eq. 4.1.2.10, to obtain:

$$\frac{F_{\text{SU}}}{D_W} = F_{\text{CD}} + P e^* (\partial \phi / \partial s) \Delta s - (\phi_p - \phi_w) \tag{4.1.2.17}$$

The derivative $(\partial \phi / \partial s)$ can be computed by

$$\frac{\partial \phi}{\partial s} = \frac{\phi_w - \phi_w'}{\Delta s} \tag{4.1.2.18}$$

Then, using Eq. (4.1.2.2), (4.1.2.7) and (4.1.2.11), Eq. (4.1.2.17) becomes

$$\frac{F_{\text{SU}}}{D_W} = F_{\text{CD}} + P e_w^* (\phi_w - \phi_w') - (\phi_p - \phi_w) \tag{4.1.2.19}$$

At the transition Peclet number, the fluxes calculated by central differencing (Eq. 4.1.2.12) and skew upwind differencing (Eq. 4.1.2.19) are equal.

It will be recalled that the above result for the skew upwind differencing flux at the west face of the control volume was derived for non-negative values of the axial and radial velocities. Similar results can be derived for other combinations of $u$ and $v$ by consistent application of the process leading to Eq. (4.1.2.19). The result is a general expression for the flux as calculated using skew upwind differencing:

$$\frac{F_{\text{SU}}}{D_W} = P e_w \left[ \sigma_w \phi_w + (1 - \sigma_w) \phi_p \right] - (P e_w - P e_w^*) \left( \sigma_w \left\{ \phi_w - \sigma_w \phi_w + \left( 1 - \sigma_w \right) \phi_w \right\} + (1 - \sigma_w) \left\{ \phi_p - \sigma_w \phi_w - \left( 1 - \sigma_w \right) \phi_w \right\} \right) \tag{4.1.2.20}$$

The parameters, $\sigma_w^u$ and $\sigma_w^v$, are switches that indicate the direction of the components of the local flow velocities

$$\sigma_w^u = \frac{1}{2} \left( 1 + \frac{\left| u_w \right|}{|u_w|} \right) \tag{4.1.2.21}$$
Each of these parameters has a value of unity if the velocity component is positive (or, by convention, non-negative) and zero if it is negative. The transition Peclet number is now given by the general result.

\[ P_{e_w} = \frac{1}{c_w - (1 - c_w)} \]  

(4.1.2.23)

In the hybrid differencing procedure, the more accurate central differencing formulation (Eq. 4.1.2.4) is used when the Peclet number is less than the transition value while the less accurate, but stable, upwind differencing result (the generalization of Eq. (4.1.2.6))

\[ \frac{F_{w_{UD}}}{D_w} = P_{e_w} [c_w^u \phi_w + (1 - c_w^u) \phi_p] \]  

(4.1.2.24)

is used when the Peclet number is greater than the transition value. Originally it was believed that a similar hybrid procedure could be developed for skew upwind differencing with Eq. (4.1.2.4) used for \( P_e < P_{e*} \) and Eq. (4.1.2.20) used for \( P_e > P_{e*} \). However, this approach proved to be unworkable since some of the coefficients derived from this hybrid formulation for use in Eq. (4.1.2.7) can be negative. As an alternative, a flux blending scheme is used in which a weighted average of the upwind differencing and the skew upwind differencing fluxes is used. The weighting (blending) factor, \( \gamma \), is chosen in such a way as to assure boundedness (i.e., all co-efficients of Eq. (4.1.1.7) are non-negative). The bounded skew-upwind differencing (BSUD) flux is defined by

\[ F_{w_{BSUD}} = \gamma_w F_{w_{SUD}} + (1 - \gamma_w) F_{w_{UD}} \]  

(4.1.2.25)

with the weighting factor restricted to the range, \( 0 \leq \gamma_w \leq 1 \). As a consequence of this definition:

\[ \frac{F_{w_{BSUD}}}{D_w} = P_{e_w} [c_w^u \phi_w + (1 - c_w^u) \phi_p] - (P_{e_w} - P_{e_w}^*) \gamma_w k_w \]

\[ \left[ c_w^u \left\{ \phi_w - c_w^v \phi_N - (1 - c_w^v) \phi_M \right\} \right] + (1 - c_w^u) \left\{ \phi_p - c_w^v \phi_S - (1 - c_w^v) \phi_N \right\} \]  

(4.1.2.26)

Finally, a bounded skew hybrid differencing (BSHD) formulation can be defined as:

\[ F_{w_{BSHD}} = \lambda_w F_{w_{CD}} + (1 - \lambda_w) F_{w_{BSUD}} \]  

(4.1.2.27)

where \( \lambda \) is permitted to assume only two values: \( \lambda = 1 \) for central
differencing \( (Pe < Pe^*) \) and \( \lambda = 0 \) for bounded skew-upwind differencing \( (Pe > Pe^*) \). Eqs. (4.1.2.26) and (4.1.2.27) are the basic working relationships to determine the flux at the west face of the control volume. The contributions of the flux to each of the co-efficients in Eq. (4.1.1.7) can be immediately identified by using Eqs. (4.1.2.26) and (4.1.2.27) in Eq. (4.1.1.5).

Equations analogous to Eq. (4.1.2.26) can be derived for the other three faces of the control volume in exactly the same manner as employed above. However, the results can be obtained by inspection as follows:

**East**

The east face flux is obtained by translating the nodal subscripts eastward such that:

<table>
<thead>
<tr>
<th>West Subscript</th>
<th>East Subscript</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>P</td>
</tr>
<tr>
<td>P</td>
<td>E</td>
</tr>
<tr>
<td>SW</td>
<td>S</td>
</tr>
<tr>
<td>NW</td>
<td>N</td>
</tr>
<tr>
<td>S</td>
<td>SE</td>
</tr>
<tr>
<td>N</td>
<td>NE</td>
</tr>
</tbody>
</table>

Of course, the lower case subscript "w" becomes "e".

**South**

The south face flux is obtained from the west flux Eq. 4.1.2.26 by rotating the nodal subscripts through 90 degrees in the counterclockwise

<table>
<thead>
<tr>
<th>West Subscript</th>
<th>East Subscript</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>S</td>
</tr>
<tr>
<td>SW</td>
<td>SE</td>
</tr>
<tr>
<td>NW</td>
<td>SW</td>
</tr>
<tr>
<td>S</td>
<td>E</td>
</tr>
<tr>
<td>N</td>
<td>W</td>
</tr>
<tr>
<td>( \sigma^u )</td>
<td>( \sigma^v )</td>
</tr>
</tbody>
</table>
North

The north face flux is derived by translating the south flux result northward:

<table>
<thead>
<tr>
<th>South Subscript</th>
<th>North Subscript</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>becomes</td>
</tr>
<tr>
<td>P</td>
<td>becomes</td>
</tr>
<tr>
<td>SE</td>
<td>becomes</td>
</tr>
<tr>
<td>SW</td>
<td>becomes</td>
</tr>
<tr>
<td>E</td>
<td>becomes</td>
</tr>
<tr>
<td>W</td>
<td>becomes</td>
</tr>
</tbody>
</table>

The results of the manipulations are summarized in Tables 3 through 5.

4.1.3 - Calculation of the Coefficients for the Finite-Difference Form of the Equations of Motion

The finite-difference form of the equations of motion, (e.g., Eq. (4.1.1.7)) can be derived directly from the flux information presented in Tables 3 through 5 and the sign conventions determined from Eq. (4.1.1.5). The resulting expressions will contain the unknown blending factor, \( \gamma \). The blending strategy requires that the terms in the equations for the coefficients most responsible for producing negative coefficients be isolated so that appropriate values for \( \gamma \) can be determined. Furthermore, the coefficients for the control volumes adjacent to the physical boundaries of the flow may require modification to incorporate the effect of the boundary conditions. Thus, to simplify manipulation and modification, some additional notation will be defined.

Let the center of the control volume (point P) be located at the Ith axial position and Jth radial position. The flux contributions (the components of the total flux) to the east face are denoted as \( E1(I,J) \), \( E2(I,J) \), \( E3(I,J) \) and the flux contributions to the north face are denoted as \( N1(I,J) \), \( N2(I,J) \), \( N3(I,J) \). These flux contributions are defined as follows:
\[
\begin{align*}
1 - u^v & \text{ becomes } 1 - v^u \\
v^v & \text{ becomes } 1 - u^u \\
1 - v^v & \text{ becomes } u^u
\end{align*}
\]

**North**

The north face flux is derived by translating the south flux result northward:

\[
\begin{array}{c|c|c}
\text{South Subscript} & \text{becomes} & \text{North Subscript} \\
\hline
S & \text{becomes} & P \\
P & \text{becomes} & N \\
SE & \text{becomes} & E \\
SW & \text{becomes} & W \\
E & \text{becomes} & NE \\
W & \text{becomes} & NW \\
\end{array}
\]

The results of the manipulations are summarized in Tables 3 through 5.

**4.1.3 - Calculation of the Coefficients for the Finite-Difference Form of the Equations of Motion**

The finite-difference form of the equations of motion, (e.g., Eq. (4.1.1.7)) can be derived directly from the flux information presented in Tables 3 through 5 and the sign conventions determined from Eq. (4.1.1.5). The resulting expressions will contain the unknown blending factor, \( \gamma \). The blending strategy requires that the terms in the equations for the coefficients most responsible for producing negative co-efficients be isolated so that appropriate values for \( \gamma \) can be determined. Furthermore, the coefficients for the control volumes adjacent to the physical boundaries of the flow may require modification to incorporate the effect of the boundary conditions. Thus, to simplify manipulation and modification, some additional notation will be defined.

Let the center of the control volume (point P) be located at the Ith axial position and Jth radial position. The flux contributions (the components of the total flux) to the east face are denoted as \( E(I,J) \), \( E2(I,J) \), \( E3(I,J) \) and the flux contributions to the north face are denoted as \( N1(I,J) \), \( N2(I,J) \), \( N3(I,J) \). These flux contributions are defined as follows:
Central Differencing:

\[
E_1(I,J) = D_E - \alpha_E C_E \\
E_2(I,J) = E_1(I,J) + C_E \\
E_3(I,J) = 0 \\
N_1(I,J) = D_N - \alpha_N C_N \\
N_2(I,J) = N_1(I,J) + C_N \\
N_3(I,J) = 0
\]  \hspace{1cm} (4.1.3.1)

Bounded Skew-Upwind Differencing

\[
E_1(I,J) = (c_e^u - 1) C_E \\
E_2(I,J) = E_1(I,J) + C_E \\
E_3(I,J) = k_e(C_E - P_e D_E) \\
N_1(I,J) = (c_n^v - 1) C_N \\
N_2(I,J) = N_1(I,J) + C_N \\
N_3(I,J) = k_n(C_N - P_n D_N)
\]  \hspace{1cm} (4.1.3.3)

The use of central vs. bounded skew-upwind differencing is determined by the value of the Peclet number at each face. The parameters \( C_E, D_E, \alpha_E, k_e, \ldots \) are local values; the subscripts \((I,J)\) have been omitted in the interest of readability. The corresponding flux contributions at the west face are given immediately by \(E_1(I-1,J), E_2(I-1,J), E_3(I-1,J)\) and the flux contributions at the south face are \(N_1(I,J-1), N_2(I,J-1), N_3(I,J-1)\).

The coefficients of the finite-difference form of the equations of motion may then be defined in terms of these flux contributions. The results are presented in Table 6. The coefficient \(A_p\) can be shown to be equal to the sum of the other eight coefficients when use is made of the mass continuity restriction:

\[
C_E - C_W + C_N - C_S = 0
\]  \hspace{1cm} (4.1.3.5)

The boundary conditions (Section 4.3) and the bounding scheme (Section 4.1.4) can be applied directly to the flux contributions so that the results shown in Table 6 are general.

4.1.4 - The Bounding Scheme

The calculation of the bounded skew-upwind differencing fluxes and, therefore, the determination of the coefficients to the finite-difference form of the equations of motion requires that the blending factor, \( \gamma \), be determined. The blending factor specifies the relative proportions of the flux computed using skew and upwind differencing. For example, at the west face of the typical control volume, Eq. (4.1.2.5) states:
\[
\frac{F_{\text{WSUD}}}{D_{\text{n}}} = \gamma_w F_{\text{SUD}} + (1 - \gamma_w) F_{\text{UD}} \quad (4.1.4.1)
\]

The co-efficients including the local blending factor are listed in Table 6.

It is possible to show that the corner co-efficients (\(A_{SW}^\prime, A_{SE}^\prime, A_{NW}^\prime, A_{NE}^\prime\)) are unconditionally non-negative. For example, consider the coefficient \(A_{SW}^\prime\):

\[
A_{SW} (I,J) = \gamma_w [c^u c^e E^3]_{I-1,J} + \gamma_s [c^u c^N^3]_{I,J-1} \quad (4.1.4.2)
\]

Both \(\gamma_w\) and \(\gamma_s\) are restricted to the range \(0 \leq \gamma \leq 1\). If both the axial and radial velocities at the west face of the control volume are positive, then both \(u\) and \(v\) at this location are unity; in any other case, either (or both) are zero. For positive \(u\) and \(v\) velocities, the flux contribution \(E^3(I-1,J)\) at the west face is positive. Therefore, the west face flux contribution to \(A_{SW}^\prime\) is always nonnegative. The same reasoning when applied to the south face leads to a similar conclusion. Therefore, \(A_{SW}^\prime\) is unconditionally non-negative. The other corner coefficients are treated in the same manner.

Now, consider the four main co-efficients (\(A_w, A_E, A_S, A_N\)). From Table 6:

\[
A_w (I,J) = E^2(I-1,J) - \gamma_w [c^u E^3]_{I-1,J} + \gamma_s [(1-c^v) c^N^3]_{I,J-1} - \gamma_n [c^v c^N^3]_{I,J} \quad (4.1.4.3)
\]

From the definitions of the flux contributions, Eqs. (4.1.3.1) through (4.1.3.4), it is evident that:

1. \(E^2(I-1,J)\) is positive if the axial velocity is positive and it is zero otherwise;

2. \(c^u c^e\) and \(E^3\) at the west face \((I-1,J)\) are positive if the axial velo-
city is positive but \( \frac{\partial u}{\partial e} \) is zero if \( u \) is negative;

(3) from the definitions of \( E_2 \) and \( E_3 \) and the fact that \( \omega \leq 1 \), it is therefore concluded that the first two terms in Eq. (4.1.4.3) must yield a non-negative result;

(4) the third term is zero unless \( u \) is positive and \( v \) is negative at the south face, in which case, it is negative;

(5) the fourth term is non-positive because the term within the brackets is always non-negative.

Therefore, it is possible that the co-efficient \( A_w \) is negative.

It is desirable that all of the co-efficients of the finite-difference form of the equations of motion (Eq. (4.1.1.7)) be non-negative for in this case the value of the dependent variable \( \zeta \) at the node \( P \) is simply a weighted average of the values of \( \zeta \) at the surrounding nodes exclusive of the (somewhat complicating) effects of local sources. A bounding scheme is a procedure to limit the values of the co-efficients of the finite-difference equations in such a manner as to produce this physically realistic result. Its principal computational advantage is to exclude under- and overshoots of the solution during the iterative procedure; these oscillations can produce severe numerical instability.

The bounding procedure used herein is based upon the following sequence:

(1) For convenience, the following quantities are defined:

\[
\hat{a} = E_2(I-1,J) - \gamma_w \left[ -u \right]_{E_3} I,J-1
\]

(4.1.4.4)

\[
\hat{a}_s = -\left[ (1-c_n) c_n^u N_3 \right] I,J-1
\]

(4.1.4.5)

\[
\hat{a}_n = [c_n c_n^u N_3] I,J
\]

(4.1.4.6)

so that

\[
A_w = \hat{a} - \gamma_s \hat{a}_s - \gamma_n \hat{a}_n
\]

(4.1.4.7)

From the previous discussion, \( \hat{a} \geq 0 \), \( \hat{a}_s \geq 0 \) and \( \hat{a}_n \geq 0 \).

(2) It is desired that \( A_w > 0 \). Therefore, the blending factors, \( \gamma_s \) and \( \gamma_n \), are the solution to the linear programming problem

\[
\hat{a}_s \gamma_s + \hat{a}_n \gamma_n \leq \hat{a}
\]

(4.1.4.8)
subject to the constraints

\[ 0 \leq \gamma_s \leq \tilde{\gamma}_s \]  \hspace{1cm} (4.1.4.9)

\[ 0 \leq \gamma_n \leq \tilde{\gamma}_n \]  \hspace{1cm} (4.1.4.10)

(3) The solution to this problem is given by:

If \( \tilde{\gamma}_s \geq \tilde{\gamma}_n \)

\[ \gamma_s = \min \{ \tilde{\gamma}_s, \tilde{\gamma}_s/\tilde{\gamma}_s \} \]  \hspace{1cm} (4.1.4.11)

\[ \gamma_n = \max \{ 0, (\tilde{\gamma}_s - \tilde{\gamma}_s \gamma_s)/\tilde{\gamma}_n \} \]  \hspace{1cm} (4.1.4.12)

If \( \tilde{\gamma}_n \geq \tilde{\gamma}_s \)

\[ \gamma_n = \min \{ \tilde{\gamma}_n, \tilde{\gamma}_n/\tilde{\gamma}_n \} \]  \hspace{1cm} (4.1.4.13)

\[ \gamma_s = \max \{ 0, (\tilde{\gamma}_n - \tilde{\gamma}_n \gamma_n)/\tilde{\gamma}_s \} \]  \hspace{1cm} (4.1.4.14)

The upper limits, \( \tilde{\gamma}_s \) and \( \tilde{\gamma}_n \), are normally equal to unity or are the values determined for the faces of adjacent control volumes; e.g., the west face of the control volume at \((I, J)\) is the east face of the control volume at \((I-1, J)\).

The resulting set of blending factors are then used to compute all of the coefficients in Table 6.

4.2 Source Terms

In this section, the finite-difference approximation to representative source terms of the governing equations are described briefly. From Eqs. (4.1.1.2) and (4.1.1.7) it can be seen that the source term is linearized into a term independent (in an explicit sense) of the dependent variable at the grid node \( P \) and a term explicitly dependent on \( \phi_p \):

\[ S_\phi = S_u + S_p \phi_p \]  \hspace{1cm} (4.2.1)

Then, using Eq. (4.1.1.7), one "solves" for \( \phi_p \):

\[ \phi_p = \frac{I_{Ai} + S_u}{A_p - S_p} \]  \hspace{1cm} (4.2.2)
The determination of $S_u$ and $S_p$ for each dependent variable may be illustrated by considering the source term for the rate of reaction of fuel, Eq. (3.3.5):

$$S_{mf} = - c \frac{f}{k} \min \left[ \frac{A_{mf}}{i}, \frac{A_{O2}}{i}, \frac{ABmpr}{i+1} \right]$$  \hspace{1cm} (4.2.3)

If either the fuel or oxidizer are the minimum of the three rates contained in the brackets, then:

$$S_{mf} = - c \frac{f}{k} A_{mf}$$  \hspace{1cm} (4.2.4)

or

$$S_{mf} = 0 + \left( - \frac{cCA}{k} \right) m_f$$  \hspace{1cm} (4.2.5)

Hence,

$$S_u = 0$$  \hspace{1cm} (4.2.6)

$$S_p = - \frac{cCA}{k}$$  \hspace{1cm} (4.2.7)

But if the third term (the product term) is the minimum, then

$$S_{mf} = - \frac{cCA}{k} \frac{ABmpr}{i+1}$$

$$= - \frac{cCA}{k} AB (f-m_f)$$  \hspace{1cm} (4.2.8)

$$= - \frac{cCA}{k} AB (f-2m_f) - \frac{cCA}{k} ABmpr$$

Then,

$$S_u = - \frac{cCA}{k} AB (f-2m_f)$$  \hspace{1cm} (4.2.9)

$$S_p = - \frac{cCA}{k} AB$$  \hspace{1cm} (4.2.10)

It is seen that Eq. (4.2.9) depends explicitly on the fuel mass fraction; necessarily, $S_u$ is evaluated using the results from the previous iteration.

Numerical stability in the determination of $S$ is enhanced if the coefficient $S_u$ is non-positive. If $S_u$ is positive, then it can be seen that the denominator in Eq. (4.2.2) may become negative (or zero) causing oscillations in the solution for $S_p$. The linearization of the source term
for the fuel mass fraction guarantees that $S_p$ is non-positive.

Other source terms in the governing equations require similar treatment. For example, the source term (per unit volume) in the tangential (swirl velocity) momentum equation is:

$$\frac{S_\omega}{\xi V} = -\frac{2}{r_p} \left( \frac{\partial}{\partial r} (r W_n) \right)$$

which is written in finite-differences as:

$$\frac{S_\omega}{\xi V} = \frac{2}{r_p \Delta r} \left[ r W_n^{n_{eff}} - r W_n^{s_{eff}} \right]$$

It is maintained that the form of Eq. (4.2.12) is essential to preserving the equivalency between the partial differential equation for swirl velocity and the finite-difference approximation. Other forms such as:

$$\frac{S_\omega}{\xi V} = -\frac{2}{r_p \Delta r} \left[ (r W)^{n_{eff}} - (r W)^{s_{eff}} \right]$$

or

$$\frac{S_\omega}{\xi V} = -\frac{2}{r_p \Delta r} \left[ (r W^{eff})^{n} - (r W^{eff})^{s} \right]$$

do not preserve the desired equivalency because the quantities $W_n^{n_{eff}}$, $W_n^{s_{eff}}$, and $W_n^{eff}$ must be interpolated at the desired locations (i.e., at $r_s$ and $r_r$). The source term, when multiplied by the cell volume ($r_p \Delta r \xi$) becomes

$$S_\omega = -2 \Delta r W_n^{n_{eff}} + 2 \Delta r W_n^{s_{eff}}$$

or

$$S_\omega = 2 \Delta r W_n^{s_{eff}} + \left( -\frac{2 \Delta r W_n^{n_{eff}}}{w_p} \right) \omega_p$$

so that

$$S_\omega = 2 \Delta r W_n^{s_{eff}}$$

and

$$S_p = -\frac{2 \Delta r W_n^{n_{eff}}}{w_p}$$

It must be noted that both $w_n$ and $w_n^{n_{eff}}$ may depend on $w_p$ and that the values
of \( w_n \), \( w \), and \( w \) in Eqs. \((4.2.17)\) and \((4.2.18)\) are obtained from values at the previous iteration.

4.3 Boundary Conditions

The boundary conditions are applied to the flux contributions as defined by Eqs. \((4.1.3.1)\) through \((4.1.3.4)\) so that the set of coefficients (e.g., Table 6) for each dependent variable is the same throughout the computational domain. This consistency simplifies the application of both (1) the algorithm for solving the set of simultaneous equations for each variable and (2) the bounding procedure.

The boundary conditions are applied to the control volumes in the vicinity of the physical boundaries for the flow field (see Fig. 1). Thus, the left-most control volumes include either the main flow or secondary flow inlets or the bluff body. The right-most control volumes include the combustor outlet. The top-most control volumes include a solid wall while the bottom-most control volumes include the axis of symmetry.

**Inlets**

The flows in either the main or secondary inlet are known and specified. It is assumed that constant values of axial velocity, swirl velocity, turbulence intensity, fuel concentration, and temperature are known for each inlet. The radial velocity is assumed to be zero and the static pressure is assumed to be the same for both inlets.

**Axis of Symmetry**

At the axis of symmetry, the normal gradient for each dependent variable, except for the radial velocity, is assumed to vanish; the radial velocity is assumed to be zero. By setting the co-efficients \( A_n \) and \( A_r \) to zero for the radial gridline adjacent to the axis of symmetry, then the finite difference form of the normal gradient becomes:

\[
\left( \frac{\Delta t}{\Delta r} \right)_{\text{Axis of symmetry}} = 0 \quad (4.3.1)
\]

For all variables, except the radial velocity, the axis of symmetry is located midway between the \( J=1 \) and \( J=2 \) radial gridlines. For the converged solution, the boundary condition (Eq. \((4.3.1)\)) produces the result:

\[
q_{1,1} = q_{1,2} \quad (\neq v) \quad (4.3.2)
\]

where \( I \) is the axial gridline index. For the radial velocity, the axis of symmetry and the radial gridline for radial velocity are coincident and the boundary condition becomes:

\[
v_{1,1} = 0 \quad (4.3.3)
\]
Outlet

At the outlet of the combustor, the axial gradient in all variables except axial velocity is assumed to vanish. By setting the co-efficients \( A_r \) and \( A_s \) at the outlet to zero, the finite-difference approximation to the gradient becomes

\[
\left( \frac{\partial \psi}{\partial x} \right)_{\text{outlet}} = 0
\]

so that

\[
\psi_{NI,J} = \psi_{NI-1,J}
\]

(4.3.5)

where \( NI \) is the number of axial grid lines. For the axial velocity, a velocity correction \( U_{INC} \) is applied uniformly so that

\[
U_{NIU,J} = U_{NIU-1,J} + U_{INC}
\]

(4.3.6)

where \( NIU = NI-1 \). The correction \( U_{INC} \) is the velocity increment necessary to conserve mass flow at the outlet.

Solid Wall

If the resolution of the grid system could be made arbitrarily fine in the vicinity of a wall, then application of the appropriate boundary conditions at the wall would be straightforward. For example, the velocity components \( u, v, w \) vanish at a wall. However, for a realistic grid system, setting the velocity to zero for components of the velocity vector parallel to the wall (by adjusting the co-efficients of the finite-difference equations) is improper because the co-efficients do not properly account for the effects of the wall; i.e., the shear is computed incorrectly. Instead, wall functions are used to compute contributions to the source terms in the governing equations. For a velocity component normal to the wall, the co-efficients may be adjusted so that this velocity component vanishes. (See the discussion for the axis of symmetry boundary condition.)

Consider the case for which the axial velocity is parallel to a wall. The flow in the region near the wall is assumed to behave as one-dimensional Couette flow. For turbulent flow, the shear stress is assumed to be constant in the Couette flow region except in the laminar sublayer immediately adjacent to the wall. Following Launder and Spalding (Ref. 2), the laminar sublayer extends from the wall to \( y^+ = 11.63 \) where

\[
y^+ = \left( \frac{\rho C_L k \sqrt{k} y}{u^*_l} \right)_P
\]

(4.3.7a)

with the density, molecular viscosity, turbulent kinetic energy and grid distance from the wall evaluated at node \( P \). If \( y^+ \) is less than 11.63, then the shear stress is given by:
\[ \tau_w = \left( \frac{u}{y} \right)_p \]  

(4.3.7b)

Otherwise the point P is within the turbulent flow region and the shear stress is calculated using the logarithmic law of the wall so that

\[ \tau_w = \left[ \xi C_{-} k \sqrt{k} \frac{u}{\ln (Ey^+)} \right]_p \]  

(4.3.8)

Here \( K \) and \( E \) are constants given in Table 1. The shear stress contribution to the source term for the axial velocity momentum equation is

\[ S_p \dot{u}_p = \left[ - \frac{\tau_w}{u_p} A_r \right] u_p + \ldots \]  

(4.3.9)

where \( A_r \) is the area of the face of the control volume adjacent to the wall.

The influence of the walls on the \( v \) and \( w \) velocity components is treated similarly. Of course, the normal distance \( y \) in Eq. (4.3.7) must be interpreted appropriately. For swirling flows, the shear stress on the top wall must be resolved into axial and azimuthal components.

For the turbulent kinetic energy equation, the coefficient corresponding to the wall node is set to zero and the source term (see Eq. 3.2.2) is given by:

\[ S_k = t_k C - \left[ \frac{3}{4} C_k \frac{k}{C_L} \frac{y^+}{y} \right]_p , \ y^+ < 11.63 \]  

(4.3.10)

\[ S_k = t_k C - \left[ \frac{3}{4} C_k \frac{k}{C_L} \frac{\ln (Ey^+) / (Ky)}{ Ky} \right]_p , \ y^+ > 11.63 \]  

(4.3.11)

The shear stress evaluated above is used in the generation term \( G \) to compute \((\nabla \cdot \dot{u} u/\partial y)\).

The turbulent dissipation rate, \( \varepsilon \), is computed in the vicinity of a wall by assuming that the rates of turbulent kinetic energy generation and dissipation are equal so that the value of \( \varepsilon \) at the edge of the Couette flow region is given by:

\[ \varepsilon_p = \left[ \frac{3}{4} C_k k}{Ky} \right]_p \]  

(4.3.12)
By defining the source for $\epsilon$ as

$$S_\epsilon = 10^{30} + 10^{30} \epsilon_p$$

(4.3.13)

then by Eq. (4.1.1.7), $\epsilon_p = \epsilon_p$.

For both the mixture fraction, $f$, and the fuel mass fraction, $m_f$, it is assumed that the flux normal to the wall vanishes. Thus, for both $f$ and $m_f$, this boundary condition is mathematically identical to the axis of symmetry boundary condition.

The enthalpy at the wall is determined using Eq. (3.3.2) with the wall temperature specified and the fuel mass fraction calculated as above.

$$h_{\text{wall}} = m_{f,\text{wall}} H_R + C_{p,m} T_{\text{wall}}$$

(4.3.14)

### 4.4 Pressure Implicit Split Operator

The finite-difference approximations to the governing equations are solved using the Pressure Implicit Split Operator (PISO) developed at Imperial College by Issa (Ref. 6). The finite-difference equations are solved iteratively. The velocities are first calculated from the momentum equations using a guessed pressure distribution; then the pressure distribution is adjusted so that the velocities satisfy the mass continuity equation and the cycle is repeated.

The PISO algorithm involves splitting operations that couple the velocity and pressure variables.

Let the superscripts *, ** and *** denote intermediate field values obtained during the operation of the algorithm which consists of a predictor step and two corrector steps.

**Predictor Step** - The pressure distribution prevailing at the $n$th iteration is used in the solution of the axial and radial velocity momentum equations which can be written in the general form:

$$A^u_i u^*_i = \sum_m A^u_i u^*_m + D^u_i \Delta^p_i P^n + S^u_i$$

(4.4.1)

where $U_i$ represents either of the velocity components, $u$ or $v$, and the operator $\Delta^i_p$ is a difference operator given by

$$\Delta^i_p = p_w - p_e$$ for $u_i = u$

$$= p_s - p_n$$ for $u_i = v$$

(4.4.2)
The subscript \( m \) denotes the nodes, E, W, NE, . . .

**First Corrector Stage** - A new velocity field \( u_i^{**} \) together with a corresponding new pressure field \( p^* \) are calculated such that the zero divergence (incompressible continuity) condition

\[
\Delta u_i^{**} = 0 \quad (4.4.3)
\]

is satisfied. The momentum equation is now written as:

\[
A_p^{u_i} u_i^{**} = \sum_m A_m^{u_i} u_i^{**}_m - D_p^{u_i} \Delta_i p^* + S_p^{u_i} \quad (4.4.4)
\]

By subtracting Eq. (4.4.1) from Eq. (4.4.4), a velocity-increment equation is obtained:

\[
A_p^{u_i} (u_i^{**} - u_i^*) = D_p^{u_i} \Delta_i (p^* - p^n) \quad (4.4.5)
\]

Combining the divergence of this equation with Eq. (4.4.3) the pressure-correction equation is obtained:

\[
L_i \left[ A_p^{u_i-1} D_p^{u_i} \Delta_i \right] p' = \Delta_i u_i^* \quad (4.4.6)
\]

where

\[
p' = p^* - p^n \quad (4.4.7)
\]

Eq. (4.4.6) is solved for the \( p' \) field so that the revised pressure distribution \( p^* \) is determined and a new velocity field \( u_i^{**} \) is calculated.

**Second Corrector Step** - A new velocity field \( u_i^{***} \) together with a corresponding pressure distribution \( p^{**} \) are calculated such that

\[
\Delta_i u_i^{***} = 0 \quad (4.4.8)
\]

The momentum equation is now written as:

\[
L_p^{u_i} u_i^{***} = \sum_m A_m^{u_i} u_i^{***}_m - D_p^{u_i} \Delta_i p^{**} + S_p^{u_i} \quad (4.4.9)
\]

Subtracting Eq. (4.4.5) from Eq. (4.4.9) yields:

\[
A_p^{u_i} (u_i^{***} - u_i^{**}) = \sum_m A_m^{u_i} (u_i^{**} - u_i^*) - D_p^{u_i} \Delta_i (p^{**} - p^*) \quad (4.4.10)
\]

This equation combined with the continuity relations (4.4.3) and (4.4.8) yields the second pressure-correction equation:

\[
L_i \left[ A_p^{u_i-1} D_p^{u_i} \Delta_i \right] p'' = \Delta_i \left[ A_p^{u_i-1} \sum_m A_m^{u_i-1} (u_i^{**} - u_i^*) \right] \quad (4.4.11)
\]

where
\[ p'' = p^{**} - p^* \] (4.4.12)

Eq. (4.4.11) is solved for the \( p'' \) field so that the revised pressure distribution \( p^{**} \) is computed and a new velocity field \( u_i^{***} \) is determined. The pressure and velocity distributions for the \((n+1)\)th iteration are taken as \( p^{**} \) and \( u_i^{***} \), respectively.

A similar procedure is used for the turbulent kinetic energy and turbulent energy dissipation equations because these equations are strongly coupled by means of their source terms. The equations for \( k \) and \( \varepsilon \) are first solved for the source term components based on the previous iteration values. A corrector step is then applied to account for the changes in the source terms.
5.0 DESCRIPTION OF COMPUTER PROGRAM

The computer program based on the mathematical model described in Section 3.0 is described in this section. Information is presented to assist the user in the installation of the program on modern large-scale computers. Additionally, an input format is provided.

5.1 General Remarks

The computer program is intended for use in the batch-operating mode on modern large-scale computers. Specifically, programming constructions have been avoided that refer to the characteristics of specific computer operating systems. In addition, all logical units referred to by the program are defined using integer constants initialized in the BLOCK DATA routine BLOCKD. In the present version of the program, these logical units have been assigned as follows:

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>LU4</td>
<td>4</td>
<td>Restart file</td>
</tr>
<tr>
<td>LU5</td>
<td>5</td>
<td>Card reader</td>
</tr>
<tr>
<td>LU6</td>
<td>6</td>
<td>Line printer</td>
</tr>
<tr>
<td>LU8</td>
<td>8</td>
<td>Scratch unit</td>
</tr>
<tr>
<td>LU9</td>
<td>9</td>
<td>Scratch unit</td>
</tr>
</tbody>
</table>

The program may be stopped periodically and the results stored in the restart file, LU4. The calculation may subsequently be continued from the latest iteration by using the restart file in conjunction with the options described on Card No. 2 of the Input Format, Section 5.7.

The present program was derived from the development version provided by Imperial College to UTRC. The Imperial College computer is taken to be a CDC 6600 computer with a FORTRAN IV compiler. Except for eliminating two minor incompatible constructions and the CDC PROGRAM card, the development program was completely compatible with the FORTRAN V compiler used on the UNIVAC 1100/81A computer at UTRC. For the convenience of users of CDC computers, the PROGRAM card has been retained but rendered inoperable in the present version (see routine AMAIN, lines 1-2). It is believed that the present version is also compatible with the IBM FORTRAN IV compiler.

No attempt was made to compile the present version of the program using the UNIVAC 1977 ASCII FORTRAN compiler since it would have been necessary to eliminate any incompatibilities between the constructions used in the development version and the 1977 ASCII standard; in addition, it is known that some 1977 ASCII standard compilers are not compatible with each other.

The workers at Imperial College have indicated throughout the program those sections of the code that are restricted to flow within a research combustor of the type shown in Fig. 1. They have labeled these sections of
the code as "Problem Dependent". No attempt has been made to determine if other sections of the code should be designated in a similar manner.

The computer program can be allocated in approximately 50000 decimal words, or 200000 bytes.

5.2 Program Flow Chart

A general flow chart of the computer program is shown in Fig. 6. The input to the program is read in subroutine MODINP; additional constants are initialized in the BLOCK DATA routine. Initial guesses are assigned for the distributions of each of the field variables. The program then proceeds as follows:

1. A pressure distribution is guessed. For the first iteration, the estimated pressure distribution is provided by subroutine MODINP. On subsequent iterations, it is assumed to be the distribution determined at the end of the previous iteration.

2. The axial and radial momentum equations are solved for the axial and radial velocity distributions using subroutines COEFU and COEFV.

3. The pressure-correction equations (i.e., the PISO algorithm) are solved using subroutine CALUVP to obtain the corrected pressure, axial velocity and radial velocity distributions.

4. The swirl velocity (actually, the product of radius and swirl velocity) distribution is solved for using subroutine CALCFL.

5. The turbulent kinetic energy and energy dissipation rate are determined using subroutine CALCFL.

6. The turbulent kinetic energy and energy dissipation rate are adjusted using the predictor-corrector technique noted in Section 4.4.

7. The distributions of the remaining dependent variables (e.g., enthalpy, mixture fraction, fuel concentration) are calculated using subroutine CALCFL.

8. The absolute values of the normalized residuals for each variable are examined at all points in the flow field. If the residuals are all less than a specified maximum value, the solution is considered to be converged; otherwise, the iteration is repeated from Step 1.

The distributions for each variable are solved using a line-by-line iterative procedure which utilizes a tridiagonal matrix algorithm (subroutine LISOLV) to solve simultaneously for the variables along each grid line. An alternating direction scanning procedure is employed to sweep the whole
The number of sweeps is usually different for each variable. Generally, two sweeps are used for the axial and radial velocities and one sweep is used for all other variables except for the primary pressure correction equation. Since this equation is strongly elliptic and has Neumann boundary conditions specified at all boundaries, at least three sweeps are generally made.

5.3 Description of Routines

A brief description of each of the routines used in the computer program is presented in this section. The principal FORTRAN variables are listed in Section 5.4, the entry point and external reference table is presented in Section 5.5, the source language listings are displayed in Section 5.6, and the input format is presented in Section 5.7.

AMAIN

AMAIN is the main program whose principal operation is to control the progress of the iterative solution described in the previous section. Additionally, AMAIN controls the rate of intermediate printout (e.g., the printing of the maximum residuals and values of the dependent variables at the monitoring grid node) and it determines which of the distributions for the dependent variables will be displayed by subroutine PRINT. For reacting flows, this routine initiates the combustion reaction by introducing at the iteration ITREAX an artificial difference in the mixture fraction and fuel concentration (e.g., by setting \( m_f = 0.9f \)) at the monitoring grid node (IMON, JMON). Finally, AMAIN retrieves dependent variable distributions from the file on logical unit LU4 to restart a calculation; and it stores these distributions in the same file at the end of the current execution so that the case may be started subsequently from the latest iteration.

BLOCKD

The BLOCK DATA routine initializes certain print heading arrays, assigns values to the constants used for logical units and for the turbulence model, and sets some miscellaneous controls.

BOUNDS

This subroutine determines the values of the flux blending factor used to adjust the flux contributions to the coefficients of the finite-difference equations such that the coefficients are non-negative. The bounding procedure is described in Section 4.1.4. It should be noted that \( \gamma \) does not appear explicitly in this subroutine; instead, the values of the flux contributions are reduced in accordance with the bounding procedure.

CALCFI

Subroutine CALCFI is a general subroutine for calculating the distributions of all scalar variables and the product of swirl velocity with radial position. The coefficients of the finite-difference equations are calculated for each variable (i.e., for each call to CALCFI). In some cases, it is known that the coefficients for one scalar are simply related
to those for another. A provision is made to determine one set of coefficients from the other without the need to recompute all of the flux contributions. Often, two sets have identical values or differ only by the ratio of the Prandtl numbers for each variable. The source term contributions to the finite-difference equations are then calculated by calling subroutine SORCFI. The modifications to the coefficients due to the boundary conditions are determined by calling subroutine MODFI. The coefficients are then bounded using subroutine BOUNDS. The underrelaxation factors are then applied. The system of simultaneous equations is then solved using subroutine LISOLV.

**CALUVP**

Subroutine CALUVP uses the coefficients assembled in subroutines COEFU and COEFV for the axial and radial momentum equations to solve for the initial estimates of the axial and radial velocity distributions, respectively, for the current iteration. The coefficients for the finite-difference form of the primary and secondary pressure-correction (predictor-corrector) equations are then calculated and the final velocity fields are determined. (See the discussion of the PISO algorithm, Section 4.4.)

**COEFU**

Subroutine COEFU is used to calculate the coefficients of the finite-difference form of the axial momentum equation. First, the convection and diffusion contributions to the coefficients are calculated. Next, the components of the source term are determined. The flux contributions to the finite-difference coefficients are then calculated. The effects of the boundary conditions are incorporated by calling the entry point MODU of subroutine MODUVP. The bounding strategy is then applied by using subroutine BOUNDS. Finally, the coefficients are stored for use by subroutine CALUVP.

**COEFV**

Subroutine COEFV is used for calculating the coefficients for the finite-difference form of the radial momentum equation. Its operation is similar to that of subroutine COEFU. The boundary conditions are applied by calling the entry point MODV of subroutine MODUVP.

**CORECT**

This subroutine determines the values of the flux blending factor used by subroutine BOUNDS to limit the coefficients of the finite-difference equations to non-negative values.

**CORTED**

The turbulent kinetic energy and energy dissipation rate equations are strongly coupled to each other by their source terms. Subroutine CORTED performs a predictor-corrector operation for the two equations to provide more accurate estimates of these variables and thereby improve the rate of convergence of the entire system of equations.
INIT

Subroutine INIT defines the grids used in the calculation, determines cell dimensions for the control volumes, and calculates the factors used for interpolating variables at each face of the control volumes. The subroutine also initializes all arrays to appropriate values.

LISOLV

This subroutine solves the system of simultaneous finite-difference equations for each variable using an alternating direction method with a tridiagonal matrix solution algorithm. The first sweep of the system of equations is from west to east, the second from south to north, etc. The total number of sweeps is specified for each variable in the input.

MODFI

Subroutine MODFI is used to modify the coefficients of the finite-difference equations for each scalar variable due to the influence of the boundary conditions appropriate for that variable. The scalars are: turbulent kinetic energy, turbulent energy dissipation rate, enthalpy, fuel mass fraction, mixture fraction, and swirl velocity (actually, the product of swirl velocity with radial position). The boundary conditions are described in Section 4.3.

MODINP

This subroutine reads the input cards, writes the input on the line printer, sets all logical variables, calculates the reference values for the residuals, and initializes the dependent variables.

MODUVP

Subroutine MODUVP modifies the coefficients for the axial and radial momentum equations and for the pressure-correction coefficients in accordance with the boundary conditions (Section 4.3). The entry point MODPRO was provided by the authors of the program at Imperial College to deal with the effects of transport properties on the coefficients that are not incorporated elsewhere in the program; presently, this entry point contains no executable code.

OUTPUT

Subroutine OUTPUT prints the values of selected integrated quantities (main flow rate, secondary flow rate, etc.) and other parameters that characterize the flow field. For reacting flows, the distributions of oxygen, nitrogen, water vapor, and carbon dioxide are also printed.

PRINT

This subroutine generates a printout of the tabulated values of the field variables.
PROPS

Subroutine PROPS is used to determine the fluid properties at each point in the flow field. It is assumed that the main flow contains air with an oxygen mass fraction of 0.233 and a nitrogen mass fraction of 0.767. The average heat capacity, molecular weight, and density can then be determined. The viscosity at each point in the flow field is the sum of the laminar viscosity and turbulent viscosity. The effective diffusivity for the turbulent kinetic energy equation is also calculated. The diffusivities for other scalars are determined in subroutine CALCFI by multiplying the diffusivity for the turbulent kinetic energy equation by the ratio of the turbulent Prandtl number for another scalar to that for the turbulent kinetic energy.

SORCFI

This subroutine calculates the linearized source term components for each scalar in accordance with Section 4.2.

5.4 Principal FORTRAN Variables

The principal FORTRAN variables are listed in this section. The variables are arranged in logically occurring groups rather than in strict alphabetical order. Variables written as var(I,J) denote two-dimensional arrays defined for each axial gridline location I and each radial gridline location J.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE(I,J)</td>
<td>Coefficients for the finite-difference equation for the control volume at point (I,J).</td>
</tr>
<tr>
<td>AW(I,J)</td>
<td>E = east, W = west, etc., P = point (I,J)</td>
</tr>
<tr>
<td>AN(I,J)</td>
<td></td>
</tr>
<tr>
<td>AS(I,J)</td>
<td></td>
</tr>
<tr>
<td>ANE(I,J)</td>
<td></td>
</tr>
<tr>
<td>ANW(I,J)</td>
<td></td>
</tr>
<tr>
<td>ASE(I,J)</td>
<td></td>
</tr>
<tr>
<td>ASW(I,J)</td>
<td></td>
</tr>
<tr>
<td>AP(I,J)</td>
<td></td>
</tr>
<tr>
<td>CAPPA,ELOG</td>
<td>Constants in the velocity law of the wall</td>
</tr>
<tr>
<td>CCEN,CIN</td>
<td>Input mass fraction of second species (fuel) in secondary and main stream, respectively.</td>
</tr>
<tr>
<td>CMU,CD,C1,C2</td>
<td>Constants in the two-equation turbulence model</td>
</tr>
<tr>
<td>CPM(I,J)</td>
<td>Specific heat of mixture</td>
</tr>
<tr>
<td>CPO2</td>
<td>Specific heats of oxygen, nitrogen, carbon dioxide, water vapor and fuel, respectively</td>
</tr>
<tr>
<td>CPN2</td>
<td></td>
</tr>
<tr>
<td>CPCO2</td>
<td></td>
</tr>
<tr>
<td>CPH20</td>
<td></td>
</tr>
<tr>
<td>CPF</td>
<td></td>
</tr>
<tr>
<td>DELCEN,DELTA</td>
<td>Input value of boundary layer thicknesses for secondary and main stream, respectively</td>
</tr>
</tbody>
</table>
DEN(I,J)  Density  
DENSIT  Input value for density for incompressible flow case  
ED(I,J)  Turbulent kinetic energy dissipation rate  
EN(I,J)  Enthalpy  
E1(I,J)  Flux contributions, east face of control volume  
E2(I,J)  
E3(I,J)  
F(I,J)  Mixture fraction  
FM(I,J)  Fuel mass fraction  
FN1(I,J)  Flux contributions, north face of control volume  
FN2(I,J)  
FN3(I,J)  
F02  Mass fraction of oxygen, nitrogen, carbon dioxide, water vapor, and products of reaction, respectively  
FN2  
FCO2  
FH20  
FPR  
GAMH(I,J)  Diffusivity for turbulent kinetic energy  
HR  Heat of reaction  
IED  Parameters used to set the logical array INCAL for turbulent energy dissipation rate, enthalpy, mixture fraction, fuel mass fraction, primary and secondary pressure corrections, swirl velocity, turbulent kinetic energy, axial velocity, and radial velocity, respectively  
IEN  
IF  
IFM  
IP  
IPP  
ISWR  
ITE  
IU  
IV  
IMON,JMON  Location for grid node used to monitor the calculation  
INCAL  Linear array for the logical variable that determines if the differential equation for the Kth dependent variable is to be solved (INCAL(K)=.TRUE.) or not solved (INCAL(K)=.FALSE.)  
INCOMP  Logical variable indicating whether flow is compressible (.FALSE.) or incompressible (.TRUE.)  
INDCOS  Parameter to indicate whether flow is two-dimensional (1) or axisymmetric (2)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>INDPRI</td>
<td>The number of iterations between the output of the tabulated field variables</td>
</tr>
<tr>
<td>INPRO</td>
<td>Logical variable indicating whether flow properties are constant (.FALSE.) or variable (.TRUE.)</td>
</tr>
<tr>
<td>IPREF,JPREF</td>
<td>Location of reference pressure node</td>
</tr>
<tr>
<td>ISCEME</td>
<td>Parameter indicating whether hybrid differencing (1) or skew-upwind differencing (2) is to be used</td>
</tr>
<tr>
<td>IT, JT</td>
<td>Maximum dimensions of the arrays var (I,J)</td>
</tr>
<tr>
<td>ITREAX</td>
<td>Iteration at which chemical reaction starts</td>
</tr>
<tr>
<td>ITSTEP</td>
<td>Number of iterations to be performed for current execution</td>
</tr>
<tr>
<td>IVISCO</td>
<td>Logical variable indicating whether viscosity is constant (.TRUE.) or variable (.FALSE.)</td>
</tr>
<tr>
<td>JEXIT</td>
<td>Radial grid line number for location of maximum radius at exit</td>
</tr>
<tr>
<td>JINS</td>
<td>Radial grid line number for location of maximum radius for secondary inlet</td>
</tr>
<tr>
<td>MAXIT</td>
<td>The maximum number of iterations to be executed</td>
</tr>
<tr>
<td>MAXSWP</td>
<td>The maximum number of sweeps to be executed by LISOLV for solving the pressure-correction equation</td>
</tr>
<tr>
<td>MODOP</td>
<td>Parameter indicating whether a new case is being started (1) or a previous case is being run using the Restart file (2)</td>
</tr>
<tr>
<td>NI, NJ</td>
<td>Number of input axial gridline and radial grid line locations, respectively</td>
</tr>
<tr>
<td>NSWP</td>
<td>A linear array denoting the number of sweeps to be used when solving for each of the dependent variables</td>
</tr>
<tr>
<td>NUMPRI</td>
<td>The number of iterations between output of the maximum residuals and monitoring node information</td>
</tr>
<tr>
<td>P(I, J)</td>
<td>Pressure</td>
</tr>
<tr>
<td>PERR</td>
<td>Maximum allowable residual in pressure correction equation</td>
</tr>
<tr>
<td>PIN</td>
<td>Input value of pressure</td>
</tr>
<tr>
<td>PRANDL</td>
<td>Laminar Prandtl number</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
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<tr>
<td>----------</td>
<td>-----------------------------------------------------------------------------</td>
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<tr>
<td>PRANDT</td>
<td>A linear array of turbulent Prandtl numbers for each dependent variable</td>
</tr>
<tr>
<td>PREF</td>
<td>Reference pressure at node (IPREF,JPREF)</td>
</tr>
<tr>
<td>PP(I,J)</td>
<td>Pressure correction</td>
</tr>
<tr>
<td>SORMAX</td>
<td>Maximum allowable residual for any dependent variable</td>
</tr>
<tr>
<td>SNORM</td>
<td>A linear array of the maximum residuals for the dependent variables</td>
</tr>
<tr>
<td>SP(I,J)</td>
<td>Coefficients in linearized source term that are dependent on and independent of the dependent variable at (I,J), respectively</td>
</tr>
<tr>
<td>SU(I,J)</td>
<td>Coefficients in linearized source term that are dependent on and independent of the dependent variable at (I,J), respectively</td>
</tr>
<tr>
<td>STOIC</td>
<td>Stoichiometric oxygen to fuel mass ratio</td>
</tr>
<tr>
<td>T(I,J)</td>
<td>Temperature</td>
</tr>
<tr>
<td>TE(I,J)</td>
<td>Turbulent kinetic energy</td>
</tr>
<tr>
<td>TCEN,TIN</td>
<td>Input values of temperature for secondary and mainstream, respectively</td>
</tr>
<tr>
<td>TURBCN,TURBIN</td>
<td>Input values of constant of proportionality for turbulent kinetic energy for secondary and mainstream, respectively</td>
</tr>
<tr>
<td>U(I,J)</td>
<td>Axial velocity</td>
</tr>
<tr>
<td>UCEN,UIN</td>
<td>Input values of axial velocity for secondary and mainstream, respectively</td>
</tr>
<tr>
<td>UGC</td>
<td>Universal gas constant</td>
</tr>
<tr>
<td>URF</td>
<td>Linear array for underrelaxation factors for dependent variables except for density and viscosity</td>
</tr>
<tr>
<td>URFDEN</td>
<td>Underrelaxation factor for density</td>
</tr>
<tr>
<td>URFVIS</td>
<td>Underrelaxation factor for viscosity</td>
</tr>
<tr>
<td>V(I,J)</td>
<td>Radial velocity</td>
</tr>
<tr>
<td>VIS(I,J)</td>
<td>Total (laminar plus turbulent) viscosity</td>
</tr>
<tr>
<td>VISCOS</td>
<td>Input value of laminar viscosity</td>
</tr>
<tr>
<td>W(I,J)</td>
<td>Swirl velocity</td>
</tr>
<tr>
<td>WCEN,WIN</td>
<td>Input values of swirl to axial velocity ratio for secondary and main stream, respectively</td>
</tr>
</tbody>
</table>
**XU**
Input linear array of axial locations of axial velocity grid lines

**YV**
Input linear array of radial locations of radial velocity grid lines

### 5.5 Entry Points and External References

The entry points for each routine and the external references by each routine are listed in this section. An asterisk is used to denote external references to FORTRAN library routines.

<table>
<thead>
<tr>
<th>Routine</th>
<th>Entry Points</th>
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5.6 Source Listings of Routines

The listing of the FORTRAN source language for each routine is presented in this section.
C
CHAPTER 1 1 1 1 1 1 INPUT DATA 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
C
CHAPTER 2 2 2 2 2 2 INITIAL OPERATIONS 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
C
CALL PARAM
C
CALL PRELIM
IF (.NOT., READ) GO TO 30
READ(LU4) NITER, U, V, P, TE, E0, EN, FM, F, VIS, UEN, W
REWIND LU4
CALL STAHTV
30 CONTINUE
CALL INITOP
C
CHAPTER 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 ITERATION LOOP 3 3 3 3 3 3 3 3 3 3 3 3 3
C
WRITE(LU6, 310) IMON, JMON
NITERS = NITERS + 1
NITERE = NITERE - NSTEP
DO 300 NITER = NITERS, NITERE
DO 333 I = 1, NI
DO 333 J = 1, NJ
DUI(I, J) = 0.0
333 CONTINUE
C
START CHEMICAL REACTION?
C
IF (NITR = NITE + 1) FM(IMON, JMON) = 0.99 * FM(IMON, JMON)
C
UPDATE FLUID PROPERTIES
C
CALL PROPS
C
UPDATE MAIN DEPENDENT VARIABLES
C
IF (INCAL(1)) CALL COEFU
IF (INCAL(2)) CALL COEFV
IF (INCAL(3)) CALL CALUVP
IF (.NOT., INCAL(9)) GO TO 113
DO 111 I = 2, NI
JSTR = JSTR(I)
JEND = JEND(I)
DO 111 J = JSTR, JEND
111 GAMH(I, J) = VIS(I, J)
DO 200 I = 1, NI
W(I, 1) = W(I, 1) * R(2)
DO 200 J = 2, NJ
200 W(I, J) = W(I, J) * R(2)
DO 210 I = 1, NI
W(I, 1) = W(I, 1) / R(2)
DO 210 J = 2, NJ
210 W(I, J) = W(I, J) / R(2)
113 CALL GAM
C
IF (INCAL(4)) CALL CALCFI(TE, ITE, 1)
IF (INCAL(5)) CALL CALCFI(E0, IEU, 2)
IF (INCAL(4)) CALL CORTE
IF (INCAL(6)) CALL CALCFI(EN, IEN, 2)
IF (INCAL(7)) CALL CALCFI(FM, IFM, 0)
IF (INCAL(8)) CALL CALCFI(F, IF, 0)
C
UPDATE BOUNDARY CONDITIONS
C
IF (IU = 1) RLSOR(IU) = RLSOR(IU) / SQRT(IU)
C-----CONDITIONAL STORAGE OF RESULTS-------------------------------
101 IF( .NOT. WRITE ) STOP
102 WRITE (LU4) NITER, U, V, P, T, LD, EN, FM, F, VIS, DLN, W
103 REWIND LU4
104 STOP
105 C-----FORMAT STATEMENTS
106 310 FORMAT (10H, 7HITER, 107H1) ----ABSORUTE RESIDUAL SOURCE
107 1 SUMS-------------I 1-----FIELD VALUES AT MONITORING LOCALITY
108 2N, 1H1, 12, 1H, 12, 1H, 19H----------1 / 2X, 3HNO, 5X, 4HUMOM, 5X, 4HUMOM,
109 35X, 4HUMOM, 5X, 4HMASS, 5X, 4HENTH, 5X, 4HT EN, 5X, 4HDISS, 12X, 1HU, 8X,
110 41H, 8X, 1H, 8X, 1HP, 8X, 2HT, 8X, 1HD/9X, 6HF, CONC, 3X, 6HM, FRC,
111 54X, 2HEN, 8X, 1HT, 7X, 2HFM, 8X, 1HF/1
112 311 FORMAT (1H, 15, 2X, 1P7E9.2, 5X, 1P6E9.2/7X, 1P2E9.2, 5UX, 1P4E9.2/)
113 320 FORMAT (/**69H *** PROGRAM TERMINATED BEFORE CONVERGENCE CRITERIO
114 IN SATISFIED ***))
115 END
DATA IT, JT/30, 30/
DATA CMU, CU, C1, C2, CAPPA, ELGU/0.99, 1.00, 1.44, 1.92, C.4187
DATA LU4, LU5, LU6, LJR, LJ9/4, 5, 6, 8, 9/
RESJML, P PK4
SUBROUTINE BOUNDS (IENDIN, JENDIN)

C------SUBROUTINE TO CALCULATE COEFFICIENTS FOR HBSO SCHEME

COMMON

1/COMMON U(30, 30), V(30, 30), P(30, 30), T(30, 30), E(30, 30), Z(30, 30), A(30, 30)
2/ FM(30, 30), P(30, 30), V(30, 30), P(30, 30), T(30, 30), E(30, 30), Z(30, 30), A(30, 30)
3/ DEN(30, 30), G(30, 30), H(30, 30), I(30, 30), J(30, 30), K(30, 30), L(30, 30)
4/ AE(30, 30), AN(30, 30), AP(30, 30), AQ(30, 30), AR(30, 30), AS(30, 30), AT(30, 30)
5/ ASW(30, 30), ASE(30, 30), ANW(30, 30), AEN(30, 30)
6/ SU(30, 30), SP(30, 30), SR(30, 30), T(30, 30), U(30, 30), V(30, 30), W(30, 30)
7/ AX(30, 30), BI(30, 30), DM(30, 30), JS(30, 30), HJ(30, 30), RV(30, 30)
8/ XSW(30, 30), XST(30, 30), XSW(30, 30), XST(30, 30), XSV(30, 30), RSV(30, 30), AV(30, 30)
9/ DXP(30, 30), DXPV(30, 30), DXP(30, 30), DXP(30, 30), DXP(30, 30), DXP(30, 30)
10/ DYPN(30, 30), DYP(30, 30), DYP(30, 30), DYP(30, 30), DYP(30, 30)
11/ DYN(30, 30), DYN(30, 30), DYN(30, 30), DYN(30, 30), DYN(30, 30)
12/ SNORM(30, 30), SNORM(30, 30), SNORM(30, 30)
13/ TAUS(30, 30), TAUS(30, 30), TAUS(30, 30)
14/ TAUSS(30, 30), TAUSS(30, 30), TAUSS(30, 30)
15/ XPUL(30, 30), XPUL(30, 30), XPUL(30, 30)
16/ XPULS(30, 30), XPULS(30, 30), XPULS(30, 30)

COMON

1/COMMON XU(30, 30), YV(30, 30), ZW(30, 30), INDCOS, INCOMP, LAMINR, VISCO, PRANDTL(10), URFL(10)
2/ URVFS, URFDEN, RESOR(10), NSWP(10), IPREF, JPREP, PRST, PREG, PRED, PRED, PREP, PREP
3/ C1, C2, CMU, CMU25, CMU5, CAPPA, CO, ELONG, PFUN, TWALL, DELTA
4/ CIN, CEN, CRN, TURBIN, EDIN, TIN, FLOWIN, DENSIT, VISCOS, ENIN, CINT
5/ CPF, CPN2, CPN2, CPN2, CPN2, CPN2, HR, STOC, FLOW, FLOWF
6/ PIN, CIN, CEN, WMF, TCF, TCF, TCF, TCF, TCF
7/ ALI, AL2, ALAMDO, ALRANGE, RSMALL, RSLARGE, NFREE, SSYM, PRANDT(10)
8/ SORMAX, MAT, ISTEP, NITER, NITERS, INOPR, NNUMPR, PERR, MAXDWP
9/ ISCEME, MODOP, IREAD, IWRITE, WCOMMT, ICECAL(10), INPRO
10/ JU, JY, JZ, JX, JIP, JP, JPP, JIP
11/ GREAT, PJ, JGC, JGC, JGC, JGC
13/ NT, NST, NSTM, NSTM, NSTM, NSTM, NSTM, NSTM, NSTM, NSTM, NSTM, NSTM, NSTM
14/ NTM, NTM, NTM, NTM, NTM, NTM, NTM, NTM, NTM, NTM, NTM, NTM, NTM
15/ NED, NED, NED, NED, NED, NED, NED, NED, NED, NED, NED, NED, NED
16/ EMB(9), EMB(9), EMB(9), EMB(9), EMB(9), EMB(9), EMB(9), EMB(9), EMB(9), EMB(9), EMB(9), EMB(9)
17/ HED(9), HED(9), HED(9), HED(9), HED(9), HED(9), HED(9)
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CHAPTER 1 1 1 POS!VITY CHECK ON THE COEFFICIENTS 1 1 1 1 1

C------INITIALISATION OF THE CONTROL WEIGHTING FACTORS TO UNITY

IEND=INJM+IENDIN
JEND=INJM+JENDIN
IF(ISCEME.EQ.1) GO TO 231
DO 200 J=2, JEND
IY=IY(J)
IY=IY(J)+JENDIN
DO 201 J=1, JEND
FN(1,J-1)=1.0
FE(J,J-1)=1.0
CONTINUE
FE(J,J)=1.0
200 CONTINUE
DO 202 J=2, IEND
J: JN(1) * JEND

C——— 1.2 MAIN LOOP
   DO 210 J = 1, JEND
   LI = IW(J)
   LIE = IE(J) * JEND
   DO 220 I = 1, LI
   IIE = IE(I)

C——— 1. CHECK FOR THE NEGATIVE COEFFICIENTS IF REQUIRED
C——— 2. ADJUST THE WEIGHTING FACTORS IF REQUIRED
C——— SOUTH SIDE
   FB = FN2(I, J-1) * SVN(1, J-1) * FN3(I, J-1)
   FL = I1.0 - SUE(I-1, J) * SVE(I-1, J) * E3(I-1, J)
   FR = SUE(I, J) * SVE(I, J) * E3(I, J)
   IF (FB = FL = FR) LT. 0.0
      1 CALL CORRECT(FB, FL, FR, FE(I-1, J) * FE(I, J))

C——— NORTH SIDE
   FB = FN1(I, J-1) * I1.0 - SVN(I, J-1) * FN3(I, J-1)
   FL = I1.0 - SUE(I-1, J-1) * I1.0 - SVE(I-1, J) * E3(I-1, J)
   FR = SUE(I, J-1) * SVE(I, J) * E3(I, J)
   IF (FB = FL = FR) LT. 0.0
      1 CALL CORRECT(FB, FL, FR, FE(I-1, J) * FE(I, J))

C——— WEST SIDE
   FB = E2(I, J-1) * SUE(I-1, J) * E3(I-1, J)
   FL = I1.0 - SVN(I, J-1) * SUN(I, J-1) * FN3(I, J-1)
   FR = SVN(I, J-1) * SUN(I, J) * FN3(I, J)
   IF (FB = FL = FR) LT. 0.0
      1 CALL CORRECT(FB, FL, FR, FN1(I, J-1), FN3(I, J))

C——— EAST SIDE
   FB = E1(I, J) * I1.0 - SUE(I, J) * E3(I, J)
   FL = I1.0 - SVN(I, J) * I1.0 - SUN(I, J-1) * FN3(I, J-1)
   FR = SVN(I, J) * SUN(I, J) * FN3(I, J)
   IF (FB = FL = FR) LT. 0.0
      1 CALL CORRECT(FB, FL, FR, FN1(I, J-1), FN3(I, J))

C——— CALCULATE THE EFFECTIVE FLUXES
   E3(I-1, J) = FE(I-1, J) * E3(I-1, J)
   FN3(I, J) = FN3(I, J-1)
   220 CONTINUE
   E3(LIE, J) = FE(LIE, J) * E3(LIE, J)
   210 CONTINUE
   DO 230 I = 2, JEND
      J: JN(I) * JEND
      LI = IW(J)
      LIE = IE(J) * JEND
      DO 300 1 = 1, LI
   230 CONTINUE

C——— 2.1 ASSEMBLY OF THE COEFFICIENTS
   DO 300 1 = 2, JEND
      LI = IW(J)
      LIE = IE(J) * JEND
      DO 300 1 = 1, LI

C——— CORNER NODAL POINTS
   ASW(I, J) = SUE(I-1, J) * SVE(I-1, J) * E3(I-1, J)
      1 * SVN(I, J-1) * SUN(I, J) * FN3(I, J-1)
   ASE(I, J) = SVN(I, J) * I1.0 - SVN(I, J-1) * FN3(I, J-1)
   ANW(I, J) = SUE(I-1, J) * I1.0 - SVE(I-1, J) * E3(I-1, J)
   ANE(I, J) = I1.0 - SVN(I, J) * SUN(I, J) * FN3(I, J)
   1

C——— 2.2 FINAL OPERATIONS
   2 2 2 2 2 2 2 2 2 2 2 2
C----STANDARD NODAL POINTS

\[ \begin{align*}
A_W(i, j) &= E2(i-1, j) - SUE(i-1, j) \times E3(i-1, j) \\
&+ (1.0 - SVN(i, j) \times SJN(i, j) \times FN3(i, j)) \\
AE(i, j) &= E1(i, j) + (1.0 - SUE(i, j) \times E3(i, j)) \\
&+ (1.0 - SVN(i, j) \times SJN(i, j) \times FN3(i, j)) \\
A_S(i, j) &= FN2(i, j-1) - SVN(i, j-1) \times FN3(i, j-1) \\
&+ (1.0 - SUE(i-1, j) \times SVE(i-1, j) \times E3(i-1, j)) \\
AN(i, j) &= FN3(i, j) - SVN(i, j) \times FN3(i, j) \\
&+ (1.0 - SVE(i-1, j) \times SVE(i-1, j) \times E3(i-1, j))
\end{align*} \]

300 CONTINUE
RETURN
END

@PRT,S TEACH@TEACH.CALCFI
60 IF (ICOEF.EQ.1) IVARO=1VAR
61 IF (ICOEF.NE.1) FACTOR=PRANDT*IVAR0/PRANDT*IVAR
62 IF (ICOEF.NE.1) AND FACTOR.EQ.1.0) GO TO 110
63 C----- WEST BOUNDARY
64 DO 10 J=2,NJM1
65 I=1WI(J)-1
66 IF (ICOEF.EQ.2) GO TO 11
67 AREAEW=RI(J)*SNS(J)
68 CE(I,J)=DEN(I,J)*UI(J)*AREAEW
69 DE(I,J)=GAMM(I,J)*AREAEW/(0.5*SEW(I+1))
70 GO TO 9
71 11 DE(I,J)=DE(I,J)*FACTOR
72 AE(I,J)=CE(I,J)
73 AN(I,J)=DE(I,J)
74 CONTINUE
75 C----- ALL OTHER LOCATIONS
76 DO 100 I=2,NIM1
77 LJS=JS(I)
78 LJN=JN(I)
79 C----- SOUTH BOUNDARY
80 LJS1=LJS-I
81 ALPHA=AU(I)
82 ALPHA1=1.0-ALPHA
83 IF (ICOEF.EQ.2) GO TO 102
84 AREAS=RV(LJS1)*SEW(I)
85 CN(I,LJS1)=DEN(I,LJS1)*VE(I,LJS1)*AREAS
86 DN(I,LJS1)=GAMM(I,LJS1)*AREAS/(0.5*SNS(I,LJS))
87 GO TO 105
88 102 DN(I,LJS1)=DN(I,LJS1)*FACTOR
89 AN(I,LJS1)=CN(I,LJS1)
90 AS(I,LJS1)=DN(I,LJS1)
91 C----- FLOW POINTS
92 DO 101 J=JS1,LJN
93 C----- COMPUTE AREAS, VOLUME AND INTERPOLATION FACTORS
94 BETAV=AV(I)
95 BETAV1=1.0-BETA
96 IF (ICOEF.EQ.2) GO TO 120
97 AREAN=RV(J)*SEW(I)
98 AREAEW=RI(J)*SNS(I)
99 VOLR=RI(J)*SNS(I)*SEW(I)
100 C----- CALCULATE CONVECTION COEFFICIENTS
101 GN=DEN(I,J)+BETAV1*DEN(I,J)*BETAV*VE(I,J)
102 CE(I,J)=GN*AREAN
103 GE(I,J)=GE*AREAEW
104 C----- CALCULATE DIFFUSION COEFFICIENTS
105 GAMM=PROP(I,J)+BETAV1*PROP(I,J)*BETAV
106 GAME=PROP(I,J)+PROP(I,J)*BETAV1
107 DNI,J)=GAMM*AREAN/DYNP(I)
108 IF (J.EQ.JN) DNI,J)=GAMM*AREAN/(0.5*SNS(I))
109 DE(I,J)=GAME*AREAW/XEPS(I)
110 GO TO 150
111 120 DN(I,J)=DN(I,J)*FACTOR
112 DE(I,J)=DE(I,J)*FACTOR
113 C----- STORE CONVECT. AND DIFF. PARTS IN MAIN COEFF. ARRAYS
114 150 AN(I,J)=CN(I,J)
115 AE(I,J)=CE(I,J)
116 AS(I,J)=DN(I,J)
117 AW(I,J)=DE(I,J)
118 101 CONTINUE
100 CONTINUE
C
C-----CALCULATE SOURCE TERMS
110 CALL SOURCII(IIVAR)
C
CHAPTER 2 2 2 2 2 2 PROBLEM MODIFICATIONS 2 2 2 2 2 2
C
CALL MODIFI(IVAR)
IF(ICOEF.EQ.0) GO TO 130
IF(ICOEF.NE.1.AND.FACTOR.EQ.1.0) GO TO 130
C
CHAPTER 3 3 3 3 3 CALCULATE BSHO COEFFICIENTS 3 3 3 3 3
C
C-----DUMP INFORMATION ON TAPE-------------------------------------
WRITE (LU9) DU, DV, GAMH, VIS, SP, PP, SPARE, DEN, GEN
REWIND LU9
C
C-----CALCULATE COEFFICIENT COMPONENTS
C
C-----NORTH SIDE
DO 600 I=2,NIM1
LJS=JS(I)-1
LJN=JN(I)
LJS=J-1
DO 600 J=LJS,LJN
BETA=AN(J)
BETA=1.0-BETA
BETA=0.5*(BETA+U(I-1,J)-U(I,J))+BETA*(U(I-1,J+1)-U(I,J+1))
VX=V(I-1,J)
CNP=AN(J)
CNP=AN(J)
CNP=AN(J)
CNP=AN(J)
SIV=0.5*SIGN(0.5, UN)
SIV=0.5*SIGN(0.5, UN)
SUN(I,J)=SIV
SUN(I,J)=SIV
SUN(I,J)=SIV
SUN(I,J)=SIV
PECRIT=1.0/(SIV-BETA1*SMALL)
PECRIT=1.0/(SIV-BETA1*SMALL)
IF(CNP/PECRIT.GT.1.0) GO TO 601
C
C-----CENTRAL DIFFERENCING
FN1(I,J)=DNP-BETA*CNP
FN3(I,J)=0.0
DNP=FN1(I,J)
DNP=FN1(I,J)
DNP=FN1(I,J)
DNP=FN1(I,J)
DNP=FN1(I,J)
IF(IX-JW(JY)+1)*I*(IX-NIM1)) 609, 608, 609
IF(IX-JW(JY)+1)*I*(IX-NIM1)) 609, 608, 609
DX=DXEP(I)
DX=DXEP(I)
DX=DXEP(I)
DX=DXEP(I)
DX=DXEP(I)
JY=JW(JY)-1
JY=JW(JY)-1
JY=JW(JY)-1
JY=JW(JY)-1
JY=JW(JY)-1
IF(IX-JW(JY)+1)*I*(IX-NIM1)) 609, 608, 609
IF(IX-JW(JY)+1)*I*(IX-NIM1)) 609, 608, 609
DK=DKEP(I)
DK=DKEP(I)
DK=DKEP(I)
DK=DKEP(I)
DK=DKEP(I)
IF(IX-JW(JY)+1)*I*(IX-NIM1)) 609, 608, 609
IF(IX-JW(JY)+1)*I*(IX-NIM1)) 609, 608, 609
TANB=UN/VN
TANB=UN/VN
TANB=UN/VN
TANB=UN/VN
TANB=UN/VN
AK=AMIN1(I,0,ABS(DY/DS*DS+B))
AK=AMIN1(I,0,ABS(DY/DS*DS+B))
FN1(I,J)=SIV-I CNP
FN3(I,J)=SIV-I CNP
FN3(I,J)=SIV-I CNP
FN3(I,J)=SIV-I CNP
FN3(I,J)=SIV-I CNP
600 CONTINUE
C
C-----SKEW DIFFERENCING
601 IX=I-TMAT(SIV)
602 IX=I-TMAT(SIV)
603 IX=I-TMAT(SIV)
604 IX=I-TMAT(SIV)
605 IX=I-TMAT(SIV)
DX=DXEP(I)
DX=DXEP(I)
DX=DXEP(I)
DX=DXEP(I)
DX=DXEP(I)
JY=JW(JY)-1
JY=JW(JY)-1
JY=JW(JY)-1
JY=JW(JY)-1
JY=JW(JY)-1
IF(IX-JW(JY)+1)*I*(IX-NIM1)) 609, 608, 609
IF(IX-JW(JY)+1)*I*(IX-NIM1)) 609, 608, 609
DK=DKEP(I)
DK=DKEP(I)
DK=DKEP(I)
DK=DKEP(I)
DK=DKEP(I)
IF(IX-JW(JY)+1)*I*(IX-NIM1)) 609, 608, 609
IF(IX-JW(JY)+1)*I*(IX-NIM1)) 609, 608, 609
TANB=UN/VN
TANB=UN/VN
TANB=UN/VN
TANB=UN/VN
TANB=UN/VN
AK=AMIN1(I,0,ABS(DY/DS*DS+B))
AK=AMIN1(I,0,ABS(DY/DS*DS+B))
FN1(I,J)=SIV-I CNP
FN3(I,J)=SIV-I CNP
FN3(I,J)=SIV-I CNP
FN3(I,J)=SIV-I CNP
FN3(I,J)=SIV-I CNP
600 CONTINUE
C
C-----EAST SIDE
DO 603 J=2,NJM1
603 CONTINUE
C
C-----EAST SIDE
DO 603 J=2,NJM1
LJW=JW(JY)-1
LJ=JW(JY)-1
LJ=JW(JY)-1
LJ=JW(JY)-1
LJ=JW(JY)-1
ALPHA=AU(I)
ALPHA=AU(I)
ALPHA=AU(I)
ALPHA=AU(I)
ALPHA=AU(I)
UE=U(I,J)
UE=U(I,J)
UE=U(I,J)
UE=U(I,J)
UE=U(I,J)
VE = 0.5*(ALPHA1*(V(I, J-1)+V(I, J)) + ALPHA*(V(I+1, J-1)+V(I+1, J)))

CEP = AC(I, J)

DEP = AW(I, J)

SU = 0.5*SIGN(0.5, CEP)

SV = 0.5*SIGN(0.5, VE)

SUE(I, J) = SU

SVI(I, J) = SV

PECRIT = 1.0/(SU-ALPHA1+SMALL)

CECRIT = PECRIT*DEP*SMALL

IF (CEP < PECRIT, GT, 0) GO TO 604

C----- CENTRAL DIFFERENCING

E1(I, J) = DEP - ALPHA1*CEP

E3(I, J) = 0.0

GO TO 605

C----- SKEW DIFFERENCING

604 IX = INT(1.0 - SIU)

DX = 0.5*SEW(IX)

JY = J - INT(SIV)

DY = DYMPJY

IF (JY = JSII - 1)*1*(JY = JN(IX)) 607, 606, 607

606 DY = 0.5*SN(IX)

607 TAN = VE/UE*SMALL

AK = MINI(1.0, ABS(DX/DY*TANE));

E1(I, J) = (SIU - 1)*CEP

E3(I, J) = WORN*AK*CEP - CECRIT

605 E2(I, J) = E1(I, J)*CEP

603 CONTINUE

C----- CALCULATE BOUNDED COEFFICIENTS

CALL BOUNDS(0, 0)

C----- RESTORE INFORMATION FROM TAPE

READ (LU9) DU, DV, GAMM, VS, SP, PP, SPARE, DEN, GEN

REWIND LU9

130 CONTINUE

C

CHAPTER 4 FINAL COEFFICIENT ASSEMBLY AND RESIDUAL SOURCE CALCULATION 4

C

RESOR1(IVAR) = 0.0

DO 300 I = 2, NIM1

LJS = JS(I)

LJN = JN(I)

DO 301 J = LJS, LJN

AP(I, J) = AN(I, J)*AS(I, J)*AE(I, J)*AW(I, J) - SP(I, J)

1

RESOR = MIN(1.0, ABS(1.0 - AS(I, J)*AE(I, J)*ANW(I, J) + ANE(I, J))

1

+ ANU(I, J)*PHI(I, J) - PHI(I, J-1)*ASU(I, J)*PHI(I, J)*SU(I, J)

9

+ ANU(I, J)*PHI(I-1, J-1)*ASE(I, J)*PHI(I, J)*SU(I, J)

1

+ ANU(I, J)*PHI(I-1, J-1)*ANE(I, J)*PHI(I+1, J)*SN(I, J)

1

VOL = R(J)*SNS(I)*SNS(J)

SORVOL = GREAT*VOL

IF (-SP(I, J), GT, 0.5*SORVOL) RESOR = RESOR1/SORVOL

RESOR(IVAR) = RESOR1(IVAR)*ABS(RESOR1)

C----- UNDER-RELAXATION

AP(I, J) = AP(I, J)/URF(IVAR)

SU(I, J) = SU(I, J)*1.0 - URF(IVAR)*AP(I, J)*PHI(I, J)

301 CONTINUE

300 CONTINUE

C

CHAPTER 5 5 5 5 5 SOLUTION OF DIFFERENCE EQUATIONS 5 5 5 5 5
M

w(m,-, q[5-27

CHAPTER 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

COMMON

1/COM1/ U(30,30), V(30,30), P(30,30), T(30,30), E(30,30), ED(30,30), EN(30,30)

2/ FM(30,30), F(30,30), VIS(30,30), PI(30,30), T(30,30), W(30,30)

3/ DEN(30,30), GAMM(30,30), GEN(30,30), DU(30,30), VO(30,30)

4/ R(30,30), An(30,30), AN(30,30), AS(30,30), AI(30,30)

5/ ASW(30,30), ASW(30,30), AW(30,30), ANW(30,30), ANW(30,30)

6/ AN(30,30), AN(30,30), AN(30,30), AN(30,30), AN(30,30)

7/ An(30,30), V(30,30), EI(30,30), W(30,30), JN(30,30), JS(30,30), R(30,30), RV(30,30)

8/ SEV(30,30), SNS(30,30), SNU(30,30), SNSV(30,30), RCL(30,30), QUI(30,30), AV(30,30)

9/ DXCP(30,30), DCON(30,30), DCON(30,30), DXCPEU(30,30), DXCPEU(30,30)

10/ DNPV(30,30), DNPV(30,30), DNPV(30,30), DNPV(30,30), DNPV(30,30)

11/ TAUW(30,30), OXU(30,30), OXU(30,30), OXU(30,30)

12/ OXU(30,30), OXU(30,30), OXU(30,30), OXU(30,30)

13/ OXU(30,30), OXU(30,30), OXU(30,30)

14/ OXU(30,30), OXU(30,30), OXU(30,30)

15/ OXU(30,30), OXU(30,30), OXU(30,30)

16/ OXU(30,30), OXU(30,30), OXU(30,30)

17/ OXU(30,30), OXU(30,30), OXU(30,30)

18/ OXU(30,30), OXU(30,30), OXU(30,30)

19/ OXU(30,30), OXU(30,30), OXU(30,30)

20/ OXU(30,30), OXU(30,30), OXU(30,30)

21/ OXU(30,30), OXU(30,30), OXU(30,30)

22/ OXU(30,30), OXU(30,30), OXU(30,30)

23/ OXU(30,30), OXU(30,30), OXU(30,30)

24/ OXU(30,30), OXU(30,30), OXU(30,30)

25/ OXU(30,30), OXU(30,30), OXU(30,30)

26/ OXU(30,30), OXU(30,30), OXU(30,30)

27/ OXU(30,30), OXU(30,30), OXU(30,30)

28/ OXU(30,30), OXU(30,30), OXU(30,30)

29/ OXU(30,30), OXU(30,30), OXU(30,30)

30/ OXU(30,30), OXU(30,30), OXU(30,30)

31/ OXU(30,30), OXU(30,30), OXU(30,30)

32/ OXU(30,30), OXU(30,30), OXU(30,30)

33/ OXU(30,30), OXU(30,30), OXU(30,30)

34/ OXU(30,30), OXU(30,30), OXU(30,30)

35/ OXU(30,30), OXU(30,30), OXU(30,30)

36/ OXU(30,30), OXU(30,30), OXU(30,30)

37/ OXU(30,30), OXU(30,30), OXU(30,30)

38/ OXU(30,30), OXU(30,30), OXU(30,30)

39/ OXU(30,30), OXU(30,30), OXU(30,30)

40/ OXU(30,30), OXU(30,30), OXU(30,30)

41/ OXU(30,30), OXU(30,30), OXU(30,30)

42/ OXU(30,30), OXU(30,30), OXU(30,30)

43/ OXU(30,30), OXU(30,30), OXU(30,30)

44/ OXU(30,30), OXU(30,30), OXU(30,30)

45/ OXU(30,30), OXU(30,30), OXU(30,30)

46/ OXU(30,30), OXU(30,30), OXU(30,30)

47/ OXU(30,30), OXU(30,30), OXU(30,30)

48/ OXU(30,30), OXU(30,30), OXU(30,30)

49/ OXU(30,30), OXU(30,30), OXU(30,30)

50/ OXU(30,30), OXU(30,30), OXU(30,30)

51/ OXU(30,30), OXU(30,30), OXU(30,30)

52/ OXU(30,30), OXU(30,30), OXU(30,30)

53/ OXU(30,30), OXU(30,30), OXU(30,30)

54/ OXU(30,30), OXU(30,30), OXU(30,30)

55/ OXU(30,30), OXU(30,30), OXU(30,30)

56/ OXU(30,30), OXU(30,30), OXU(30,30)

57/ OXU(30,30), OXU(30,30), OXU(30,30)

58/ OXU(30,30), OXU(30,30), OXU(30,30)

59/ OXU(30,30), OXU(30,30), OXU(30,30)

CHAPTER 1


READ(U4) AE, AW, AN, AS, AP, ASW, ASE, AN, AN, AN, AN, SU

CALL LISOL(1, 1) READ(U4) AE, AW, AN, AS, AP, ASW, ASE, AN, AN, AN, AN, SU

CALL LISOL(1, 1) READ(U4) AE, AW, AN, AS, AP, ASW, ASE, AN, AN, AN, AN, SU

C---WEST BOUNDARY

DO 10 J = 1, NM1

I = I + 1

AREA = R(J) * SNS(J)

C(1) = D(E(1, J) * U(1, J) * AREA)

10 A(I, J) = 0.0

C---ALL OTHER LOCATIONS
DO 100 I=2,NIM1
LJS=JS(I)
LJN=JN(I)
C------SOUTH BOUNDARY
LJSM1=LJS-1
AREAS=RV(LJSM1)*SEW(I)
CN=DEN(I,LJSM1)*V(I,LJSM1)*AREAS
AM(I,LJSM1)=0.0
ALPHA1=1.0-ALPHA
C------FLOW POINTS
DO 101 J=LJS,LJN
C------COMPUTE AREAS AND INTERPOLATION FACTORS
AREAN=RV(J)*SEW(I)
BETA=AV(IJ)
BETA1=BETA/ALPHA1
AREAEW=RIJ*SNS(J)
C------CALCULATE COEFFICIENTS
DENN=DEN(I,J)*BETA1*DEN(I,J)*BETA
DENE=DEN(I,J)*ALPHA1*DEN(I,J)*ALPHA
AS(I,J)=AN(I,J-1)
AM(I,J)=DENN*AREAN*DV(I,J)
AW(I,J)=AE(I,J-1)
AE(I,J)=DENN*AREA*DU(I,J)
C------CALCULATE SOURCE TERMS
CS=CN
CV=CT(IJ)
CN=DENN*V(I,J)*AREAN
CE=DENE*U(I,J)*AREA
CJT=CE
SMP=CN-CS+CE-CW
SII,J=0.0
SU(I,J)=SMP
C------COMPUTE SUM OF ABSOLUTE MASS SOURCES
RESOR IP=RESOR IP*ABS(SMP)
101 CONTINUE
100 CONTINUE
C
C-2.2------PROBLEM MODIFICATIONS
C
CALL MODP
C
C-2.3------FINAL COEFFICIENT ASSEMBLY
C
DO 300 I=2,NIM1
LJS=JS(I)
LJN=JN(I)
DO 301 J=LJS,LJN
PP(J,J)=0.0
301 AP(I,J)=AN(I,J)*AS(I,J)*AE(I,J)*AM(I,J)-SP(I,J)
300 CONTINUE
112 REWIND LUN
C
C-2.4------SOLUTION OF DIFFERENCE EQUATIONS
C
PRES=RESOR(IP)
CALL LISOLV(D,PP,IP,2,2)
C
C-2.5------CORRECT VELOCITIES AND PRESSURE
C

PPREF=PP(IPREF,JPREF)
DO 500 I=2,NIU
LJS=JS(I)
LJN=JN(I)
DO 500 J=LJS,LJN
IF (I.EQ.IE(J)) GO TO 501
DU(I,J)=DU(I,J)+PPP(I,J)-PP(I+1,J)
UI(I,J)=UI(I,J)+DU(I,J)
500 IF (I.EQ.LJN) GO TO 500
DU(I,J)=DU(I,J)-PPP(I,J-1)
UI(I,J)=UI(I,J)
500 PPI,J=PI,J+PPI,J-PPREF

CHAPTER 3 3 PISO ALGORITHM SECOND CORRECTOR STAGE
C
READ(LUN4) AE,AW,AN,AS,AP,ASW,ASE,ANW,ANE,SU
C
C-3.1----EVALUATION OF U=SUM(AI*UI) AND CORRECT U VELOCITIES
C-----VALUES TEMPORARILY STORED IN PP(I,J) ARRAY
DO 520 I=2,NIUM1
LJS=JS(I)
LJN=JN(I)
DO 520 J=LJS,LJN
PPP=AW(I,J)*DU(I-1,J)+AE(I,J)*DU(I+1,J)+AS(I,J)*DU(I,J-1)
1 +AN(I,J)*DU(I,J)
2 +ASW(I,J)*DU(I-1,J-1)+ASE(I,J)*DU(I+1,J-1)
3 +ANE(I,J)*DU(I+1,J)+ANE(I,J)*DU(I,J+1)
PPP=PPP/PPP
UI(I,J)=UI(I,J)+PPP
520 PPI,J=PP
DO 520 I=2,NIUM1
LJS=JS(I)
LJN=JN(I)
DO 520 J=LJS,LJN
520 DOU(I,J)=PP(I,J)
READ(LUN4) AE,AW,AN,AS,AP,ASW,ASE,ANW,ANE,SU
C
C-3.2----EVALUATION OF V=SUM(AI*VI) AND CORRECT V VELOCITIES
C-----VALUES TEMPORARILY STORED IN PP(I,J) ARRAY
DO 530 I=2,NIUM1
LJS=JS(I)
LJN=JN(I)-1
DO 530 J=LJS,LJN
PPP=AW(I,J)*DVJ-1(I,J)+AE(I,J)*DVJ(I+1,J)+AS(I,J)*DVJ(I,J-1)
1 +AN(I,J)*DVJ(I,J)
2 +ASW(I,J)*DVJ(I-1,J-1)+ASE(I,J)*DVJ(I+1,J-1)
3 +ANE(I,J)*DVJ(I+1,J)+ANE(I,J)*DVJ(I,J+1)
PPP=PPP/PPP
VII(I,J)=VII(I,J)+PPP
530 PPI,J=PP
DO 531 I=2,NIUM1
LJS=JS(I)
LJN=JN(I)-1
DO 531 J=LJS,LJN
531 DVII(I,J)=PP(I,J)
C
C-3.3-----ASSEMBLY OF SECONDARY PRESSURE EQUATION COEFFICIENTS
RESOR(IPP)=0.0
DO 540 J=2,NJM1
540 CVT(J)=0.0
DO 545 I=2,NIM1
LJS=JS(I)
LJN=JN(I)
CN=0.0
ALPHA=AU(I)
ALPHA1=1.0-ALPHA
DO 545 J=LJS,LJN
AREAN=RV(J)*SEW(I)
BETA=AV(J)
BETA1=1.0-BETA
AREA EW=R(J)*SN(J)
DEN=DEN(I,J)*BETA1+DEN(I+1,J)*BETA
DEN=DEN(I,J)*ALPHA1+DEN(I+1,J)*ALPHA
CS=CN
CW=CVT(J)
CN=DENN*DVI,J)*AREAN
CE=DENN*DVI,J)*AREAEW
CVT(J)=CE
SUI,J)=-CE-CN-CN-CS)
PP(J,J)=0.0
RESOR(IPP)=RESOR(IPP)+ABS(SU(J,J))
READ(LUN) DU,DV,AE,AW,AN,AS,AP
REWIND LUN
C
C-3.4------SOLUTION OF DIFFERENCE EQUATION
C
C
PRES=RESOR(IPP)
CALL LISOLV(DO,0,PP,IP,2,2)
PPREF=PP(IP,IPREF,JPREF)
C
C-3.5------CORRECT VELOCITIES AND PRESSURE
C
DO 580 I=2,NIM1
LJS=JS(I)
LJN=JN(I)
DO 580 J=LJS,LJN
IF (I,NE.,IE(I,J))
1 U(I,J)=U(I,J)+DU(I,J)*(PP(I,J)-PP(I+1,J))
1 V(I,J)=V(I,J)+DV(I,J)*(PP(I,J)-PP(I,J+1))
P(I,J)=PI(J)+PP(I,J)-PPREF
580 CONTINUE
CALL MODU1
RETURN
END

@PRINTS TEACH*TEACH.COFU
1  (SNS(J)*R(J))
2    SWT(J)=SUE(J)
3    IF(LAMINJ) GO TO 102
4      SUI(J,J)=SU1(I,J)-0.66667*(DEN(I,J)+DEN(I,J))*TE(I,J)
5    1
6
7  102  IF(INCOMP) GO TO 101
8     DUDX=U(J)*U(J)-U(I,J)/SEW(I,J)
9     DUDXW=U(J)*W(I,J)/SEW(I,J)
10     SUI=VJ(I,J)+V(I,J)/SEW(I,J)
11     DRVDP=RV(I,J)*V(I,J)+V(I,J)/SEW(I,J)
12     SUZ=VIS(I,J)+V(I,J)/SEW(I,J)
13     DKV=VIS(I,J)+V(I,J)/SEW(I,J)
14    1
15
16    101  CONTINUE
17    100  CONTINUE
18
19  C
20  C  CHAPTER 2 2 2 2 2 PROBLEM MODIFICATIONS 2 2 2 2 2 2 2
21  C
22  C  CALL MODU
23  C
24  C  CHAPTER 3 3 3 3 3 CALCULATE BSHD COEFFICIENTS 3 3 3 3 3 3
25  C
26  C  ------DUMP INFORMATION TO TAPE-----------------------------
27      WRITE(LU9) DU,DV,GAMH,DISP,PP,SPARE,DEN,GEN
28    REWIND LU9
29  C
30  C  ------CALCULATE COEFFICIENT COMPONENTS
31          DO 600 J=2,NIUM
32            JS=JS(I)-1
33            JN=JN(I)
34            DO 600 J=JS,JN
35            BETA=AV(J)
36            UN=BETA*U(J)+BETA*U(J+1)
37            VN=0.5*(V(J)+V(J+1))
38            CNCN=AN(J)
39            DNP=AS(J,J)
40            SIU=5.*SIGN(DNP,UN)
41            SIV=5.*SIGN(CNP,SIU)
42            SUN=5.*SIGN(SIV,SIU)
43            SVA=5.*SIGN(SUN,SIU)
44            CRIT=PECRIT*DNP*SMALL
45          IF(168*CRIT*SMALL<0) GO TO 601
46    600  CONTINUE
47
48  C  ------CENTRAL DIFFERENCING
49    FH(I,J)=DNP*BETA*CNP
50    FM3(I,J)=0.0
51    GO TO 602
52
53  C  ------SKEW DIFFERENCING
54    601  DX=SEW(I+INT(I,0.5-SIU))
55    601  CONTINUE
56    DX=SEW(I+INTX)
57    INTX=INT(I,0.5-SIU)
58    DY=0.5*SNS(J+INT(I,0.5-SIV))
59    YANB=UN/(VN+SMALL)
60    AK=AINT(I,0.0,ABS(DY/DX*YANB))
C-----UNDER-RELAXATION
240   AP(I,J)=AP(I,J)/URF(IU)
241   SU(I,J)=SU(I,J)*(1.-URF(IU))*AP(I,J)*U(I,J)
242   DU(I,J)=DU(I,J)/AP(I,J)
243   301 CONTINUE
244   300 CONTINUE
245
C  CHAPTER 5 5 5 SOLUTION OF DIFFERENCE EQUATION 5 5 5 5 5
246
C
247   WRITE(LUT) AE,AW,AN,AS,AP,ASW,ASE,ANL,ANE,SU
248
249   RETURN
250
251 END

@PRT,S TEACH#TEACH#COEFV
DVSt = R(J+1)*(V(1,J+1)-V(1,J))/SNS(J+1)

SOF(J)= VIS(J+1) * DVSt

10 CONTINUE

C----- ALL OTHER LOCATIONS

DO 100 J = 2, NJVM1
  LIW = LW(J)
  LIE = LE(J)

C----- WEST BOUNDARY

LIWMI = LWMI1
AREAEW = RW(J)*SNSV(J)
CE = 0.5*DEN(LIWM1,J)*DEN(LIWM1,J+1)*U(LIWM1,J+1)
   *AREAEW
WSE = 0.5*(VIS(LIWM1,J)+VIS(LIWM1,J+1))
DE = VISE*AREAEW/(0.5*SEW(LIWM1))
DUDE = (U(LIWM1,J+1)-U(LIWM1,J))/SNSV(J)
AE(LIWM1,J) = CE
AN(LIWM1,J) = DE
TSUE = VSE*DUDE

C----- FLOW POINTS

DO 101 I = LW, LIE

C----- COMPUTE AREAS, VOLUME AND INTERPOLATION FACTORS

AREA = RW(J)*SEW(I)
AREAEW = RW(J)*SNSV(J)
VOL = AREAEW*SEW(I)
ALPHA = AU(I)

C----- CALCULATE CONVECTION COEFFICIENTS

GSE = DEN(I,J)*ALPHA1*DEN(I+1,J)*ALPHA1*U(I,J)
GNE = IDS(I+1,J)*ALPHA1*DEN(I+1,J+1)*ALPHA1*U(I,J+1)
CE = 0.5*GSE*GNE*AREAEW
VW = V(I,J)
W = V(I,J)

C----- CALCULATE DIFFUSION COEFFICIENTS

VSE = 0.5*(VIS(I+1,J)+VIS(I,J+1))+ALPHA
1 = (VIS(I+1,J)+VIS(I,J+1))/(ALPHA*AREA)
DN = VIS(I,J)*AREA/DYNP(J)
DE = VISE*AREA/AE/DYNP(I)

C----- CALCULATE COEFFICIENTS OF SOURCE TERMS

SMP = CN+AN(I,J-1)+CE-AE(I-1,J)
CP = AMAX1(DV(J), SMP
DV(J) = VOL/DYNP(J)

C----- STORE CONVECT. & DIFF. PARTS IN MAIN COEFF. ARRAYS

AE(I,J) = CE
AN(I,J) = CN
AW(I,J) = DE
AS(I,J) = DN

C----- CALCULATE SOURCE TERMS

SUI = CP*(V(I,J)-DV(I,J)*(P(I,J+1)-P(I,J))
SP = CP
IF (INDCOS.EQ.2) SP = SP*(1-JJ-0.5*(VIS(I,J)+VIS(I,J+1))
1 = VOL/RV(J)**2
IF (VISCOS) GO TO 102
SUE = TSUE
SUS = SSV(I)
DUDE = DUS*TSUE
TSUE = VIS*DUDE
DVSt = R(J+1)*(V(I,J)+V(I,J+1))/SNSV(J)
TSUE = VIS*DVSt
SUI(J) = SUI(J)+TSUE*SEW(I)*TSUN*SUS*VOL/VOL/
1201 (RV(I,J) = SNSV(I,J))
121 SST(I,J) = SNSV(I,J)
122 IF (INDCOS=EQ,2) SP(I,J) = SP(I,J) - 0.5*(VIS(I,J)*VIS(I,J+1))
123 1 IF VOL/RV(I,J)**2
124 IF (LAMINR) GO TO 102
125 SU(I,J) = SU(I,J) - 0.66667*DEN(I,J)*TE(I,J+1)-DEN(I,J)*TE(I,J))
126 1 IF VOL/SNSV(I,J)
127 C------ADDITIONAL SOURCE DUE TO SWIRL
128 102 IF (INDCOS=EQ,1) GO TO 103
129 SWS=DEN(I,J)*W(I,J)*2/R(I,J)
130 SWN=DEN(I,J)*W(I,J)*2/R(I,J)
131 SU(I,J) = SU(I,J) + (SWN+SWS)*0.5*VOL
132 103 IF (INCOMP) GO TO 101
133 DUDXN=(U(I,J+1)-U(I-1,J+1))/SEW(I)
134 DUDXS=(U(I,J)-U(I-1,J))/SEW(I)
135 SU(I,J) = SU(I,J) + (DUDXN-VIS(I,J)*DUDXS)*VOL/SNSV(I,J)
136 DRV=RV(I,J)*V(I,J+1)-RV(I,J+1)*V(I,J)/SNSV(I,J)
137 DRV=RV(I,J)*V(I,J+1)-RV(I,J+1)*V(I,J)/SNSV(I,J)
138 SU(I,J) = SU(I,J) - 0.66667*(SU1+SU2)
139 IF (*NOT.*VIS(CO)) GO TO 101
140 SU(I,J) = SU(I,J) + SU1+SU2
141 106 CONTINUE
142 
143 C CHAPTER 2 2 2 2 2 2 PROBLEM MODIFICATIONS 2 2 2 2 2 2
144 C CALL MODV
145 
146 C CHAPTER 3 3 3 3 3 CALCULATE BSHD COEFFICIENTS 3 3 3 3 3
147 C
148 C------DUMP INFORMATION ON TAPE-------------------------------
149 WRITE(LU9) DU,DV,GAH,VIS,SP,PP,SPARE,DEN,GEN
150 REWIND LU9
151 
152 C------CALCULATE COEFFICIENT COMPONENTS
153 
154 C------NORTH SIDE
155 DO 600 I=2,N1
156 LJS=JS(I-1)
157 LJN=JN(I-1)
158 DO 600 J=LJS,LJN
159 UN=0.5*(U(I,J+1)+U(I-1,J+1))
160 VN=0.5*(V(I,J+1)+V(I-1,J+1))
161 CNP=AM(I,J)
162 DNP=AS(I,J)
163 SU=0.5*SIGN(0.5,UN)
164 SIV=0.5*SIGN(0.5,CNP)
165 SUN(I,J)=SU
166 SVN(I,J)=SIV
167 PECRIT=1.0/(SIV-0.5)
168 CMCRIT=PECRIT*DNP
169 IF (CNP/CMCRIT.GT.1.0) GO TO 601
170 
171 C------CENTRAL DIFFERENCING
172 FN1(I,J)=DNP-0.5*CNP
173 FNS(I,J)=0.0
174 GO TO 602
175 
176 C------SHEW DIFFERENCING
177 601 IF=I-INT(SIV)
178 DX=DXEP(IF)
179 JY=J+INT(1.0-SIV)
IF((X-IW(JJ)+1)<(IX-NJMV1)) 609, 608, 609

608 DX = 0.5 * SE(I)
609 DY = 0.5 * SN(J)

TAN(BN) = UN / (VN * SMALL)

AK = AMIN(I,J) * ABS(DY/DX * TANG(N) )

FN1(I,J) = (SIV - 1) * CNP
FN3(I,J) = WCORNR * AK * (CNP - CNCRIT)

602 FN2(I,J) = FN1(I,J) + CNP
600 CONTINUE

C ---- EAST SIDE
DO 603 J = 2, NJVM1
LIW = IW(JJ) - 1
LIE = IE(JJ)
DO 603 I = LIW, LIE

ALPHA = AU(I)

ALPHA1 = 1.0 - ALPHA
UE = 0.5 * U(I+1,J) + U(I,J) + 1
VE = ALPHA1 * V(I,J) + ALPHA * V(I+1,J)

CEP = AE(I,J)

DEP = AM(I+1,J)

SIV = 0.5 * SN(I,J)
SIV = 0.5 * SN(I,J)
SIV = 0.5 * SN(I,J)
SIV = 0.5 * SN(I,J)
SUE = I,J = SIV
SUE = I,J = SIV
SUE = I,J = SIV
SUE = I,J = SIV

IF(CEP < CEVIR, GT.1.0) GO TO 604

C ---- CENTRAL DIFFERENCING
CEVIR = DEP - ALPHA * CEP

CEP = I,J = DEP - ALPHA * CEP
CEP = I,J = 0.0
GO TO 605

604 DX = 0.5 * SE(I+1,J) + INT(I,J) + 1.0 - SIV)
604 CONTINUE

INTX = INT(I,J) + 1.0 - SIU
INTY = INT(I,J) + 1.0 - SIV

QD = SN(I,J)
TANTE = UE * SMALL
AK = AMIN(I,J) * ABS(DY/DX * TANTE)

E1(I,J) = (SIV - 1) * CEP
E1(I,J) = (SIV - 1) * CEP
E1(I,J) = (SIV - 1) * CEP
E1(I,J) = (SIV - 1) * CEP

605 E2(I,J) = E1(I,J) + CEP
603 CONTINUE

C ---- CALCULATE BOUNDED COEFFICIENTS
CALL BOUNDS (D, 1)

C ---- RESTORE INFORMATION FROM TAPE---------------------------------------------
READ LU9, DU, DV, GAMH, VIS, SP, PP, SPARE, DEN, GEN

C ---- CHAPTE R 4 FINAL COEFF. ASSEMBLY AND RESIDUAL SOURCE CALCULATION
RES(IVI) = 0.0
DO 300 J = 2, NJVM1
LIW = IW(J)
LIE = IE(J)
DO 300 I = LIW, LIE

AP(I,J) = AM(I,J) * AS(I,J) * AF(I,J) * AW(I,J) - SP(I,J)

1 + AS(L,J) * AP(I,J) * ANW(I,J) * ANL(I,J)
RESOR1 = AN(I,J) + V(I,J) + AS(I,J) + AE(I,J) + V(I+1,J)
1. AW(I,J) = V(I,J) - AP(I,J) - V(I,J) - SU(I,J)
2. ASW(I,J) = V(I,J) + J + 1 - ASE(I,J) + V(I,J) - J - 1
3. ANW(I,J) = V(I,J) + J + 1 - ANE(I,J) + V(I,J) + J + 1

VOL = R(I,J) * SW(I,J) * SNS(I,J)
SORVOL = GRT * V
IF (-SP(I,J) .GT. 0.5 * SORVOL) RESOR1 = RESOR1 / SORVOL
RESOR1(V) = RESOR1(V) + ABS(RESOR1)

C---- UNDER-RELAXATION
AP(I,J) = AP(I,J) / URF(V)
SU(I,J) = SU(I,J) + (1. - URF(V)) * AP(I,J) + V(I,J)
DV(I,J) = DV(I,J) / AP(I,J)

CONTINUE

CHAPTER 5.5.5 SOLUTION OF DIFFERENCE EQUATION 5.5.5.5

WRITE(LUN4) AE, AW, AN, AS, AP, ASW, ASE, ANW, ANE, SU
REWIND LUN
RETURN
END
@PR1,5 TEACH@TEACH@CORECT
SUBROUTINE CORRECT(FR, FL, FR, WL, WR)
C
C------ROUTINE FOR OPTIMISING WEIGHTING FACTORS
C
IF(FL.GT.FR) GO TO 1
WL = AMIN1(WL, FB/(FL+1.0E-30))
WR = AMAX1(0.0, (FB-WL*FL)/FR)
RETURN
1 CONTINUE
WR = AMIN1(WR, FB/(FR+1.0E-30))
WL = AMAX1(0.0, (FB-WR*FR)/FL)
RETURN
END

@PRT,S TEACH_TEACH_CORTED
SUBROUTINE CORTED

COMMON,U(30,30),V(30,30),P(30,30),T(30,30),ED(30,30),EN(30,30)

COM2,RF(10),INDCOS,INCOMP,LAMINP,TVISCO,PRANDTL,RSN(10),RFPRE,PREP,PRES

BEGIN,END,RESOR(10),NSP(10),IPREF,PREP,PRES

C1,C2,CJ,CHU2,CUMU2,CAMPA,CD,EBLOG,PFUN,TWALL,DELTA

CIN,CEC,TEIN,TORBIN,CIN,TIN,FLOWN,DENSIT,TVISCOS,ENIN,CINT

CPF,CPF2,CPF3,CPF4,CPF5,CP02,CP03,CP04,CP05,CP1,CP2,CP3,CP4,CP5

CIN,CEC,WME,TECH,TWALL,TBLU,CP2,CP3,CP4,CP5

ALIS,ALONE,DARLE,BSMALL,LSMALL,MM,MMFREE,SSYM,PRANDT(10)

SORT,MAXT,STEP,STEP,STEP,STEP,STEP,STEP,STEP,STEP,STEP,STEP,STEP,STEP

STEP,STEP,STEP,STEP,STEP,STEP,STEP,STEP,STEP,STEP,STEP,STEP,STEP,STEP

NSMU,NSMU,NSMU,NSMU,NSMU,NSMU,NSMU,NSMU,NSMU,NSMU,NSMU,NSMU,NSMU

COMMON,ULU(30),LU31(30),LU32(30),LU33(30),LU34(30),LU35(30),LU36(30)

END

DIMENSION SUO(30,30),SP0(30,30),PHIO(30,30)

EQUIVALENCE(SUO(1,1),ASW(1,1),(SPO(1,1),ASW(1,1))

REWIND

C----- CORRECT TURBULENCE ENERGY FIELD

CALL VISC

CALL SOLVF ITE

CALL MODF ITE

READ(LUNIT) AP,SP0,SU0,PHIO

DO 150 I=2,NIM1

LJS=JS(I)

LJN=JN(I)

APSTAR=AP(I,J)-(SP(I,J)-SP0(I,J))/URF(I)

SUSTAR=SU(I,J)+(URF(I)*APSTAR*PHIO(I,J))

150 CONTINUE

C----- CORRECT ENERGY DISSIPATION FIELD

CALL SOLF(ED)

CALL MODF(ED)

READ(LUNIT) AP,SP0,SU0,PHIO

DO 250 I=2,NIM1

LJS=JS(I)

LJN=JN(I)

APSTAR=AP(I,J)-(SP(I,J)-SP0(I,J))/URF(ED)

250 CONTINUE
SUSTAR = SU(1; J1) \cdot (1 \cdot J - URF(I; E)) \cdot APSTAR \cdot PHI(1, J)
E(I, J) = (AP(1, J) \cdot ED(1, J) \cdot SUSTAR - SU(1, J)) / APSTAR

END
SUBROUTINE INIT

COMMON

CHAPTER 1

ENTRY GRID

COMMON
CHAPTER 2 2 2 2 2 2 SET VARIABLES TO ZERO 2 2 2 2 2 2

ENTRY SET
DO 200 I=1,NI
TAUN(I)=0.0
TAUS(I)=0.0
TAUNS(I)=0.0

108 R(J)=0.5*(RV(J)+RV(J-1))
R(1)=R(2)
Y(J)=Y(2)
Y(NJ)=2.*Y(NJV)-Y(NJM1)
R(NJ)=1.0
IF (INDCOS.EQ.2) R(NJ)=Y(NJ)
DXPW(I)=0.0
DXEP(NI)=0.0
DO 101 I=1,NJM1
DXEPL(I)=X(I+1)-X(I)
101 DXPW(I+1)=DXEP(I)
DYPS(I)=0.0
DYNP(NJ)=0.0
DO 102 J=1,NJM1
DYNP(J)=Y(J+1)-Y(J)
102 DYPS(J+1)=DYNP(J)
SEU(I)=0.0
SEW(I)=0.0
DO 103 I=1,NJM1
SEU(I)=XU(I)-XU(I-1)
SNS(I)=0.0
SNH(I)=0.0
DO 104 J=1,NJM1
SNS(J)=YV(J)-YV(J-1)
DXPWU(I)=0.0
DXEPU(NIU)=0.0
DO 106 I=1,NIU1
DXEPU(I)=XU(I+1)-XU(I)
106 DXPWU(I+1)=DXEPU(I)
SEUU(I)=0.0
SEWU(NIU)=0.0
DO 107 I=1,NIU1
SEUU(I)=0.5*(DXEPU(I)+DXPWU(I))
DYPSV(I)=0.0
DYNPV(NJV)=0.0
DO 109 J=1,NJV1
DYNPV(J)=YV(J+1)-YV(J)
109 DYPSV(J+1)=DYNPV(J)
SNSV(I)=0.0
SNSV(NJV)=0.0
DO 110 J=1,NJV1
SNSV(J)=3.5*(DYNPV(J)+DYPSV(J))
DO 121 J=1,NIU1
121 AU(I)=(XU(I))-X(I))/DXEP(I)
AU(NIU)=1.0
AU(I)=1.0
DO 122 J=1,NJV1
AV(I)=0.0
AV(J)=0.0
AV(NJ)=1.0
AV(I)=0.0
RETURN
TAUSS(I) = 0.0
DO 200 J = 1, NJ
AL(I, J) = 0.0
AN(I, J) = 0.0
AP(I, J) = 0.0
AS(I, J) = 0.0
AW(I, J) = 0.0
ASE(I, J) = 0.0
ANE(I, J) = 0.0
ANE(I, J) = 0.0
UI(I, J) = 0.0
VI(I, J) = 0.0
VI(I, J) = 0.0
PI(I, J) = 0.0
PP(I, J) = 0.0
DEN(I, J) = DENSIT
VIS(I, J) = VISCOS
GAMH(I, J) = VISCOS/PRANDT(ITE)
TE(I, J) = 0.0
ED(I, J) = 0.0
DV(I, J) = 0.0
SU(I, J) = 0.0
SPI(I, J) = 0.0
GEN(I, J) = 0.0
SPARE(I, J) = 0.0
EN(I, J) = 0.0
FM(I, J) = 0.0
FI(I, J) = 0.0
CPH(I, J) = CPIN
DO 210 J = 1, NJ
TAUWS(J) = 0.0
TAUE(J) = 0.0
TAUW(J) = 0.0
RESOR(1) = 0.0
RESOR(2) = 0.0
RESOR(3) = 0.0
RESOR(4) = 0.0
RESOR(5) = 0.0
RESOR(6) = 0.0
RESOR(7) = 0.0
RESOR(8) = 0.0
RESOR(9) = 0.0
RESOR(10) = 0.0
RETURN
END
C-----ASSM PIBM E TMCA COEFFICIENTS
A(J)=AN(I,J)
C(I)=AE(I,J)*PHI(I,J)+AW(I,J)*PHI(I,J)+SU(I,J)

IF(IVAR/=3)C(I)=C(I)

1 +AE(I,J)*PHI(I,J)+AW(I,J)*PHI(I,J)

2 .ASE(I,J)*PHI(I,J)+ASW(I,J)*PHI(I,J)

C-----CALCULATE COEFFICIENTS OF RECURRANCE FORMULA
TER=1./((A(I,J)*AS(I,J)*A(I,J)+SMALL)

A(I,J)=A(I)*TERM

101 C(I)=C(I)*AS(I,J)*C(I+1)*TERMN

C-----OBTAIN NEW PHI's
DO 102 JJ=JSTART,JEND

102 PHI(I,J)=A(I,J)*PHI(I,J+1)+C(J)

100 CONTINUE

IXSL=IXSL

IXSL=0

IF (IXSL.EQ.2) IXSL=1

IF (IXSL.EQ.1) GO TO 120

C

CHAPTER 2

2

2

2

2

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2

2

S-N SWEEP

2

2

2

2

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2

2

2

C

JSTART=1

JEND=MJ-1+JENDIN

JSUM=JSTART+JEND

C-----COMMENCE S-N SWEEP

JYSL=JYSW

220 DO 200 J=JSTART,JEND

200 J=J

GO TO 20

22 J=JSUM-J

20 CONTINUE

IST=I(W(J)

IEND=I(E(J)+IENDIN

ISM=JSTART-1

A(I,SM)=0.0

C(I,SM)=PHI(I,SM)

C-----COMMENCE W-E TRAVERSE

DO 201 I=ISTART,JEND

201 C(I)=C(I)*TERM

C-----ASSEMBLE TDMA COEFFICIENTS

A(I)=AE(I,J)

C(I)=AN(I,J)+PHI(I,J)+SU(I,J)

IF(IVAR/=3)C(I)=C(I)

1 +AE(I,J)*PHI(I,J)+AW(I,J)*PHI(I,J)

2 .ASE(I,J)*PHI(I,J)+ASW(I,J)*PHI(I,J)

TER=1./((A(I,J)*AS(I,J)*A(I,J)+SMALL)

A(I,J)=A(I)*TERM

201 C(I)=C(I)*AS(I,J)*C(I-1)*TERM

C-----OBTAIN NEW PHI's

DO 202 II=ISTART,JEND

202 PHI(I,J)=A(I)*PHI(I+1,J)+C(I)

200 CONTINUE

JYSL=JYSW

116 IF (JYSL.EQ.2) JYSL=1

117 IF (JYSL.EQ.1) GO TO 220

400 CONTINUE
IF (IVAR .NE. 3) RETURN
RESORP = 0.
DO 500 I = 2, NIM1
LJS = JS(I)
LJN = JN(I)
DO 500 J = LJS, LJN
SRESOR = AW(I, J) * PHI(I - 1, J) * AE(I, J) * PHI(I + 1, J) * AS(I, J) * PHI(I, J - 1)
      500 RESORP = RESORP + ABS(SRESOR)
      RESORP = RESORP / PRES
500 IF (NCOUNT .GE. MAXSWP) GO TO 502
      IF (RESORP .GT. PERR) GO TO 111
502 CONTINUE
RETURN
END
C-1.4 - SYMMETRY AXIS AT THE BOTTOM (SOUTH BOUNDARY)

121 DO 160 I=ISTP1,N1
122 AN(I,1)=0.0
123 AS(I,1)=0.0
124 160 TE(I,1)=TE(I,2)

C-1.5 - OUTLET (EAST BOUNDARY)

127 DO 130 J=2,JEXIT
128 AE(NIM1,J)=0.0
129 AM(NIM1,J)=0.0
130 130 TE(N,J)=TE(NIM1,J)
131 RETURN

C

CHAPTER 2 2 2 2 2 2 2 2 2 2 2 2 DISSIPATION 2 2 2 2 2 2

C

200 CONTINUE

C

TERM=GREATER_CMU75/CAPPA

C-2.1 - TOP WALL (NORTH BOUNDARY)

C

140 DO 440 I=2,NIM1
141 J=JN(I)
142 YP=YY(J)-Y(J)
143 AN(I,J)=0.0
144 AS(I,J)=0.0
145 SU(I,J)=TERM*TE(I,J)**1.5/YP
146 440 SP(I,J)=GREATER

C

C-2.2 - SIDE WALL OF BLUFF BODY (WEST BOUNDARY)

148 JSTR=JINS+1
149 DO 222 J=JSTR,JSTEP
150 I=IW(J)
151 XP=XU(I)-X(I)
152 AE(I-1,J)=0.0
153 AM(I-1,J)=0.0
154 SU(I,J)=TERM*TE(I,J)**1.5/XP
155 SP(I,J)=GREATER
156 222 CONTINUE

C

C-2.3 - TOP WALL OF BLUFF BODY (SOUTH BOUNDARY)

159 DO 240 I=2,NSTEP
160 J=JS(I)
161 YP=YY(J)-Y(J)
162 AN(I,J-1)=0.0
163 AS(I,J-1)=0.0
164 SU(I,J)=TERM*TE(I,J)**1.5/YP
165 240 SP(I,J)=GREATER

C

C-2.4 - SYMMETRY AXIS AT THE BOTTOM (SOUTH BOUNDARY)

168 DO 280 I=ISTP1,N1
169 AN(I,1)=0.0
170 AS(I,1)=0.0
171 280 ED(I,1)=ED(I,2)

C

C-2.5 - OUTLET (EAST BOUNDARY)

174 DO 230 J=2,JEXIT
175 AE(NIM1,J)=0.0
176 AM(NIM1,J)=0.0
177 230 ED(N,J)=ED(NIM1,J)
178 RETURN
CHAPTER 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3
C
C 300 CONTINUE
C
C-3.1-TOP WALL (NORTH BOUNDARY)
  DO 505 I=2,NIM1
    J=JN(I)
    AN(I,J)=0.0
    AS(I,J)=0.0
    SU(I,J)=SU(I,J)+DN(I,J)*(CPM(I,J)*T_WALL+FMI(I,J)*HR)
  505 SP(I,J)=SP(I,J)-DN(I,J)
C
C-3.2-SIDE WALL OF BLUFF BODY (WEST BOUNDARY)
  JSTR=JINS(I)
  DO 510 J=JSTR,JSTEP
    I=IW(J)
    AE(I-1,J)=0.0
    AM(I-1,J)=0.0
    SU(I,J)=SU(I,J)+DE(I-1,J)*(CPM(I,J)*TBLUF+FMI(I,J)*HR)
  510 SP(I,J)=SP(I,J)-DE(I-1,J)
C
C-3.3-TOP WALL OF BLUFF BODY (SOUTH BOUNDARY)
  DO 515 I=ISTP1,N1
    J=JN(I)
    AN(I,J)=0.0
    AS(I,J)=0.0
    SU(I,J)=SU(I,J)+DN(I,J-1)*(CPM(I,J)*TBLUF+FMI(I,J)*HR)
  515 SP(I,J)=SP(I,J)-DN(I,J-1)
C
C-3.4-SYMMETRY AXIS AT THE BOTTOM (SOUTH BOUNDARY)
  DO 520 I=ISTP1,N1
    AN(I,1)=0.0
    AS(I,1)=0.0
    T(I,1)=T(I,2)
  520 EN(I,1)=EN(I,2)
C
C-3.5-OUTLET (EAST BOUNDARY)
  DO 525 J=JX,JEAT
    AE(J,N1)=0.0
    AM(J,N1)=0.0
    T(J,1)=T(NM1,J)
  525 ENMIN(J)=ENMIN(J)
C
C CHAPTER 4 4 4 4 4 4 SPECIES CONCENTRATION 4 4 4 4 4 4
C
C 400 CONTINUE
C
C-4.1-SYMMETRY AXIS AT THE BOTTOM (SOUTH BOUNDARY)
  DO 410 I=ISTP1,N1
    410 FM(I,1)=FM(I,2)
C
C-4.2-OUTLET (EAST BOUNDARY)
  DO 420 J=NM1,NJ
    420 FMJ=NIM1,J
C
C CHAPTER 5 5 5 5 MIXTURE FRACTION 5 5 5 5 5 5 5 5 5
C 500 CONTINUE
C-5.1-SYMMETRY AXIS AT THE BOTTOM (SOUTH BOUNDARY)
   DO 550 I=ISP1,N1
      550 F(I,1)=F(I,2)
C-5.2-OUTLET (EAST BOUNDARY)
   DO 560 J=1,NJ
      560 F(NI,J)=F(NIM1,J)
   RETURN
C CHAPTER 6  6  6  6  SWIRL  6  6  6  6
C 600 CONTINUE
C-6.1-TOP WALL (NORTH BOUNDARY)
   DO 601 I=2,NIM1
      J=JN(I)
      YP=YY(J)-Y(J)
      YPLUSN(I)=DEN(I,J)*CMU25*SORT(TE(I,J))*YP/VISCOS
      VPLUS=ALOG1+LOG1+YPLUSN(I)/CAPPA
      IF(YPLUSN(I).LE.11.63) GO TO 602
      TMULT=DEN(I,J)*CMU25*SORT(TE(I,J))
      TMULT=TMULT/VPLUS
   GO TO 603
   602 TMULT=VISCOS/YP
   603 TAUNS(I)=TMULT*W(I,J)/R(J)
      T3=SEM(I)*AV(I-J,J)*R(I-J)/W(I,J)/R(J)
      SP(I,J)=SP(I,J)-T3/W(I,J)
      T2=2.0*SEM(I)*WS*VISS
      SUI(I,J)=SUI(I,J)*T2
      AN(I,J)=0.0
      AS(I,J)=0.0
   601 CONTINUE
   TAUNS(I1)=TAUNS(I2)
   TAUNS(NI)=TAUNS(NIM1)
C-6.2-TOP WALL OF BLUFF BODY (SOUTH BOUNDARY)
   DO 604 I=2,ISTEP
      J=JS(I)
      YP=YY(J)-Y(J)
      YPLUS(I)=DEN(I,J)*CMU25*SORT(TE(I,J))*YP/VISCOS
      VPLUS=ALOG1+LOG1+YPLUS(I)/CAPPA
      IF(YPLUS(I).LE.11.63) GO TO 605
      TMULT=DEN(I,J)*CMU25*SORT(TE(I,J))
      TMULT=TMULT/VPLUS
   GO TO 606
   605 TMULT=VISCOS/YP
   606 TAUNS(I)=TMULT*W(I,J)/R(J)
      T3=SEM(I)*AV(I-J,J)*R(I-J)/W(I,J)/R(J)
      T2=2.0*SEM(I)*WN*VISS
      SP(I,J)=SP(I,J)-T3/W(I,J)
      AN(I,J-1)=0.0
      AS(I,J-1)=0.0
   604 CONTINUE
   TAUNS(I1)=TAUNS(I2)
C

C-6.3-SIDE WALL OF BLUFF BODY (WLAST BOUNDARY)
JSTR=JNS+1
DO 607 J=JSTR,JSTEP
I=IWI(J)
XP=XU(I)-X(I)
XPLUSW(J)=DEN(I,J)*SQRT(TF(I,J))*CMU25*XP/VISCO
VPLUS=ALOG(EXP(XPLUSW(J)))/CAPPA
IF (XPLUSW(J).LE.11.63) GO TO 608
TMULT=_DEN(I,J)*CMU25*SQRT(TF(I,J))
TMULT=TMULT/VPLUS
GO TO 609
608 TMULT=VISCO/XP
609 TAUSS(I,J)=TMULT*W(I,J)
SP(I,J)=SP(I,J)-TMULT*SNS(J)*R(J)
AE(I-1,J)=0.0
AW(I-1,J)=0.0
607 CONTINUE
C

C-6.4-SYMMETRY AXIS AT THE BOTTOM (SOUTH BOUNDARY)
DO 610 I=2,NI
AN(I,1)=0.0
AS(I,1)=0.0
610 WI(I,1)=WI(I,2)

C

C-6.5-OUTLET (EAST BOUNDARY)
DO 611 J=2,JEXIT
AE(NIM1,J)=0.0
AW(NIM1,J)=0.0
611 MN1+J=WN(MN1,J)
RETURN
END

*PRRT,S TEACH*TEACH.MODINP
C
1005 FORMAT(20AN4)
C
1010 FORMAT(8I10)
C
READ(L5,1010) ITSTFP,MODOP
C
READ(L5,1010) ISCEME,INDCOS,KNPRO,KNCOMP,KVISCO,KLAMNR
C
READ(L5,1010) NI,NJ,ISTEP,JSTEP,JEXIT,JINS,IMON,JMON
C
READ(L5,1010) IU,IV,IP,ITE,IED,IEN,IFM,IF
C
READ(L5,1010) ISWR,IPP
C
ISWDUM( 1) = IU
ISWDUM( 2) = IV
ISWDUM( 3) = IP
ISWDUM( 4) = ITE
ISWDUM( 5) = IED
ISWDUM( 6) = IEN
ISWDUM( 7) = IFM
ISWDUM( 8) = IF
ISWDUM( 9) = ISWR
ISWDUM(10) = IPP
C
READ(L5,1010) (NSWP(I),I=1,10)
C
1015 FORMAT(8E10.5)
C
READ(L5,1015) VISCOS, DENSIT, TWALL, TBLU1F
C
READ(L5,1015) UIN, WIN, TIN, CIN, TURBIN, DELTA, PIN
C
READ(L5,1015) UCEN, WCEN, TCEN, CCEN, TUPBCN, DELECN
C
READ(L5,1015) STOIC, HR, WMF
C
READ(L5,1015) CP02, CPN2, CPC02, CPH20
C
READ(L5,1015) (CPFTRM(I),I=1,5)
C
DO 1020 J=1,NI
READ(L5,1015) XU(I)
C
1020 CONTINUE
C
DO 1025 J=1,NJ
READ(L5,1015) YV(J)
C
1025 CONTINUE
C
READ(L5,1030) PREF, IPREF, JREF, PERR, MAXSWP
C
1030 FORMAT(10.5, 2I10,E10.5,1LG)
C
READ(L5,1035) SORMAX, MAXIT, INDPRI, NUMPRI, ITREAT
C
1035 FORMAT(10.5, 4I10)
C
WRITE(L6,2005) (TITLE(I),I=1,20)
C
2005 FORMAT(I1,10X,'TURBULENT FLOW IN A BLUFF-BODY COMBUSTOR'),
C  WRITE(LU6,2010) ISTEP
2010 FORMAT(/10X,'NUMBER OF ITERATIONS TO EXECUTE',1X,110)
C  IF(MODOP.EQ.2) WRITE(LU6,2015)
2015 FORMAT(/10X,'MODOP = 1, THIS IS A NEW CASE')
2020 FORMAT(/10X,'MODOP = 2, START FROM RESTART FILE')
C  IF(ISCEME.EQ.1) WRITE(LU6,2025)
2025 FORMAT(/10X,'ISCEME = 1, USE HYBRID DIFFERENCING')
2030 FORMAT(/10X,'ISCEME = 2, USE SKEW DIFFERENCING')
C  IF(INDCOS.EQ.1) WRITE(LU6,2032)
2032 FORMAT(/10X,'INDCOS = 1, CARTESIAN CO-ORDINATES')
2035 FORMAT(/10X,'INDCOS = 2, CYLINDRICAL CO-ORDINATES')
C  IF(KNPRO.LE.0) WRITE(LU6,2040)
2040 FORMAT(/10X,'KNPRO = 0, FLUID PROPERTIES ARE CONSTANT')
2045 FORMAT(/10X,'KNPRO = 1, FLUID PROPERTIES ARE VARIABLE')
C  IF(KNCOMP.LE.0) WRITE(LU6,2050)
2050 FORMAT(/10X,'KNCOMP = 0, FLOW IS COMPRESSIBLE')
2055 FORMAT(/10X,'KNCOMP = 1, FLOW IS INCOMPRESSIBLE')
C  IF(KVISCO.LE.0) WRITE(LU6,2060)
2060 FORMAT(/10X,'KVISCO = 0, VISCOSITY IS VARIABLE')
2065 FORMAT(/10X,'KVISCO = 1, VISCOSITY IS CONSTANT')
C  IF(KLAMNR.LE.0) WRITE(LU6,2070)
2070 FORMAT(/10X,'KLAMNR = 0, FLOW IS TURBULENT')
2075 FORMAT(/10X,'KLAMNR = 1, FLOW IS LAMINAR')
C  WRITE(LU6,2080) N, NJ, ISTEP, JSTEP, JEXIT, JINS, ISM, JMON
2080 FORMAT(/10X,'GRID CONTROLS'/
X/10X,'N  = 15',
X/10X,'NJ = 15',
X/10X,'ISTEP = 15',
X/10X,'JSTEP = 15',
X/10X,'JEXIT = 15',
X/10X,'JINS = 15',
X/10X,'JMON = 15',
X/)
C  WRITE(LU6,2100)
2100 FORMAT(/10X,'DEPENDENT VARIABLE EQUATION CONTROLS'/
X/10X,'VARIABLE',22X,'SWITCH NO. SWEEPS UNDER RELAX',
X/10X,'FACTO',
WRITE(LU6,2105) (ISWDDM(I),NSWP(I),URF(I),I=1,10),URFVIS,URFDEN
2105 FORMAT/
X/10X,'U VELOCITY',22X,'2112, E12.5',
X/10X,'V VELOCITY',22X,'2112, E12.5',
X/10X, "PRIMARY PRESSURE CORRECT", 2112, F12.5,
X/10X, "TURBULENCE ENERGY", 2112, F12.5,
X/10X, "ENERGY DISSIPATION", 2112, F12.5,
X/10X, "ENTHALPY", 2112, F12.5,
X/10X, "FULL CONCENTRATION", 2112, F12.5,
X/10X, "MIXTURE FRACTION", 2112, F12.5,
X/10X, "SWIRL VELOCITY", 2112, F12.5,
X/10X, "SEC. PRESSURE CORRECT.", 2112, F12.5,
X/10X, "VISCOSITY", 2112, F12.5,
X/10X, "DENSITY", 2112, F12.5,
X/

C WRITE(LU6,2120) VISCOS, DENSIT, TWALL, TBLUF

2120 FORMAT
X/10X, VISCOSITY, N-SEC/M**2*, E12.5,
X/10X, DENSITY, KG/M**3*, E12.5,
X/10X, WALL TEMPERATURE, K*, E12.5,
X/10X, BLUFF BODY TEMPERATURE, K*, E12.5,
X/

C WRITE(LU6,2150)

2150 FORMAT(/10X, 'FLOW CONDITIONS...',
X/10X, 'VARIABLE',
WRITE(LU6,2155) UIN, UCEN, WIN, WCEQ, TIN, TCEQ, CIN, CCEN,
X)

2155 FORMAT
X/10X, AXIAL VELOCITY, M/SEC*, 2E12.5,
X/10X, SWIRL/AXIAL VEL. RATIO*, 2E12.5,
X/10X, TEMPERATURE, K*, 2E12.5,
X/10X, CONC.-SECOND COMPONENT*, 2E12.5,
X/10X, TURB. INTENSITY FACTOR, 2E12.5,
X/10X, BNDY. LAYER THICKNESS, M*, 2E12.5,
X/10X, PRESSURE, N/M**2*, E12.5,
X/

C WRITE(LU6,2160) STOIC, HR, WHF

2160 FORMAT
X/10X, STOIC. 02/FUEL MASS RAT., E12.5,
X/10X, HEAT OF COMBUSTION, J/KG*, E12.5,
X/10X, FUEL MOLECULAR WEIGHT, E12.5,
X/

C WRITE(LU6,2165) CP02, CPN2, CPCO2, CP2H20

2165 FORMAT
X/10X, CP-02, J/KG-K*, E12.5,
X/10X, CP-N2, J/KG-K*, E12.5,
X/10X, CP-CO2, J/KG-K*, E12.5,
X/10X, CP-N20, J/KG-K*, E12.5,
X/

C WRITE(LU6,2170) (CPFRM11), E=1.5

2170 FORMAT(/10X, 'CO-EFFICIENTS OF THE POLYNOMIAL FOR THE HEAT * ',
X/10X, 'CAPACITY FOR THE SECOND COMPONENT (E.G., FUEL) !',
X/10X, 'CP = [C1* C2*T + C3*T**2 + C4*T**3 + C5*T**4]*UGC/WHF',
X/10X, 'WITH T IN DEG K AND CP IN J/KG-K*',
X/10X, 'C1 = ', E12.5,
X/10X, 'C2 = ', E12.5,
X/10X, 'C3 = ', E12.5,
X/10X, 'C4 = ', E12.5,
X/10X, 'C5 = ', E12.5,)
C-------SET VERTICAL TRAVERSE LIMITS
   DO 110 J = 1, NJ
   JS(J) = 2
   VN(J) = NJ - 1
   IF(I-LEISTEP) JS(I) = JSTEP + 1
110    CONTINUE

C-------SET HORIZONTAL TRAVERSE LIMITS
   DO 120 I = 1, NI
   IW(I) = 2
   IF(J-LEISTEP) IW(J) = ISTEP + 1
   IF(J = NI - 1)
120    CONTINUE
   CALL GRID
   RSMALL = YV(JSTEP)

C

C-1.2-------CONTROL VARIABLES

C-----DEPENDENT VARIABLE SELECTION
   DO 130 I = 1, 10
   INCAL(I) = .FALSE.
130    CONTINUE

C
   IF(IU .EQ. 1) INCAL(IU) = .TRUE.
   IF(IIV .EQ. 2) INCAL(IIV) = .TRUE.
   IF(IIP .EQ. 3) INCAL(IIP) = .TRUE.
   IF(ITE .EQ. 4) INCAL(ITE) = .TRUE.
   IF(ITE .EQ. 5) INCAL(ITE) = .TRUE.
   IF(INEN .EQ. 6) INCAL(INEN) = .TRUE.
   IF(INIF .EQ. 7) INCAL(INIF) = .TRUE.
   IF(INISW .EQ. 8) INCAL(INISW) = .TRUE.

C
   INPRO = .FALSE.
   INCOMP = .FALSE.
   IVISCO = .FALSE.
   LAMINR = .FALSE.
   IF(KNPRO .GT. 0) INPRO = .TRUE.
   IF(KNCOMP .GT. 0) INCOMP = .TRUE.
   IF(KIVISCO .GT. 0) IVISCO = .TRUE.
   IF(KLAMINR .GT. 0) LAMINR = .TRUE.

C-------BOUNDARY CONDITIONS

C-------PRESSURE CALCULATION
   CLC  RETURN

C-------CHAPTER 2 2 2 2 2 2 PRELIMINARY OPERATIONS

C-2.1-------FLUID AND FLOW PROPERTIES
   DO 20 IVAR = 1, 9
   PRANDL(IVAR) = 0.7
20    PRANDT(IVAR) = 0.9
   PRANDL(ISWR) = 1.0

C

C-2.2-------TURBULENCE CONSTANTS
   CMU25 = SQRT(SQRT(CMU))
   CMU25 = CMU25 ** 3
   PRANDT(ITE) = 1.0
   PRANDT(ITE) = CMU * CMU * (C2 - C1) / (CMU ** 0.5)
   PRANDT(IFM) = 0.5
5-62

C  5-62
C

360  PRANDT[1] = 0.5
361  PRANDT[I(N)] = 0.5
362  PRANDT[I(SWRI)] = 1.0
363  PFUN = PRANDT[I(N)] / PRANDT[I(SWRI)]
364  CPIN = 0.767 * CPN2 * 0.233 * CP02
365  PFUN = 0.24 * (PFUN**0.75 - 1.0) * (1.0 + 0.2P/FXP(I(N), 0.07, PFUN))

C  -2.3--SET VARIABLES TO ZERO
C
C  -2.4--BOUNDARY VALUES
C
370  TEIN = TURBIN*UIN**2
371  TALLN = 0.0
372  ALAMDA = 0.005
373  EDIN = TEIN * 1.5 / (0.09 * DELTA) * CMU75
374  TECN = TURBCN*UCEN**2
375  EDCN = TECN * 1.5 / (0.09 * DELCEN) * CMU75
376  ENTRY START

C
C  CHAPTER 3 SET VARIABLES TO STARTING VALUES 3 3 3 3 3 3 3
C
C  C-3.1--INITIALISE VARIABLE FIELDS
C
381  JSTR = JS{1}
382  JEND = NJM1
383  DO 21 J = JSTR, JEND
384    U(1, J) = UIN
385    FM(I, J) = CM
386    EN(I, J) = CPIN * TIN
387    F(I, J) = CM
388    V(I, J) = 0.0
389    W(I, J) = WIN * UIN
390  21 CONTINUE
391  TP = TCEN
392  TP2 = TP * TP
393  TP3 = TP2 * TP
394  TP4 = TP3 * TP
395  CPF = (CPFRM{1} + CPFRM{2} * TP + CPFRM{3} * TP2
396       CPFRM{4} * TP3 + CPFRM{5} * TP4) / UGC/WMF

C
C
397  DO 28 I = 1, ISTEP
398    DO 20 J = 1, JINS
399      FM(I, J) = CM
400      EN(I, J) = HR * CPF * TCEN
401      CPM(I, J) = CM
402      T(I, J) = TCEN
403      F(I, J) = CM
404      U(I, J) = UCEN
405      V(I, J) = 0.0
406      W(I, J) = UCEN
407      TE(I, J) = TCEN
408      ED(I, J) = EDCN
409      DEN(I, J) = PIN/WMF / (UGC*TCEN)
410    20 CONTINUE
411  28 CONTINUE

C
C  C-3.2--CALCULATE MASS, MOMENTUM & TOTAL KINETIC ENERGY FLOW AT THE INLET
C
412  ENIN = 0.0
413  CINT = 0.0
414  XMINT = 0.0
415  XM0IN = 0.0

C
C
FLOWIN=0.0
AMONIN=0.0
DO 25 J=JSTR,JEND
25 ARDEN=DEN(1,J)*R(J)*SNS(J)
ENIN=ENIN+ARDEN*U(1,J)*EN(1,J)
CINT=CINT+ARDEN*U(1,J)*F(1,J)
XMININ=XMININ+ARDEN*U(1,J)**3
XMONIN=XMONIN+ARDEN*U(1,J)**2
AMONIN=AMONIN+ARDEN*U(1,J)*R(J)*U(1,J)
FLOWIN=FLOWIN+ARDEN*U(1,J)
FLOWA=2.0*PI*FLOWIN
DO 35 J=2,NINS
35 ARDEN=DEN(ISTEP,J)*R(J)*SNS(J)
ENIN=ENIN+ARDEN*U(ISTEP,J)*EN(ISTEP,J)
CINT=CINT+ARDEN*U(ISTEP,J)*F(ISTEP,J)
XMININ=XMININ+ARDEN*U(ISTEP,J)**3
XMONIN=XMONIN+ARDEN*U(ISTEP,J)**2
AMONIN=AMONIN+ARDEN*U(ISTEP,J)*U(ISTEP,J)*R(J)
FLOWIN=FLOWIN+ARDEN*U(ISTEP,J)
SNOD=2.0*AMONIN/XMONIN*RLARGE
FLOWF=2.0*PI*FLOWIN-FLOWA
UFIELD=2.0*FLOWIN/(DENSIT*RLARGE**2)
IF(INDCOS.EQ.1) UFIELD=FLOWIN/(DENSIT*RLARGE)
ULARGE=UFIELD
UEXIT=2.0*FLOWIN/(DENSIT*REXIT**2)
IF(INDCOS.EQ.1) UEXIT=FLOWIN/(DENSIT*REXIT)
IF(IREAD) GO TO 202
DO 26 I=2,NIMI
JSTAR=JS(I)
JLAST=JN(I)
DO 26 J=JSTAR,JLAST
U(I,J)=UFIELD
IF(I.LE.ISTEP) U(I,J)=UIN
26 CONTINUE
DO 27 J=2,JEXIT
27 U(NIU,J)=UEXIT
DO 29 I=2,NIMI
JSTR=JS(I)
JEND=JN(I)
DO 29 J=JSTR,JEND
30 W(I,J)=WIN0.5*U(I,J)*U(I-1,J)
30 CONTINUE
DO 200 I=2,NIU
JSTAR=JS(I)
JLAST=JN(I)
DO 300 J=JSTAR,JLAST
TN(I,J)=TEIN
ED(I,J)=EDIN
300 CONTINUE
DO 230 J=2,JEXIT
WIN,J)=WIN0.5*UEXIT
TE(NI,J)=TLIN
330 CONTINUE
ED(NI,J)=EDIN
DO 213 J=2,JEXIT
FM(NI,J)=CIN
F(NI,J)=CIN
213 EN(NI,J)=CPIN*TIN
DO 212 I=1,NI
JSTAR=JS(I)
JLAST=JN(I)
DO 212 J=JSTAR,JLAST
FM(I,J) = CIN
F(I,J) = CIN
212 EN(I,J) = CPIN*TIN
202 CONTINUE
JSTR = JSR(I)
JEND = JN(I)
DO 201 J = JSTR, JEND
TE(I,J) = TEIN
ED(I,J) = EDIN
201 VISI(I,J) = DEN(I,J)*TE(I,J)**2*CMU/ED(I,J)*VISCOS
DO 203 I = 2, NIM1
YPLUS(I) = 0.0
IF(NOT, NFREE) YPLUS(I) = 11.0
203 CONTINUE
DO 220 J = 1, NJ
XPLUS(J) = 0.0
XPLUSE(J) = 0.0
220 CONTINUE
DO 204 J = JINS1, JSTEP
204 XPLUS(J) = 11.0
DO 240 I = 1, NIM1
U(I,NJ) = UIN
V(I,NJ) = VIN
W(I,NJ) = WIN*UIN
TE(I,NJ) = TEIN
ED(I,NJ) = EDIN
VISI(I,NJ) = DEN(I,NJ)*TE(I,NJ)**2*CMU/ED(I,NJ)*VISCOS
FM(I,NJ) = CIN
F(I,NJ) = CIN
240 ENI(I,NJ) = CPIN*TIN
ENI(NJ) = WIN*UIN
TE(NI,NJ) = TEIN
ED(NI,NJ) = EDIN
ENI(NJ) = CPIN*TIN
FINI(NJ) = CIN
FINI(NJ) = CIN
VISI(NJ) = DEN(INI,NJ)*TE(INI,NJ)**2*CMU/ED(INI,NJ)*VISCOS
GO TO 250
245 DO 246 I = 1, NI
U(I,NJ) = 0.0
V(I,NJ) = 0.0
W(I,NJ) = 0.0
TE(I,NJ) = 0.0
ED(I,NJ) = 0.0
ENI(I,NJ) = 0.0
FINI(NJ) = 0.0
FI(I,NJ) = 0.0
246 VISI(I,NJ) = VISCOS
250 CONTINUE
P(LPRE) = PPRE
CALL PROPS
C
C-3.3-------CALCULATE SOURCE NORMALISATION FACTORS
SNORM(IU) = XMONIN
SNORM(IN) = XMONIN
SNORM(IP) = FLOWIN
IF(I*LE.1STEP) YPLUSS(I)=DEN(I,J)*SRT(TE(I,J))*YP*TERM1
   J=JN(I)
   YP=YY(I,J)-Y(J)
   YPLUSN(I)=DEN(I,J)*SRT(TE(I,J))*YP+TERM1
   20 CONTINUE
   C
   C-2.2-TOP WALL (NORTH BOUNDARY)
   DO 210 I=2,NIUM1
      J=JN(I)
      YP=YY(I,J)-Y(J)
      SRTK=SRT(0.5*TE(I,J)*TE(I+1,J))
      DENU=0.5*(DEN(I,J)+DEN(I+1,J))
      YPLUSA=0.5*(YPLUSS(I)+YPLUSN(I+1))
      IF(YPLUSA+LE.11.63) GO TO 211
      TMULT=DENU*CDTERM*SRTK/ALOG(ELOG*YPLUSA)
   210 CONTINUE
   C
   C-2.3-TOP WALL OF BLUFF BODY (SOUTH BOUNDARY)
   DO 410 I=2,ISTEP
      J=JS(I)
      YP=YY(I,J)-Y(J)
      SRTK=SRT(0.5*TE(I,J)*TE(I+1,J))
      DENU=0.5*(DEN(I,J)+DEN(I+1,J))
      YPLUSA=0.5*(YPLUSS(I)+YPLUSN(I+1))
      IF(YPLUSA+LE.11.63) GO TO 411
      TMULT=DENU*CDTERM*SRTK/ALOG(ELOG*YPLUSA)
   410 CONTINUE
   C
   C-CORNER CELLS
   ALPH=M(I)
   ALPHA1=1.0-ALPHA
   YPLUSA=DENU*SRTK*CMU25*YP/VISCOS
   IF(YPLUSA+LE.11.63) GO TO 416
   TMULT=DENU*CDTERM*SRTK/ALOG(ELOG*YPLUSA)
   416 CONTINUE
   C
   C-4.2-SYMMETRY AXIS AT THE BOTTOM (SOUTH BOUNDARY)
   DO 500 I=ISTP1,NIU
      AN(I,1)=0.0
   500 CONTINUE
C \[ A^{(1,1)} = U^{(1,2)} \] 

C \[ 430 \] \[ U^{(1,1)} = U^{(1,2)} \] 

CHAPTER 3 3 3 INTEGRAL CONTINUITY EQUATION AT OUTLET 3 3 3 3

C ENTRY MODU

ARDEN=0.0

FLOW=0.0

I=NIM

ALPHA=AU(I)

ALPHA1=1.0-ALPHA

DO 204 J=2, JEXIT

ARDEN=(ALPHA*DEN(I,J)+ALPHA1*DEN(I-1,J))*R(J)*SNS(J)

ARDET=ARDEN+ARDEN

DO 204 J=2, JEXIT

AE(NIM,J)=0.0

AW(NIM,J)=0.0

205 U(NIM,J)=U(NIM1,J)+UINC

RETURN


C ENTRY MODV

C C-4.1-SIDE WALL OF BLUFF BODY (WEST BOUNDARY)

DO 360 J=JINS, JSTEP

I=IW(J)

X=XU(I-1)-X(I)

SQRTK=SQR(T(0.5+TE(I,J)+TE(I+1,J))

DENV=0.5*(DEN(I,J)+DEN(I+1,J))

XPLUSA=0.5*(XPLUS(I+1,J)+XPLUSW(I,J))

IF(XPLUSA*EL.E.11.63) GO TO 371

TMULT=DENV*CDTERM*SQRTK/ALOG(ELOG*XPLUSA)

GO TO 372

TMULT=VISCO/XP

371 TAUW(J)=TMULT*W(I,J)

IF (J.EQ.JINS) GO TO 375

IF (J.EQ.JSTEP) GO TO 373

GO TO 374

C C- CORNER CELLS

373 BETA=AV(J)

GO TO 378

375 BETA=1.0-AV(J)

378 XPLUS=DENV*SQRTK*CMU*25*XP/VISCO

IF(XPLUSA*EL.E.11.63) GO TO 376

TMULT=DENV*CDTERM*SQRTK/ALOG(ELOG*XPLUSA)

GO TO 377

TMULT=VISCO/XP

376 TAUW(J)=TMULT*V(I,J)

THULT=TMULT*BETA

AE(I-1,J)=2.0*1.0-BETA)*AE(I-1,J)

AW(I-1,J)=1.0-BETA)*AW(I-1,J)

GO TO 379

374 AE(I-1,J)=0.0

AW(I-1,J)=0.0

379 SP(I,J)=SP(I,J)-TMULT*SNSV(J)*RV(J)

360 CONTINUE
C-4.2-OUTLET (LAST BOUNDARY)
DO 320 J=2,JEXIT
  AE(NIM1,J)=0.0
  A(NIM1,J)=0.0
  320 V(NI,J)=V(NIM1,J)
RETURN
C
CHAPTER 5 5 5 5 5 5 PRESSURE CORRECTION 5 5 5 5 5 5 5
C
ENTRY MODP
C
C-5.1-SYMMETRY AXIS AT THE BOTTOM (SOUTH BOUNDARY)
DO 480 I=ISTP1,NI
  AS(I,2)=0.0
  480 P(I,1)=P(IT,2)
RETURN
END
@PRT,5 TEACH*TEACH,OUTPUT
CALL PRINT(1,1,N1,NJ,IT,JX,Y,SPARE,HEN02)
DO 320 I=1,N1
DO 320 J=1,NJ
320 SPARE(I,J)=0.767*(1.0-F(I,J))
CALL PRINT(1,1,N1,NJ,IT,JX,Y,SPARE,HEN02)
DO 330 I=1,N1
DO 330 J=1,NJ
330 SPARE(I,J)=3.0*(F(I,J)-FM1(I,J))
CALL PRINT(1,1,N1,NJ,IT,JX,Y,SPARE,HEN02)
DO 340 I=1,N1
DO 340 J=1,NJ
340 SPARE(I,J)=0.545*SPARE(I,J)
CALL PRINT(1,1,N1,NJ,IT,JX,Y,SPARE,HEN02)
UAILD=0.0
FUADT=0.0
ENUADT=0.0
TUADT=0.0
DO 341 J=1,NJ
UAARDEN=UIN1(I,J)*R(I,J)*SNS(J)*DEN1(I,J)
UAILD=UAILD+UAARDEN
FUARD=FNI(I,J)*UAARDEN
ENUARD=ENIN1(I,J)*UAARDEN
TUARD=TNI(I,J)*UAARDEN
FUADT=FUADT+FUARD
ENUADT=ENUADT+ENUARD
TUADT=TUADT+TUARD
341 CONTINUE
FOUT=FUADT/UAILD
ENOUT=ENUADT/UAILD
TUOUT=TUADT/UAILD
FIN=CINT/FLOWIN
ENIN=ENIN1/FLOWIN
FLOWT=2.0*PI*FLOWIN
WRITE(LUG,101)FLOWT,FINT,FOUT,ENIN1,ENOUT,TIN,TOUT
1 FORMAT(*8,7HFLOWIN=,1PE11.3,/) 
2   *1DX,5HFIN=,1PE11.3,1DX,5HFOUT=,1PE11.3,/
3   *1DX,5HLENIN=,1PE11.3,9X,6HENOUT=,1PE11.3,/
4   *1DX,5HTIN=,1PE11.3,1DX,5HTOUT=,1PE11.3,/
5   RETURN
C
CHAPTER 3 3 3 3 3 3 3 3 3 3 3
C
ENTRY FINOP
C-----CALCULATION OF NON-DIMENSIONAL TURBULENCE ENERGY AND LENGTH SCALE
DO 400 I=2,NIM1
JSTR=JS(I)
JEND=NJ
DO 400 J=JSTR,JEND
SU(I,J)=EU(I,J)*DEN1(I,J)/(0.5*(ABS(TAUS(I))+ABS(TAUS(I-1))))
400 SPF(I,J)=EU(I,J)*DEN1(I,J)/(0.5*(ABS(TAUS(I))+ABS(TAUS(I-1))))
CALL PRINT(1,1,N1,NJ,IT,JX,Y,SU,HEP1)
CALL PRINT(1,1,N1,NJ,IT,JX,Y,SP,HEN1)
C-----CALCULATION OF SHEAR-STRESS COEFFICIENT ALONG LARGE DUCT WALL
WRITE(LUG,402)
DO 510 I=1,NIM1
SSCS=SQR(TAUS(I)**2+TAUNS(I)**2)
RESTM=SQR(TAUN(I)**2+TAUNS(I)**2)
RESTWS=SQR(TAUS(I)**2+TAUNS(I)**2)
IF (I.LE.ISTEP) SSCS=RESTM(1+DENS1*ULARGE*ULARGE)
510 CONTINUE
1050 CONTINUE
C
C
CONTINUE
FORMAT(/9X,1I1,3X,SHXU(I),5X,10HS,S,COEF.)
FORMAT(5X,15F11.3)
WRITE(LU6,405) J,YVD,SSCW

CONTINUE
FORMAT(/9X,1HJ,3X,SHYV(JI),5X,10HS,S,COEF.,1X,10HS,S,COEFW.)
FORMAT(5X,15F11.3)

C----CALCULATION OF STREAM FUNCTION

DO 500 I=1,NI
DO 600 J=1,NJ

500 SPARE(I,J)=0.0
DO 600 I=1,NI
LJ=JS(I)
LJN=JN(I)
LJSM1=LJS-
AREAEW=0.25*(R(LJS)*RV(LJSM1))*DYNP(LJSM1)
SPARE(I,J)=SPARE(I,LJSM1)+0.5*(UI(I,LJSM1)+U(I,LJS))*AREAEW
DO 600 J=LJS,LJN
AREAEW=RV(J)*DYNP(J)
SPARE(I,J+1)=SPARE(I,J)+0.5*(UI(I,J)+U(I,J+1))*AREAEW

600 CONTINUE
TERM=DENSIT*UIN*RSMAH
DO 601 I=1,NI
LJS=JS(I)
LJN=NJ
DO 601 J=LJS,LJN
SPARE(I,J)=SPARE(I,J)/TERM

601 CONTINUE
CALL PRINT(1,1,NIU,NJ,IT,JT,XU,Y,SPARE,HEDC)
RETURN
END

@PRT,S TEACH*TEACH,PRINT
SUBROUTINE PRINT(ISTART, JSTART, JEND, IEND, IT, JT, X, Y, PHI, HEAD)

COMMON /COM3/LU4,LU5,LU6,LU8,LU9

DIMENSION PHI(IT, JT), X(IT), Y(JT), HEAD(9), STORE(12)

DIMENSION F(8), F(13), F(14)

DATA F(1), F(2), F(3), F(4), F(5), F(6), F(7), F(8)
  /4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4 /
DATA F(9), F(10), F(11), F(12), F(13)
  /4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4 /
DATA F(14), F(15), F(16), F(17), F(18)
  /4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4 /
DATA F(19), F(20), F(21), F(22), F(23), F(24), F(25), F(26), F(27)
  /4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4 /
DATA F(28), F(29), F(30), F(31), F(32), F(33), F(34), F(35), F(36), F(37)
  /4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4,4H4 /
DATA HI, HY, 4H4, 4H4, 4H4, 4H4, 4H4, 4H4, 4H4, 4H4, 4H4, 4H4, 4H4, 4H4 /

ISKIP = 1
JSKIP = 1
LINLIM = 12
LINSTA = ISTART

C ----- PRINT ARRAY HEADING
WRITE(LU6, 1800) HEAD

1100 CONTINUE
LINEND = LINSTA + (LINLIM - 1) * ISKIP
IF4 = (LINEND - LINSTA) / ISKIP + 1
F(5) = F(4) / IF4
FD(3) = F(4) / IF4 + 1

C ----- PRINT LINE HEADING
WRITE(LU6, F) HI, (I, I = LINSTA, LINEND, ISKIP), HY
WRITE(LU6, 1900)

C ----- PRINT PHII ARRAY 2 2 2 2 2 2 2 2 2 2 2 2 2 2
DO 2200 JJ = JSTART, JEND, JSKIP
  J = JSTART + JEND - JJ
  IS = 0
  DO 2100 I = LINSTA, LINEND, ISKIP
    A = PHI(I, JJ)
    IF((ABS(A) .LT. 1.0D-20) .AND. IS .LT. 15) THEN
      STORE(IS) = A
      WRITE(LU6,FD) J, (STORE(I), I = 1, IS), Y(JJ)
    ELSE
      WRITE(LU6, 2900) (X(I), I = LINSTA, LINEND, ISKIP)
      LINSTA = LINEND + ISKIP
      IF (LINEND .LT. IEND) GO TO 1100
    END
  2100 RETURN
1800 FORMAT(/1X, 24(2H*, -1.7X, Y*4, 7X, 20(12H*, 1))
1900 FORMAT(3H, J)
2900 FORMAT(/4H X =, 12E10.3)
END
*TP4* *UGC*/44.0

CPH20 = (1.670E-1.1084E-3*TP4*1.521E-6*TP2*2.9637E-9*TP3*8.0702E-13

*TP4* *UGC*/19.0

CPN2 = (3.6748*1.208E-3*TP4*7.324E-6*TP2*6.321E-10*TP3*2.2577E-13

*TP4* *UGC*/28.0

CP02 = (3.6256*1.8752E-3*TP4*7.0555E-6*TP2*6.7635E-9*TP3*2.1556E-12

*TP4* *UGC*/32.0

GO TO 1112

1111 CPC02 = (4.4608*3.0982E-3*TP4*1.2392E-6*TP2*2.274E-10*TP3*1.5526E-14

*TP4* *UGC*/44.0

CPH20 = (2.7168*2.959E-3*TP4*8.0224E-7*TP2*1.0227E-10*TP3*4.8472E-15

*TP4* *UGC*/18.0

CPN2 = (2.8963*1.5155E-3*TP4*5.7235E-7*TP2*9.9807E-11*TP3*6.5224E-16

*TP4* *UGC*/28.0

CP02 = (3.6200*3.612E-4*TP4*1.9652E-7*TP2*3.6202E-11*TP3*2.8946E-15

*TP4* *UGC*/32.0

CPF = (CPFRM(1)*CPFRM(2)*TP + CPFTRM(3)*TP2

+ CPFTRM(4)*TP3 + CPFTRM(5)*TP4)*UGC/WMF

1112 CONTINUE

CPM1(J, J) = CPC02*FCO2*CPH20*FH20*CPN2*FN2*CP02*FO2*CPF*FM(I, J)

C------ TEMPERATURE

TOLO = T(I, J)

T(I, J) = T(E, I, J) - TM(I, J)*/HR/CPM1(J, J)

IF (T(I, J) > LE + TIM) T(I, J) = TIN

IF (ABS(TOLO - T(I, J)) < T(I, J) / LE * 0.01) GO TO 1120

1115 CONTINUE

1120 CONTINUE

C------ MEAN MOLECULAR WEIGHT INVERSE

AVMINV = FM(I, J) / MF + FCO2 / 44.0 + FH20 / 18.0 + FN2 / 28.0 + FO2 / 32.0

C------ NEW DENSITY

DENOLD = DEN1(I, J)

DENP = PIN/(UGC*TOLO*J1*AVMINV)

DEN1(I, J) = URFDEN * DENP + (1.0 - URFDEN) * DENOLD

100 CONTINUE

DO 105 J = 2, JEXIT

CPM1(J, J) = CPM1(NM1, J)

DP(NM1, J) = DEN1(NM1, J)

IF (.NOT. SSYM) GO TO 150

105 CONTINUE

DO 110 I = 2, NM1

CPM1(I, J) = CPM1(I, J)

110 CONTINUE

C

CHAPTER 2 2 2 2 2 2 2 EDDY VISCOITY 2 2 2 2 2 2

C

ENTRY VISC

DO 200 I = 2, NM1

JSTR = JS(I)

JEND = JN(I)

DO 210 J = JSTR, JEND

VISOLD = VISI(J, J)

IF (EDI(J, J) LT SMALL) GO TO 220

VISI(J, J) = DEN1(J, J)*TE(J, J)*CMU*EDJ(J, J)*VISCOS

GO TO 230

220 VISI(J, J) = VISCOS

230 VISI(J, J) = URFVIS*VISI(J, J) * (1.0 - URFVIS) * VISOLN

210 CONTINUE

DO 240 J = 2, JEXIT

240 VISI(NM1, J) = VISCOS(NM1, J)
200 CONTINUE
IF(.NOT.SSYM) GO TO 500
DO 400 I=2,NIM1
400 VIS(I,1)=VIS(I,2)
500 CONTINUE

CHAPTER 3 3 3 3 3 3 3 3 OTHER DIFFUSION COEFF 3 3 3 3 3 3 3
ENTRY GAM
IPHI=ITE
DO 300 I=2,NI
JSR=JS(I)
JEND=JN(I)
DO 300 J=JSR,JEND
300 GAMH(I,J)=VISCOS/PRAVDL(IPHI)+(VIS(I,J)-VISCOS)/PRAVDT(IPHI)
RETURN
END

@PRT,S TEACH@TEACH.SORCFI
FXM1=AU(I-1)
FY=AV(J)
FYM1=AV(J-1)

UP=0.5*(UI-1,J)*U(I,J)
UN=0.5*(UI-1,J)+U(I,J)*FY*UP*1.0-FY
US=0.5*(UI-1,J)+U(I,J)+1.0-FYM1*UP+FYM1

VDY=(UN-USD)/SNS(I)
VP=0.5*(VI-1,J)*VI,J)
VE=0.5*(VI,J)+VI,J)*FX*VP*1.0-FX

WW=0.5*(VI,J)+VI,J)*1.0-FX*VP*1.0-FX

VDY=(VE-VW)/SEW(I)
GENJ=GENJ+VDY*VDY**2

IF(INDCS=EQ.0) GO TO 1108
WW=WW+0.5*(FXM1+1.0-FX)*W(I-1,J)

WE=W(I,J)+FXM1*W(I+1,J)*FX

WDY=(WE-VW)/SEW(I)

WN=W(I,J)+1.0-FY)*W(I,J)/R(J)*1.0-FY

WS=WS+1.0-FY)*W(I,J)/R(J)*1.0-FY**2

VDY=WN+0.5*(W(VI,J-1)/R(J)-1)*1.0-FY

GENJ=GENJ+VDY*VDY**2+2*WDY*WDY**2

108 GEN(J,J)=GENJ

IF(INDCS=EQ.1) GO TO 114

VDR=V(I,J)/R(J)**2

GENJ=GENJ+0.5*(VDR+V(I,J)/R(J))**2

114 IF(INDCP=EQ.0) GO TO 115

DRY=(R(J)**2*(V(I,J)-1.0-FY)*V(I,J-1))/(R(J)*SNS(J))

GEN(J,J)=GEN(J,J)-0.6666*(DUDY+DRY)

115 SU(I,J)=CP*GEN(I,J)+SNS(I,J)*VISCOS*VOL

SP(I,J)=CP*GEN(I,J)+SNS(I,J)*VISCOS

120 CONTINUE

110 RETURN

CHAPTER 2 2 2 2 ENERGY DISSIPATION 2 2 2 2

200 CONTINUE

DO 210 I=2,NIM1

LS=JS(I,1)

LJN=JN(I,1)

DO 220 J=LS,LJN

VOL=RI(J)*SNS(J)*SEW(I)

SM=CN(J,1)-CN(I,J-1)*CE(I,J)-CE(I,J-1,J)

CP=AMAXID(0.0,SM)

SU=CP*GEN(I,J)+SM*GEN(I,J)+CMU*DEN(I,J)*TE(I,J)*VOL

SP=CP*GEN(I,J)+SM*DEN(I,J)*ED(I,J)*VOL/TE(I,J)

IF(INDCP) GO TO 220

DUDY=(UI,J-1-U(I-1,J))/SEW(I)

DRY=(R(J)**2*(V(I,J)-1.0-FY)*V(I,J-1))/(R(J)*SNS(J))

SU=SU+1.0-FY)*GEN(I,J)+SNS(I,J)*VISCOS*

220 CONTINUE

210 CONTINUE

RETURN

CHAPTER 3 3 3 3 3 ENTHALPY 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3

300 CONTINUE

DO 301 I=2,NIM1

LS=JS(I)

LJN=JN(I)
DO 301 J=LJS,JLN
   SMP=CN1(I,J-1)+CE(I,J)-CE(I-1,J)
   CP=AMAX1(0.0,SMP)
   SU(I,J)=CP*EN(I,J)
 301 SP(I,J)=-CP
RETURN

CHAPTER 4 4 4 4 4 4 FULL CONCENTRATION 4 4 4 4 4 4 4 4 4 4 4 4 4

400 CONTINUE
   DO 401 I=2,NIM1
      LJS=JS(I)
      LJN=JM(I)
      DO 401 J=LJS,LJN
         VOL=R(J)*SNS(I)*SEW(I)
         SMP=CN1(I,J)-CN1(I,J-1)+CE(I,J)-CE(I-1,J)
         CP=AMAX1(0.0,SMP)
         FO2=AMAX1(0.0,0.233*(STOIC*0.233)*F(I,J)+STOIC*FM(I,J))
         FPR=AMAX1(0.0,1.0*(F(I,J)-FM(I,J))
         R1=FM(I,J)
         R2=FO2/STOIC
         R3=0.5*FPR/(STOIC+1.0)
         TMULT=.0001(DEN(I,J)+ED(I,J))/TE(I,J)
         RMIN=AMAX1(R1,R2,R3)
         IF RMIN<=0.0 OR RMIN.RGE.R3 GO TO 410
         SU(I,J)=CP*FM(I,J)
         SPI(I,J)=-CP+TMULT*SMALL*VOL
      410 GO TO 401
   410 SPI(I,J)=CP+TMULT*0.5*FM(I,J)*VOL
RETURN

CHAPTER 5 5 5 5 MIXTURE FRACTION 5 5 5 5 5 5 5 5 5 5

500 CONTINUE
   DO 501 I=2,NIM1
      LJS=JS(I)
      LJN=JM(I)
      DO 501 J=LJS,LJN
         SMP=CN1(I,J)-CN1(I,J-1)+CE(I,J)-CE(I-1,J)
         CP=AMAX1(0.0,SMP)
         SU(I,J)=CP*FM(I,J)
 501 SP(I,J)=-CP
RETURN

CHAPTER 6 6 6 6 6 6 6 SWIRL VELOCITY 6 6 6 6 6 6 6 6 6

600 CONTINUE
   DO 601 I=2,NIM1
      LJS=JS(I)
      LJN=JM(I)
      DO 601 J=LJS,LJN
         VOL=R(J)*SNS(I)*SEW(I)
         SMP=CN1(I,J)-CN1(I,J-1)+CE(I,J)-CE(I-1,J)
         CP=AMAX1(0.0,SMP)
         SU(I,J)=CP*W(I,J)
         SP(I,J)=-CP
         IF (J.NE.LJN.AND.(J.NE.LJS.OR.I.GT.ISTEP)) GO TO 601
   601 GO TO 610
WT = (AV(J) + W(I, J+1)) / R(J+1) + (1.0 - AV(J)) * W(I, J) / R(J) * RV(J)
WS = (AV(J-1) + W(I, J)) / R(J) + (1.0 - AV(J-1)) * W(I, J-1) / R(J-1) * RV(J-1)

VISN = AV(I) + VIS(I, J+1) + (1.0 - AV(J)) * VIS(I, J)

VISS = AV(J-1) + VIS(I, J) + (1.0 - AV(J-1)) * VIS(I, J-1)
SORN = 2.0 * W(I) * VISN
SORS = 2.0 * W(I) * VISS
SP(I, J) = SP(I, J) - SORN * SOW(I) / W(I, J)
SU(I, J) = SU(I, J) + SORS * SOW(I)

CONTINUE
END

@PR1, S TEACH, TEACH, WPAFB1
5.7 Input Format
<p>| TITLE | Alphanumeric data for title of case |</p>
<table>
<thead>
<tr>
<th>ITSTEP</th>
<th>MODOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of iterations to be run during present execution</td>
<td></td>
</tr>
<tr>
<td>= 1 New case - start with first iteration</td>
<td></td>
</tr>
<tr>
<td>= 2 Start case using distributions of dependent variables stored in Restart file on logical unit L114</td>
<td></td>
</tr>
<tr>
<td>CARD NO. 3</td>
<td>FORMAT (B110)</td>
</tr>
<tr>
<td>------------</td>
<td>---------------</td>
</tr>
<tr>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ISCEME</td>
</tr>
<tr>
<td>ISCEME</td>
<td>= 1 Use hybrid differencing</td>
</tr>
<tr>
<td>INDCOS</td>
<td>= 1 Cartesian co-ordinates</td>
</tr>
<tr>
<td>KNPRO</td>
<td>= 0 Fluid properties are constant</td>
</tr>
<tr>
<td>KNCOMP</td>
<td>= 0 Flow is compressible</td>
</tr>
<tr>
<td>KVISCO</td>
<td>= 0 Viscosity is variable</td>
</tr>
<tr>
<td>KLAMNR</td>
<td>= 0 Flow is turbulent</td>
</tr>
</tbody>
</table>
### CARD NO. 4  FORMAT (8110)

<p>| | | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NI</td>
<td>NJ</td>
<td>ISTEP</td>
<td>JSTEP</td>
<td>JEXIT</td>
<td>JINS</td>
<td>IMON</td>
<td>JMON</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **NI**: Number of axial gridline locations (NI ≤ 30)
- **NJ**: Number of radial gridline locations (NJ ≤ 30)
- **ISTEP**: Axial gridline number of downstream end of centerbody
- **JSTEP**: Radial gridline number of outside radius of centerbody
- **JEXIT**: Radial gridline number of maximum radius at exit (use JEXIT = NJ-1)
- **JINS**: Radial gridline number of inside radius of centerbody
- **IMON**: Axial gridline number of node used for monitoring output
- **JMON**: Radial gridline number of node used for monitoring output
These variables are used to determine which dependent variables are to be calculated; that is, which partial differential equations will be solved. If a switch is input with a value other than indicated below, the corresponding variable is **NOT** calculated.

<table>
<thead>
<tr>
<th>IU</th>
<th>IV</th>
<th>IP</th>
<th>ITE</th>
<th>IED</th>
<th>IEN</th>
<th>IFM</th>
<th>IF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

- IU  = 1 Axial velocity
- IV  = 2 Radial velocity
- IP  = 3 Primary pressure correction
- ITE = 4 Turbulent kinetic energy
- IED = 5 Turbulent energy dissipation rate
- IEN = 6 Enthalpy
- IFM = 7 Fuel concentration
- IF  = 8 Mixture fraction
<table>
<thead>
<tr>
<th>ISWR</th>
<th>IPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>10</td>
</tr>
</tbody>
</table>
Number of sweeps through difference equations per iteration for the Kth dependent variable where K = 1 through 8 corresponds to the variables calculated as specified on Card No. 5

<table>
<thead>
<tr>
<th>K</th>
<th>Variable</th>
<th>Recommended Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Axial velocity</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Radial velocity</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>Primary pressure correction</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Turbulent kinetic energy</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Turbulent energy dissipation rate</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Enthalpy</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>Fuel concentration</td>
<td>1</td>
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<tr>
<td>8</td>
<td>Mixture fraction</td>
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</tbody>
</table>
**NSWP(K)**

Number of sweeps through the difference equation per iteration for variables calculated as specified on Card 5A.

<table>
<thead>
<tr>
<th>K</th>
<th>Variable</th>
<th>Recommended Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Swirl velocity</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>Secondary pressure correction</td>
<td>1</td>
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</tbody>
</table>
**URF(K)**

Underrelaxation factor of the Kth dependent variable calculated as specified on Card No. 5

<table>
<thead>
<tr>
<th>K</th>
<th>Variable</th>
<th>Recommended Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Axial velocity</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>Radial velocity</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>Primary pressure correction</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>Turbulent kinetic energy</td>
<td>0.7</td>
</tr>
<tr>
<td>5</td>
<td>Turbulent energy dissipation rate</td>
<td>0.7</td>
</tr>
<tr>
<td>6</td>
<td>Enthalpy</td>
<td>0.6</td>
</tr>
<tr>
<td>7</td>
<td>Fuel concentration</td>
<td>0.6</td>
</tr>
<tr>
<td>8</td>
<td>Mixture fraction</td>
<td>0.6</td>
</tr>
<tr>
<td>Underrelaxation Factor For</td>
<td>Recommended Value</td>
<td></td>
</tr>
<tr>
<td>---------------------------</td>
<td>-------------------</td>
<td></td>
</tr>
<tr>
<td>URF(9)</td>
<td>Swirl velocity</td>
<td>0.7</td>
</tr>
<tr>
<td>URF(10)</td>
<td>Secondary pressure correction</td>
<td>0.7</td>
</tr>
<tr>
<td>URFVIS</td>
<td>Viscosity</td>
<td>1.0</td>
</tr>
<tr>
<td>URFDEN</td>
<td>Density</td>
<td>0.4</td>
</tr>
<tr>
<td>CARD NO. 8</td>
<td>FORMAT (8E10.5)</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>VISCOS</td>
<td>DENSIT</td>
</tr>
</tbody>
</table>

<p>| VISCOS  | Laminar viscosity, N-sec/M^2 |
| DENSIT  | Density, KG/M^3               |
| TWALL   | Temperature of combustor outer wall, K |
| TBLUF   | Bluff body surface temperature, K |</p>
<table>
<thead>
<tr>
<th>CARD NO. 9</th>
<th>FORMAT (BE10.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80</td>
<td></td>
</tr>
<tr>
<td>UIN</td>
<td>WIN</td>
</tr>
</tbody>
</table>

UIN  | Axial velocity of main (outer) flow, M/sec
WIN  | Ratio of swirl to axial velocity of main flow
TIN  | Temperature of main flow, K
CIN  | Concentration (mass fraction) of secondary component (e.g., fuel) in main flow
TURBIN | Turbulence constant for main flow. Turbulent kinetic energy = TURBIN*UIN**2
DELTA | Boundary layer thickness for each surface (bluff body and wall) of main flow, M
PIN  | Pressure at inlet for both main and secondary flow, Pascal
<table>
<thead>
<tr>
<th>CARD NO. 10</th>
<th>FORMAT (8E10.5)</th>
</tr>
</thead>
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```
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80
```

- **UCEN**: Axial velocity of secondary (inner) flow, m/sec
- **WCEN**: Ratio of swirl to axial velocity of secondary flow
- **TCEN**: Temperature of secondary flow, K
- **CCEN**: Concentration (mass fraction) of secondary component in secondary flow
- **TURBCN**: Turbulence constant for secondary flow
  
  \[
  \text{Turbulent kinetic energy} = \text{TURBCN} \times \text{UCEN}^2
  \]
- **DELCEN**: Boundary layer thickness for secondary flow, m
<table>
<thead>
<tr>
<th>STOIC</th>
<th>HR</th>
<th>WMF</th>
</tr>
</thead>
</table>

**STOIC**

Stoichiometric oxygen to fuel mass ratio

**HR**

Heat of combustion, J/Kg

**WMF**

Fuel (secondary component) molecular weight
Heat capacities used during program initialization and for cases in which flow properties are constant. Therefore, these heat capacities must be input.

- **CPO2**: Heat capacity for oxygen, J/kg-K
- **CPN2**: Heat capacity for nitrogen, J/kg-K
- **CPCO2**: Heat capacity for carbon dioxide, J/kg-K
- **CPH2**: Heat capacity for water, J/kg-K
Heat capacity variation with temperature for secondary (e.g., fuel) component

\[
\text{CPF} = \left[ \text{CPFTRM}(1) + \text{CPFTRM}(2) \times T + \text{CPFTRM}(3) \times T^{2} \times 2 
+ \text{CPFTRM}(4) \times T^{3} + \text{CPFTRM}(5) \times T^{4} \right] \times \text{UGC/WMF}
\]

where CPF = Secondary component heat capacity, J/kg-K

T = Temperature, K

UGC = Universal gas constant = 8314.9 J/kg-mol-K

WMF = Secondary component molecular weight
There are NI of these cards, each containing one value of XU(I) where XU(I) is the axial location (in meters) of the Ith axial gridline for the axial velocity.

The axial storage locations for all other dependent variables are defined by $X(I) = 0.5(XU(I) + XU(I-1))$, $2 \leq I \leq NI - 1$

**Rule 1:** For the upstream physical boundary located at an axial distance XB (typically, $XB = 0$), input $XU(2) = XB$ and $XU(1) = -XB$

**Rule 2:** For the downstream physical boundary located at an axial distance XB, input $XU(NI-1) = XB = XU(NI)$
There are NJ of these cards, each containing one value of YV(J) where YV(J) is the radial location (in meters) of the Jth radial gridline for the radial velocity.

The radial storage locations for all other dependent variables are defined by

\[ Y(J) = 0.5 \times (YV(J) + YV(J-1)), \quad 2 \leq J \leq NJ - 1 \]

**Rule 1:** For the centerline in axisymmetric flow input \( YV(1) = 0 \)

**Rule 2:** For the upper physical boundary located at a radial distance RB input \( YV(NJ-1) = RB = YV(NJ) \)
<table>
<thead>
<tr>
<th>CARD NO. 16</th>
<th>FORMAT (E10.5,2110,E10.5,110)</th>
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</thead>
<tbody>
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<td></td>
</tr>
<tr>
<td><strong>PREF</strong></td>
<td><strong>IPREF</strong></td>
</tr>
</tbody>
</table>

**PREF**
Reference pressure, Pascal

*(NOTE: For incompressible flow, it is sufficient to use PREF = 0.0 and this value is recommended by the authors of the development version of the program.)*

**IPREF**
Axial gridline number for PREF

**JPREF**
Radial gridline number for PREF

**PERR**
Tolerance for residual in the primary pressure-correction equation.
Recommended value = 0.05

**MAXSWP**
Maximum number of sweeps through the primary pressure-correction equation.
<table>
<thead>
<tr>
<th>Card No. 17</th>
<th>Format (E10.5,4110)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>SORMAX</th>
<th>MAXIT</th>
<th>INDPRI</th>
<th>NUMPRI</th>
<th>ITREAX</th>
</tr>
</thead>
</table>

**SORMAX**  
Maximum residual for field variables (recommended range .001 to .005). As a practical matter, there is no suitable means of normalizing the residual for turbulent energy dissipation rate. As a result, the maximum residual for this variable tends to be large compared to residuals for all other variables. Therefore, the program continues to execute iterations until the criterion specified by ITSTEP (Card No. 2) or MAXIT (this card) is satisfied. The user decides whether the case must be continued by examining the change in the maximum residual for turbulent energy dissipation rate between the first and last iteration.

**MAXIT**  
The maximum total number of iterations that can be run irrespective of the additional iterations requested by ITSTEP (see Card No. 2).

**INDPRI**  
Number of iterations between outputs of the distributions for the dependent variables.

**NUMPRI**  
Number of iterations between outputs of the monitoring node information.

**ITREAX**  
Start chemical reaction on iteration ITREAX; this variable is used to permit flow calculation to stabilize prior to start of combustion. Typically, ITREAX = 30.
Three test cases are described in this section. The first two cases are based upon flow conditions and data supplied to UTRC by W. M. Roquemore of Wright-Patterson Air Force Base in consultation with the NASA Project Monitor. These data were obtained for nonswirling flows in a research combustor of the type shown in Fig. 1. Both a cold flow run and a hot flow run are simulated. The cold flow and hot flow nonswirling test cases are designated cases WPAFB1 and WPAFB2, respectively. The third case (WPAFB3) is derived from the hot flow test case without swirl by including swirl in the main (outer) stream and neglecting chemical reaction. It is included only to provide confirmation that the swirl option is operational.

For all the cases, the main flow consisted of air with a flow rate of 2 kg/sec. For the cold flow test cases, the secondary flow consisted of carbon dioxide having a flowrate of 6 kg/hr; for the hot flow test case, the same flow rate was used but the carbon dioxide was replaced with propane. The secondary inlet temperature and flow velocity also differed between the hot and cold flow cases. It was assumed that the turbulence was isotropic. From the test data provided to UTRC, it was estimated that the ratio of turbulent kinetic energy to the square of the flow velocity in each stream was 0.005. The inlet flow conditions are summarized in Table 7.

The primary purpose of the test cases was to demonstrate that the computer program is capable of producing a physically realistic result with a minimum of user intervention. Achieving an accurate comparison between calculated and measured results was considered to be of secondary importance. Therefore, a relatively coarse grid system, consisting of twelve axial and ten radial grid lines, was used for all calculations. The grid system is shown schematically in Fig. 7. The numbering of the grid lines is consistent with that defined in Sections 5.4 and 5.7.
6.1 Cold Flow Test Case Without Swirl

The cold flow test case without swirl (case WPAFB1) was run for a total of 100 iterations. A listing of the input cards and a copy of the printout corresponding to iterations 1 through 5 are included in Appendix 1. A copy of the printout for iterations 31 through 100 is also included in Appendix 1. All input values for underrelaxation factors, number of sweeps per iteration, etc. were the same for all of the runs.

At the end of 100 iterations, the calculation had not converged since some of the residuals exceeded the input maximum, SORMAX = 0.001. Generally, SORMAX is assigned a value between 0.001 and 0.005. The residuals for fuel concentration (F.CONC.) and mixture fraction (M.FRAC.) are about 0.01. However, for purposes of illustrating the operation of the program, these residuals may be considered to be small enough. No suitable length scale has been defined in the program for normalizing the turbulent energy dissipation rate. It is seen that the final value of the residual (DISS) for this variable is 1.78; however, since the value of DISS on the first iteration was 96200, the iteration for turbulent energy dissipation has probably converged. Therefore, the case has essentially converged as of the 100th iteration. Approximately 1670 seconds of UNIVAC 1100/81A machine time were used for this calculation.

The computed variation of centerline velocity with axial distance is shown by the solid line in Fig. 8. The measured data correspond to carbon dioxide flow rates of 4 and 8 kg/hr; data are not available for the carbon dioxide flow rate of 6 kg/hr used in the calculation. It can be seen that the calculated results show a more rapid initial deceleration of centerline velocity than that shown by the data. This could be the result of a greater rate of mixing of the two streams with the rapid mixing the result of severe numerical diffusion due to the very coarse grid used for the calculation. Similar behavior is exhibited by the calculated results for axial variation of centerline carbon dioxide concentration shown in Fig. 9 which are compared to measured data at the simulated flow rate.
6.2 Hot Flow Test Case Without Swirl

The hot flow test case without swirl (case WPAFB2) was run for 125 iterations; a listing of the input cards and a copy of the results for iterations 1 through 125 are shown in Appendix 2. The final residual for the fuel concentration and the mixture fraction is slightly greater than the specified maximum (SORMAX = 0.001). The residual for the turbulent dissipation rate decreased from a value of 135000 on the first iteration to a value of 463 on the last iteration. Therefore, this case has converged. Use of the combustion model was initiated on the 30th iteration. All underrelaxation factors, number of sweeps per iteration, etc. remained fixed throughout the entire calculation which used approximately 2080 seconds of UNIVAC 1100/81A machine time.

The calculated and measured variations of axial velocity are shown in Fig. 10 and of temperature in Fig. 11. A comparison of calculated and measured temperature profiles is shown in Fig. 12 for a downstream location. In all cases the predicted results exhibit greater mixing between the main and secondary streams than that shown by the data; again the greater mixing could be due to numerical diffusion caused by the use of a very coarse grid.
6.3 Cold Flow Test Case With Swirl

A cold flow test case (case WPAFB3) was run to demonstrate that the computer program was operating properly. The case was terminated after twenty iterations. A listing of the input cards and a copy of the results are included in Appendix 3. The calculation has obviously not converged but appears to be stable. This test case is provided only for documentation purposes and to aid the user in installing the computer program on another computer system.
7.0 REFERENCES


# 8.0 LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Co-efficient in finite-difference equations</td>
</tr>
<tr>
<td>a</td>
<td>Flow area</td>
</tr>
<tr>
<td>( a )</td>
<td>Flux contribution</td>
</tr>
<tr>
<td>C</td>
<td>Convective flux</td>
</tr>
<tr>
<td>( C_p )</td>
<td>Heat capacity</td>
</tr>
<tr>
<td>( C_1, C_2, C_3 )</td>
<td>Constants in turbulence model</td>
</tr>
<tr>
<td>D</td>
<td>Diffusive flux</td>
</tr>
<tr>
<td>E</td>
<td>Constant in law of the wall</td>
</tr>
<tr>
<td>( E_1, E_2, E_3 )</td>
<td>Flux contributions, east face of control volume</td>
</tr>
<tr>
<td>F</td>
<td>Flux</td>
</tr>
<tr>
<td>f</td>
<td>Mixture fraction</td>
</tr>
<tr>
<td>G</td>
<td>Turbulence generation term</td>
</tr>
<tr>
<td>h</td>
<td>Enthalpy</td>
</tr>
<tr>
<td>( H_R )</td>
<td>Heat of reaction</td>
</tr>
<tr>
<td>I</td>
<td>Index for nodes - axial direction</td>
</tr>
<tr>
<td>i</td>
<td>Stoichiometric oxygen to fuel mass ratio</td>
</tr>
<tr>
<td>J</td>
<td>Index for nodes - radial direction</td>
</tr>
<tr>
<td>K</td>
<td>Constant in law of the wall</td>
</tr>
<tr>
<td>k</td>
<td>Skewing interpolation factor or turbulent kinetic energy</td>
</tr>
<tr>
<td>M</td>
<td>Molecular weight</td>
</tr>
<tr>
<td>m</td>
<td>Mass fraction</td>
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<tr>
<td>( N_1, N_2, N_3 )</td>
<td>Flux contributions, north face of control volume</td>
</tr>
<tr>
<td>Pe</td>
<td>Peclet number</td>
</tr>
<tr>
<td>R</td>
<td>Universal gas constant</td>
</tr>
<tr>
<td>( R_f )</td>
<td>Reaction rate</td>
</tr>
<tr>
<td>S</td>
<td>Source</td>
</tr>
</tbody>
</table>
s  Distance along streamline
u  Axial velocity
v  Radial velocity
x  Axial co-ordinate
y  Distance from wall
\rho  Interpolation factor
\Gamma  Exchange co-efficient
\nu  Blending factor
\hat{e}  Coordinate indicator (0 for planar, 1 for axisymmetric)
v  Differential volume
\hat{\sigma}_{x,y}  Control volume dimensions
\alpha_{x,y}  Internodal distances
c  Turbulent energy dissipation rate
\phi  Hybrid differencing switch (1 for central differencing, 0 for bounded skew-upwind differencing)
c  Dependent variable
c  Density
c_{u,v}  Flow velocity direction switches
c_{\tau}  Turbulent Prandtl number for \tau
\tau  Shear stress

Subscripts
BSHD  Bounded skew hybrid differencing
BSUD  Bounded skew-upwind differencing
CD  Central differencing
CO_2  Carbon dioxide
E  East node
e  East face
\text{eff}  Effective value
\( f \)  
\( H_2O \)  
\( \dot{z} \)  
\( m \)  
\( \text{max} \)  
\( \text{min} \)  
\( N \)  
\( N_2 \)  
\( n \)  
\( \text{NE} \)  
\( \text{NW} \)  
\( O_2 \)  
\( P \)  
\( \text{pr} \)  
\( S \)  
\( s \)  
\( \text{SE} \)  
\( \text{SW} \)  
\( \text{SUD} \)  
\( t \)  
\( u \)  
\( \text{UD} \)  
\( W \)  
\( w \)  
\( \dot{\phi} \)  

**Superscripts**

\((\quad)^u\)  

Axial velocity
Radial velocity

Transition

For co-efficients, value not associated with

For co-efficients, value associated with
9.0 TABLES
### TABLE 1

Turbulence Model Constants

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<td>$\sigma_\varepsilon$</td>
<td>$\kappa^2/{(C_2 - C_1) C_\nu^{1/2}}$</td>
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<tr>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>T &gt; 1000K</td>
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<tr>
<td>C₁</td>
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</tr>
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<td>C₂</td>
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### TABLE 3

**Definition of Bounded Skew Hybrid Differencing Fluxes**

- **West**
  \[
  \frac{F_{WBSHD}}{D_W} = \lambda_W F_{wC} + (1 - \lambda_W) F_{wBSUD}
  \]

- **East**
  \[
  \frac{F_{EBSHD}}{D_E} = \lambda_E F_{eC} + (1 - \lambda_E) F_{eBSUD}
  \]

- **South**
  \[
  \frac{F_{SBSHD}}{D_S} = \lambda_S F_{sC} + (1 - \lambda_S) F_{sBSUD}
  \]

- **North**
  \[
  \frac{F_{NBSHD}}{D_N} = \lambda_N F_{nC} + (1 - \lambda_N) F_{nBSUD}
  \]
TABLE 4

Central Differencing Fluxes

West

\[
\frac{F_{WCD}}{D_N} = \left[ \frac{P_{e_b} (1 - 0) + 1}{\cdot} \right] \cdot \cdot + \left( \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot 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**TABLE 5**

**Bounded Skew-Upwind Differencing Fluxes**

**West**

\[
\frac{F_{wBSUD}}{D_w} = P_{ew} \left[ c_w^u c_w^v + (1 - c_w^u) \xi_p \right] - (P_{ew}^* - P_{ew}) \gamma_w k_w \\
+ \left( 1 - c_w^u \right) \left[ \xi_p^w - c_w^v c_{SW} - (1 - c_w^v) \xi_{NW} \right]
\]

**East**

\[
\frac{F_{eBSUD}}{D_e} = P_{ee} \left[ c_e^u \xi_e + (1 - c_e^u) \xi_E \right] - (P_{ee}^* - P_{ee}) \cdot e^k_e \\
+ \left( 1 - c_e^u \right) \left[ \xi_E - c_e^v c_{SE} - (1 - c_e^v) \xi_{NE} \right]
\]

**South**

\[
\frac{F_{sBSUD}}{D_s} = P_{es} \left[ c_s^v c_s^u + (1 - c_s^v) \xi_p \right] - (P_{es}^* - P_{es}) \gamma_s k_s \\
+ \left( 1 - c_s^v \right) \left[ \xi_p + (1 - c_s^u) \xi_{SE} - c_s^v c_{SW} \right]
\]

**North**

\[
\frac{F_{nBSUD}}{D_n} = P_{en} \left[ c_n^v \xi_n + (1 - c_n^v) \xi_p \right] - (P_{en}^* - P_{en}) \gamma_n k_n \\
+ \left( 1 - c_n^v \right) \left[ \xi_n^w - (1 - c_n^u) \xi_{NE} - c_n^v c_{NW} \right]
\]
TABLE 6

Coefficients of the Finite-Difference Equations

\[ A_w(I,J) = E_2(I-1,J) - \gamma_w \left[ \alpha_e E_3 \right]_{I-1,J} + \gamma_s \left[ (1 - \gamma_v) \frac{c_u}{n} N_3 \right]_{I,J-1} - \gamma_n \left[ \frac{v}{u} \frac{c_u}{n} N_3 \right]_{I,J} \]

\[ A_e(I,J) = E_1(I,J) + \gamma_e \left[ (1 - \gamma_v) \frac{c_u}{e} E_3 \right]_{I,J} + \gamma_s \left[ (1 - \gamma_v)(1 - \gamma_u) \frac{c_u}{n} N_3 \right]_{I,J-1} - \gamma_n \left[ \frac{v}{u} \frac{c_u}{n} N_3 \right]_{I,J} \]

\[ A_g(I,J) = N_2(I,J-1) - \gamma_s \left[ \frac{c_v}{n} N_3 \right]_{I,J-1} + \gamma_w \left[ (1 - \gamma_v) \frac{c_v}{e} E_3 \right]_{I-1,J} - \gamma_e \left[ \frac{u}{v} \frac{c_v}{e} E_3 \right]_{I,J} \]

\[ A_n(I,J) = N_1(I,J) + \gamma_n \left[ (1 - \gamma_v) \frac{c_u}{n} N_3 \right]_{I,J} + \gamma_w \left[ (1 - \gamma_v)(1 - \gamma_u) \frac{c_u}{e} E_3 \right]_{I-1,J} - \gamma_e \left[ \frac{u}{v} (1 - \frac{c_v}{e}) E_3 \right]_{I,J} \]

\[ A_{se}(I,J) = \gamma_v \left[ \frac{c_v}{n} (1 - \frac{c_u}{n}) N_3 \right]_{I,J-1} - \gamma_e \left[ (1 - \frac{c_v}{e}) \frac{c_v}{e} E_3 \right]_{I,J} \]

\[ A_{ne}(I,J) = \gamma_u \left[ \frac{c_u}{e} (1 - \frac{c_v}{e}) E_3 \right]_{I-1,J} - \gamma_n \left[ (1 - \frac{c_v}{n}) \frac{c_u}{n} N_3 \right]_{I,J} \]

\[ A_{ne}(I,J) = -\gamma_e \left[ (1 - \gamma_u)(1 - \gamma_v) \frac{c_u}{e} E_3 \right]_{I,J} - \gamma_n \left[ (1 - \gamma_v)(1 - \gamma_u) \frac{c_u}{n} N_3 \right]_{I,J} \]

NOTE: The blending factors \( \gamma_w, \gamma_e, \gamma_s \) and \( \gamma_n \) are the factors appropriate for the \((I,J)\) node as determined by the procedure discussed in Section 4.1.4.
TABLE 7
Inlet Flow Conditions for Test Cases

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<tr>
<th>Case</th>
<th>WPAFB1</th>
<th>WPAFB2</th>
<th>WPAFB3</th>
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<td>49.3</td>
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<td>0.005</td>
<td>0.005</td>
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<td><strong>Secondary Flow</strong></td>
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<td>Temperature, K</td>
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<td>Turbulent Kinetic Energy/ (Sec. Velocity)^2</td>
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<td>Pressure, Pa</td>
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</table>
Fig. 2 Grid System for Scalars and Tangential Velocity
Fig. 3 Relative Positions of Axial Velocity, Radial Velocity, and Scalar Grid Systems

1 = AXIAL LOCATION OF AXIAL VELOCITY

J = RADIAL LOCATION OF RADIAL VELOCITY

83-8-30-8
Fig. 5 Control Volume for Skew Upwind Differencing for West Face of Control Volume and Positive Velocity Components
Fig. 6 Program Flow Chart
Fig. 8 Centerline Axial Velocity Distribution for Cold Flow Test Case Without Swirl
Fig. 9 Centerline CO₂ Concentration Distribution for Cold Flow Test Case Without Swirl
Fig. 10 Centerline Axial Velocity Distribution for Hot Flow Test Case Without Swirl
Fig. 11 Centerline Temperature Distribution for Hot Flow Test Case Without Swirl
Fig. 12 Temperature Profile for Hot Flow Test Case Without Swirl
### TEACH\*TEACH(2)\*WPAFB1(3)

#### WPAFB1 - COLD FLOW TEST CASE

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#### 2PRTS TEACH\*TEACH\*WPAFB2
TURBULENT FLOW IN A BLUFF-BODY COMBUSTOR
FOR PAF81 - COLD FLOW TEST CASE

NUMBER OF ITERATIONS TO EXECUTE
MODOP = 1, THIS IS A NEW CASE
ISCFME = 2, USE SKEW DIFFERENCING
INUCOS = 2, CYLINDRICAL CO-ORDINATES
KNPR = 1, FLUID PROPERTIES ARE VARIABLE
MNCOMP = 1, FLOW IS INCOMPRESSIBLE
KVISCO = 0, VISCOSITY IS VARIABLE
KLAMNR = 0, FLOW IS TURBULENT

GRID CONTROLS
NI = 12
NJ = 10
ISTEP = 2
JSTEP = 6
JEIT = 9
JXWS = 6
JRON = 4

DEPENDENT VARIABLE EQUATION CONTROLS

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<th>NO. SWEEPS UNDER RELAX FACTOR</th>
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<tr>
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VISCOSITY N-SEC/MM#2 = 10000-04
DENSITY KG/MM#3 = 11600+01
WALL TEMPERATURE K = 29300+03
BLUFF BODY TEMPERATURE K = 29300+03

FLOW CONDITIONS...
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CO-EFFICIENTS OF THE POLYNOMIAL FOR THE HEAT CAPACITY FOR THE SECOND COMPONENT (E.G., FUEL)

\[
CP = (C_1 + C_2T + C_3T^2 + C_4T^3 + C_5T^4) \times \text{UGC/WMF}
\]

with \( T \) in deg K and \( CP \) in J/kg-K

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**AXIAL STORAGE LOCATIONS FOR AXIAL VELOCITY**

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**RADIAL STORAGE LOCATIONS FOR RADIAL VELOCITY**

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## Turbulent Flow with Combustion in a Bluff-Body Combustor

**Flow Rate of Main Stream (Air):** kg/s

**Flow Rate of Secondary Stream (Fuel):** kg/s

**Temperature of Main Stream:** K

**Temperature of Secondary Stream:** K

**Pressure at Inlet:** m/Hg

**Concentration of Fuel in Main Stream:**

**Concentration of Fuel in Secondary Stream:**

### Iteration Results

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<th>WM Conc</th>
<th>WM Mom</th>
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***Program Terminated Before Convergence Criterion Satisfied***

### Velocity Values

**U Velocity (m/sec)**

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**H2O MASS FRACTION**

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**#BKPPT PRINTS**

```
A1-11
```

```
FLOWIN: 2.021+00
FIN: 8.321-04
ENIN: 3.377+05
TIN: 2.930+02
```

```
FOUT: 3.398-05
ENOUT: 2.977+05
TOUT: 2.930+02
```
TURBULENT FLOW IN A BLUFF-BODY COMBUSTOR
FOR WPAFB 1 - COLD FLOW TEST CASE

NUMBER OF ITRATIONS TO EXECUTE 70
MODOP = 2, START FROM RESTART FILE
IScheme = 2, USE SKEL DIFFERENCING
INDCOS = 2, CYLINDRICAL CO-ORDINATES
KNPROM = 1, FLUID PROPERTIES ARE VARIABLE
KNCMP = 1, FLOW IS INCOMPRESSIBLE
KNISCO = 0, VISCOSITY IS VARIABLE
KLAMN1 = 0, FLOW IS TURBULENT

GRID CONTROLS
NI = 12
NJ = 10
ISTEP = 2
JSTEP = 6
JXINT = 9
JYINT = 2
IMON = 5
JMON = 5

DEPENDENT VARIABLE EQUATION CONTROLS
VARIABLE SWITCH NO. SWEEPS UNDER RELAX FACTOR
U VELOCITY 1 2 70000.000
V VELOCITY 2 3 70000.000
PRIMARY PRESSURE CORRECT 3 4 10000.000
TURBULENCE ENERGY 4 5 70000.000
ENERGY DISSIPATION 5 6 60000.000
ENTHALPY 6 7 60000.000
FULL CONCENTRATION 7 8 60000.000
MIXTURE FRACTION 8 9 60000.000
SWING VELOCITY 9 10 60000.000
SEC. PRESSURE CORRECT 10 1 70000.000
VISCOSITY 11 40000.000
DENSITY 12 40000.000

VISCOSITY N-SEC/MM**2 -18800.004
DENS1TY KG/MM**3 -11600.001
WALL TEMPERATURE K 29300.003
BLUFF BODY TEMPERATURE K 29300.003

FLOW CONDITIONS...
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CO-EFFICIENTS OF THE POLYNOMIAL FOR THE HEAT CAPACITY FOR THE SECOND COMPONENT (E.G., FUEL)

\[ CP = C_1 + C_2 T + C_3 T^2 + C_4 T^3 + C_5 T^4 \]  
WITH T IN DEG K AND CP IN J/KG-K

\[ \begin{align*}  
C_1 & = \text{240000}+01 \\
C_2 & = \text{48000}+02 \\
C_3 & = \text{6600}+05 \\
C_4 & = \text{200}+02 \\
C_5 & = \text{6127}+15 \\
\end{align*} \]

AXIAL STORAGE LOCATIONS FOR AXIAL VELOCITY

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RADIAL STORAGE LOCATIONS FOR RADIAL VELOCITY

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INFLUENCE PRESSURE PASCAL 900000
JPLF
JPFL
TFL FOR RESIDUAL FOR
PRESSURE CORRECT. CON.
MAX. NO. OF SWEEPS FOR
PRESS. CORRECT. CON.
50

MAX. RESIDUAL FOR FIELD VARIABLE 10000-02
MAX. NO. OF ITERATIONS TO BE RUN 100
NO. OF ITERATIONS BETWEEN TABULATION OF FIELD VARIABLES 1
NO. OF ITERATIONS BETWEEN OUTPUT OF MONITORING INFORMATION
ITERATION TO START CHEMICAL REACTION 500
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| FLOW RATE OF SECONDARY STREAM (FUELS), KG/SEC | 1.661±03 |
| TEMPERATURE OF MAIN STREAM, K | 2.93J±02 |
| TEMPERATURE OF SECONDARY STREAM, K | 2.93J±02 |
| PRESSURE AT INLET, N/M² | 2.59±04 |
| CONCENTRATION OF FUEL IN MAIN STREAM | 0.00±00 |
| CONCENTRATION OF FUEL IN SECONDARY STREAM | 0.00±00 |
| SWIRL NUMBER | 0.00±00 |

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### Note

These tables provide data for various physical properties across different temperatures and densities. The data is comma-separated with values for each parameter at different intervals.
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**Graphs and Tables:**

- **Graph 1:** A graph showing CO2 mass fraction with data points for various elements.
- **Graph 2:** A graph showing H2O mass fraction with data points for various elements.

**Data Points:**

- **CO2 Mass Fraction:**
  - Values range from 0.00 to 1.00.
- **H2O Mass Fraction:**
  - Values range from 0.00 to 1.00.

**Additional Notes:**

- The graphs are labeled with data points for specific elements, indicating the concentration levels of CO2 and H2O.
- The graphs are part of a larger dataset, possibly related to environmental or chemical analysis.

**Legend:**

- The graphs may be part of a scientific report or a technical manual, providing detailed information on the relationship between CO2 and H2O concentrations in a given context.
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The table above represents a hot flow test case with various numerical values.
TURBULENT FLOW IN A BLUFF-BODY COMBUSTOR
FOR EPABMF - HOT FLOW TEST CASE

NUMERICAL OF ITERATIONS TO EXECUTE: 12

MCDOP = 1, THIS IS A NEW CASE
IMCME = 2, USE SCHW Differencing
INDUS = 2, CYLINDRICAL CO-ORDINATES
KMLNO = 1, FLUID PROPERTIES ARE VARIABLE
KMCMP = 1, FLOW IS INCOMPRESSIBLE
KBISO = 0, VISCOSITY IS VARIABLE
KLAMM = 0, FLOW IS TURBULENT

GRID CONTROLS

NI = 12
NJ = 16
ISTEP = 6
JSTEP = 6
JXII = 6
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JUN = 6

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VISOSITY = SEC/MM**2           | 1.80000E-4 |
UNITY = ML/MM**2              | 1.10200E+1 |
SLIC PRESSURE TIME            | 1.10200E+1 |
INITIAL TEMPERATURE           | 1.10200E+1 |
INIT. DIL Temperature         | 1.10200E+1 |
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CF-EFFICIENTS OF THE POLYNOMIAL FOR THE HEAT CAPACITY FOR THE SECOND COMPONENT (E.G., FUEL)

\[
CF = (C1 + C2\cdot T + C3\cdot T^2 + C4\cdot T^3 + C5\cdot T^4) \cdot \text{HEAT} / \text{CMF}
\]

WITH T IN DEG K AND CP IN J/KG-K

- C1 = -24825+00
- C2 = -36714+01
- C3 = -19574+04
- C4 = -46923+08
- C5 = -29010+12

AXIAL STORAGE LOCATIONS FOR AXIAL VELOCITY

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RADIUS STORAGE LOCATIONS FOR RADIAL VELOCITY

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MAX. RESIDUAL FOR FIELD VARIABLE 7
NO. OF ITERATIONS TO BE RUN 10000-61
NO. OF ITERATIONS BETWEEN TABULATION 10000-61
OF FIELD VARIABLES
NO. OF ITERATIONS BETWEEN OUTPUT OF 1
MONITORING INFORMATION
ITERATION TO START CHEMICAL REACTION 3
### Turbulent Flow with Combustion in a Pluff-Pody Combustor

| Item | Flow Rate of Main Stream (Air), kg/s | Flow Rate of Secondary Stream (Fuel), kg/s | Temperature of Main Stream, K | Temperature of Secondary Stream, K | Pressure at Inlet, kN/mm² | Concentration of Fuel in Main Stream | Concentration of Fuel in Secondary Stream | Swirl Number | Field Values at Monitoring Location, 5, 41-
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**PROGRAM TERMINATED BEFORE CONVERGENCE CRITERION SATISFIED**

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WPAFB3 - COLD FLOW TEST CASE WITH SWIRL

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@BKRPT PRINTS
TURBULENT FLOW IN A BLUFF-BODY COMBUSTOR
FOR WPAFB3 - COLD FLOW TEST CASE WITH SWIRL

NUMBER OF ITERATIONS TO EXECUTE 20
MODOP = 1, THIS IS A NEW CASE
ISCEME = 2, USE SKEW DIFFERENCING
INDCOS = 2, CYLINDRICAL CO-ORDINATES
KNPRO = 1, FLUID PROPERTIES ARE VARIABLE
KNCOMP = 1, FLOW IS INCOMPRESSIBLE
KVISO = 0, VISCOSITY IS VARIABLE
KLAMR = 0, FLOW IS TURBULENT

GRID CONTROLS
NI ....... 12
NJ ....... 10
ISTEP ..... 2
JSTEP ..... 6
JEXIT ..... 9
JINS ..... 12
IMON ..... 5
JMON ..... 4

DEPENDENT VARIABLE EQUATION CONTROLS

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| WALL TEMPERATURE | K | 29300+01 |
| BLUFF BODY TEMPERATURE | K | 29300+01 |

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CO-EFFICIENTS OF THE POLYNOMIAL FOR THE HEAT CAPACITY FOR THE SECOND COMPONENT (E.G., FUEL)

\[ CP = (C1 + C2*T + C3*T^2 + C4*T^3 + C5*T^4) \times \text{UGC / WBF} \]

WITH T IN DEG K AND CP IN J/KG-K

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JPREF            7
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MAX. NO. OF SWEEPS FOR PRESS. CORRECT. EQU.  50
MAX. RESIDUAL FOR FIELD VARIABLE  10000-02
MAX. NO. OF ITERATIONS TO BE RUN  300
NO. OF ITERATIONS BETWEEN TABULATION  500
OF FIELD VARIABLES
NO. OF ITERATIONS BETWEEN OUTPUT OF MONITORING INFORMATION  1
ITERATION TO START CHEMICAL REACTION  500
### Turbulent Flow with Combustion in a Bluff-Body Combustor

**Flow Rate of Main Stream (Air), kg/s**: 2.019×10^4

**Flow Rate of Secondary Stream (Fuel), kg/s**: 1.633×10^4

**Temperature of Main Stream, K**: 2.933×10^4

**Temperature of Secondary Stream, K**: 4.000×10^4

**Pressure at Inlet, MPa**: 9.800×10^4

**Concentration of Fuel in Main Stream**: 0.000

**Concentration of Fuel in Secondary Stream**: 1.000×10^3

**Swirl Number**: 1.609×10^4

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**KIN. ENERGY (M*2/SEC*2)**

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**DISSIPATION (M*2/SEC*3)**

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**FUEL CONCENTRATION**

**MIXTURE FRACTION**

**ENTHALPY (H2, SFC42)**