COMPUTATIONAL FLOW PREDICTION
IN CYCLONE CHAMBERS

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ABSTRACT

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A theoretical prediction procedure has been developed to analyze the physical processes taking place in cyclone chambers. For this, the transient two-dimensional (2-D) Los Alamos SOLA solution algorithm has been extended to include the effects of the tangential velocity component for the flowfield which is assumed to be axisymmetric. The numerical solution procedure utilizes a simplified form of the Marker and Cell solution technique focussing attention on the steady-state case. A rapidly convergent algorithm is achieved by applying the method developed by the Imperial College group for treating the outlet boundary condition. Predictions for a cyclone chamber with a single-or a multi-set of tangential inlets show that a useful characterization of their flowfield is now becoming available.
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter/Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>1</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENT</td>
<td>11</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>111</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>v</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>vii</td>
</tr>
<tr>
<td><strong>CHAPTER 1 - INTRODUCTION</strong></td>
<td></td>
</tr>
<tr>
<td>1.1 THE PHENOMENON</td>
<td>1</td>
</tr>
<tr>
<td>1.2 PREVIOUS WORK</td>
<td>2</td>
</tr>
<tr>
<td>1.3 METHOD OF APPROACH</td>
<td>3</td>
</tr>
<tr>
<td><strong>CHAPTER 2 - THEORETICAL MODEL</strong></td>
<td></td>
</tr>
<tr>
<td>2.1 THE PROBLEM</td>
<td>5</td>
</tr>
<tr>
<td>2.2 GOVERNING EQUATIONS</td>
<td>6</td>
</tr>
<tr>
<td>2.3 THE FLOW REGION AND GRID SYSTEM</td>
<td>8</td>
</tr>
<tr>
<td><strong>CHAPTER 3 - SOLUTION PROCEDURE</strong></td>
<td></td>
</tr>
<tr>
<td>3.1 THE FINITE DIFFERENCE EQUATIONS</td>
<td>9</td>
</tr>
<tr>
<td>3.2 PRESSURE CORRECTION EQUATIONS</td>
<td>12</td>
</tr>
<tr>
<td>3.3 BOUNDARY CONDITIONS</td>
<td>14</td>
</tr>
<tr>
<td>3.4 STABILITY CONSIDERATIONS</td>
<td>16</td>
</tr>
<tr>
<td>3.5 COMPUTATIONAL PROCEDURE</td>
<td>21</td>
</tr>
<tr>
<td><strong>CHAPTER 4 - RESULTS AND DISCUSSIONS</strong></td>
<td></td>
</tr>
<tr>
<td>4.1 SINGLE-SET INLET CYCLONE-FLOW</td>
<td>23</td>
</tr>
<tr>
<td>4.2 MULTI-SET INLET CYCLONIC FLOW</td>
<td>27</td>
</tr>
<tr>
<td><strong>CHAPTER 5 - CONCLUSIONS</strong></td>
<td>29</td>
</tr>
</tbody>
</table>
REFERENCES

FIGURES

APPENDIX A

APPENDIX B

Page

30
33-61
62-64
65-72
LIST OF FIGURES

Figure 1: Cyclone Chamber Schematic and Physical Dimensions.
Figure 2: Coordinate System.
Figure 3: General Mesh Arrangement.
Figure 4: Arrangement of Finite Difference Variables in a Typical Cell.
Figure 5: Typical Marker and Cell Mesh Structure.
Figure 6: Rigid, No-Slip Boundary Conditions.
Figure 7: Rigid, Free-Slip Boundary Conditions.
Figure 8: Numerical And Actual Velocity Distribution for Flows With Large Reynolds Numbers.
Figure 9: Continuative Outflow.
Figure 10: Boundary Condition On the Axis Of Symmetry.
Figure 11: Inlet Boundary Conditions.
Figure 12: Schematic of a Single-Set of Inlets Cyclone Chamber and arrangement of the Radial Stations.
Figure 13: Tangential Velocity Profiles at Radial Station Z_3 for Different Inlet-Swirl Strengths.
Figure 14: Tangential Velocity Profiles at Radial Station Z_3 for Different Inlet Flowrates.
Figure 15: Axial Velocity Profiles at Radial Station Z_3 for Different Inlet Flowrates.
Figure 16: Tangential Velocity Profiles at Radial Station Z_3 for Different Constant Viscosities.
Figure 17: Axial Velocity Profiles at Radial Station Z_3 for Different Constant Viscosities.
Figure 18: Tangential velocity distribution for the Radial Station $Z_1$.

Figure 19: Tangential Velocity Distribution for $Z_4$.

Figure 20: Axial Velocity Profile for $Z_1$.

Figure 21: Axial Velocity Distribution for $Z_2$.

Figure 22: Axial Velocity Profile for $Z_3$.

Figure 23: Axial Velocity Profile for $Z_4$.

Figure 24: Radial Velocity Distribution for $Z_1$.

Figure 25: Radial Velocity Profile for $Z_2$.

Figure 26: Schematic of two Sets of Inlets (Near the Top and Base Plates) Cyclone Chamber and Arrangements of the Radial Stations.

Figure 27: Computer Vector Graph for $U$ and $V$ Velocity Components with $S = 0.5$.

Figure 28: Tangential Velocity Profiles with $S = 0.5$ and Inlet Velocities of $U_{IN}$ and $2 U_{IN}$ on Top and Bottom Respectively.

Figure 29: Computer Vector Graph for $U$ and $V$ Velocity Components with $S = 0.5$.

Figure 30: Tangential Velocity Profiles with $S = 0.5$ and Inlet Velocities of $2 U_{IN}$ and $U_{IN}$ on the Top and Bottom Respectively.

Figure 31: Tangential Velocity Distribution for the Radial Station $Z_3$ for the Inlet Swirl Strengths of 0.5 and 1.0.
NOMENCLATURE

D  chamber's diameter, m, (ft)
d  diameter of the outlet port, m, (ft)
Div divergence
g  body acceleration, m/s^2, (ft/s^2)
h  height of the inlet port, m, (ft)
L  chamber's length, m, (ft)
o  order of magnitude
P  ratio of pressure to density,
    (N/m^2)/kg, (lb/ft^2/lbm)
Q  volume flowrate, m^3/s, (ft^3/s)
R  radius m, (ft), Reynolds number
S  inlet swirl strength, S = W_{IN}/U_{IN}
t  time, s
U  velocity component in x direction, m/s, (ft/s)
V  velocity component in y direction, m/s, (ft/s)
W  velocity component in θ direction, m/s, (ft/s)
X, Y, θ radial, axial and tangential directions
Z  radial station
z  distance of the radial station from the base plate m, (ft)
a  upstream - differencing constant
δ  boundary layer thickness, m, (ft)
Δt  time increment, s
Δx, Δy radial and axial distances between two neighboring mesh points, m, (ft)
ΔP  pressure increment, N/m^2/kg, (lb/ft^2/lbm)
- viii -

c: pressure - iteration convergence criterion

v: kinematic viscosity, m^2/sec, (ft^2/sec)

\phi: generalized property

\omega: over relaxation factor

SUBSCRIPTS

e: effective properties

IN: properties at the inlet port.

i, j: mesh-point indexes

L: properties based on the chamber's length

o: distance of the velocity component in i, j cell from the datum

OUT: properties at the outlet port

SUPERSCRIPyTS

\eta: time level t

\overline{ }: average quantities
CHAPTER 1

INTRODUCTION

The main problem of energy recovery from solid wastes centers upon the design of efficient combustion chambers, which must be such, as to cause retention of fuel particles until they are completely burnt. The combustion chambers for solid fuel, which approach the desired characteristics, are cyclone furnaces with vortex action to segregate heavy and light particles.

Prior knowledge of the aerodynamic flow pattern within such chambers is necessary for a furnace designer to select an optimum configuration for an efficient, pollution-free furnace design. However, the extreme complexity of the natural mechanism involved renders the problem of setting up a mathematical model for the flow pattern more difficult. In general, the difficulties involved are:

a) The inability of the mathematical equations to truly portray the flow phenomenon in great precision.

b) The failure of the existing mathematical methods to give an exact solution to the set of partial differential equations.

Recent development of high-speed electronic computing machines provides the means to solve these equations using numerical methods with a high degree of accuracy. The present work may be considered as a first step towards solving multi-dimensional cyclone chamber problems with complex boundary conditions.

1.1 THE PHENOMENON

Vortex chambers are used extensively in furnace engineering and several other high temperature applications. In general, they have a
cylindrical configuration with a central axis outlet and circumferential inlets. Entry of fluid through the tangential inlets produces a swirling motion inside the vortex chamber. The inlets may be arranged near the outlet end of the chamber or at the opposite end or both. The advantages and main characteristics of the cyclone process are primarily due to the particular pattern of the flow-field produced. It in turn, depends on a number of design parameters, including the diameter and length of the chamber, size of the outlet, size and location of the inlets, and also the velocity and supply rates through the inlets.

The objective of the present work is to predict numerically the vortex flow-field within a chamber taking into consideration the geometric configuration and inlet flow conditions.

1.2 PREVIOUS WORK

The subject of confined vortex flows found in Cyclone Chambers has received considerable attention in the past twenty years owing to the great potential of such a system.

In a comprehensive survey article, Syred et al., reviewed the combustion problems of low calorific-value gases in various types of cyclone combustors. The early experimental work of Kalisheovshevshii and Gachev was directed towards the detailed investigation of the velocity and temperature distributions for a horizontal cyclone furnace. Later, Baluev and Troyankin performed an outstanding experimental study about the cold aerodynamic structure of gas flow in a vertical chamber. Continuing their investigations, the same authors further studied the effects of several design parameters on the aerodynamics of the same experimental model. An extensive research about the turbulent flow structure of such flows was carried out by Ustimenko and Bukhman. Troyankin and Baluev further extended the investigations of their model.
to include the effects of the chamber's resistance on the flow and the furnace's aerodynamic efficiency. Finally, an article by Tager et al. revealed the relationship between the chamber's outlet diameter and its overall flow pattern. The above experimental work was accomplished using stationary models consisting of tangential inlet(s), either near the top or near the bottom plate of the chamber. The furnaces used were positioned either horizontally or vertically.

In the area of theoretical investigation, Wormley provided an analytical foundation to the study of vortex flow in short cylindrical chambers. Most of the subsequent theoretical work is based upon Wormley's original analysis. A semi-analytical investigation for a liquid in a swirl chamber was conducted by Koval and Michailov.

Most of the theoretical models attempted so far used either short or long chambers. This is due to the fact that certain approximations can be made allowing investigators to reduce the Navier-Stokes equation in a form amenable to analytical treatment. The fact that a cyclone furnace does not belong to either of the two, above-mentioned categories leads to a much more complex flow field. Furthermore, the associated equations can only be solved utilizing numerical methods.

1.3 METHOD OF APPROACH

Consideration is given to the development of a primitive-variable, finite-difference solution procedure for an axisymmetric swirling flow in cyclone chambers. The present work is developed from a previous concept concerning the solution of a 2-D non-swirling flow using the Los Alamos technique for treating the transient case, and the Imperial College method for treating the steady-state case directly.
The transient two-dimensional Los Alamos SOLA prediction technique has been extended to include the computation of an axisymmetric swirling flow. Attention is directed towards the steady-state form of the flow-field. The outlet conditions have been modified using the Imperial College method for rapid convergence. The principal interest is centered upon keeping the algorithm simple, with the appreciation that any user-oriented sophistications can be added as required to the basic algorithm.

Useful computational results on the aerodynamics of the cyclone-chamber performance for several input conditions and configurations indicate that a tool for the furnace designer to predict cyclone flow pattern is now becoming possible.
CHAPTER 2
THEORETICAL MODEL

Consideration is given to the development of a finite-difference solution procedure for 2-D swirling flows in cyclone chambers. Chapter 2 and 3 of the thesis present the Marker and Cell (MAC) simulation and solution techniques, focusing attention directly on the primitive pressure and velocity variables. A 2-D version is described in Reference 10, upon which the present work is based. An Eulerian finite-difference formulation is developed using pressure and velocity as the main dependent variables. In addition, the U and V velocity components are positioned between the nodes where pressure and tangential velocity variables are stored. At each time step, the time-marched expressions for U, V and W are substituted into the continuity equation for each cell, and the guess-and-correct iterative process on pressure and velocity corrections are performed until continuity is sufficiently well satisfied.

2.1 THE PROBLEM

A schematic and physical dimensions of the mathematical model used to simulate the processes is illustrated in figure 1. The cyclone chamber studied has a cylindrical shape with a constant cross-sectional area. Fluid, of uniform velocity, is admitted into the chamber through swirling vanes which regulate the relative strength of the tangential (\(W_{IN}\)) and radial (\(U_{IN}\)) velocity components. Inlets are located along the upper and lower periphery of the chamber's wall. The outlet is located centrally on the top plate and a special restriction is arranged to prevent flow escaping from the top inlet directly to the outlet port.

The theoretical model is designed to correctly simulate the flow with respect to its geometric configuration, physical properties
of the fluid and boundary conditions.

2.2 GOVERNING EQUATIONS

In order to arrive at a model amenable to mathematical treatment, some simplifications are necessary. The fluid is assumed to be incompressible with constant kinematic viscosity \( \nu \). The flow is also assumed to be axisymmetrical, therefore, all the dependent variables \( U, V, W \) and \( P \) become only functions of \( x, y \) and \( t \). Commencing with the 3-D equation of fluid motion, and taking into consideration the axisymmetry of the problem, the governing equations are then given as:

Continuity,

\[
\frac{\partial U}{\partial x} + \frac{U}{x} + \frac{\partial V}{\partial y} = 0
\]  

(2.2.1)

U-momentum

\[
\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - \frac{W}{x} = - \frac{\partial P}{\partial x} + \nu \left( \frac{\partial^2 U}{\partial x^2} + \frac{1}{x} \frac{\partial U}{\partial x} + \frac{\partial^2 U}{\partial y^2} - \frac{U}{x^2} \right) + g_x
\]  

(2.2.2)

V-momentum

\[
\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} = - \frac{\partial P}{\partial y} + \nu \left( \frac{\partial^2 V}{\partial x^2} + \frac{1}{x} \frac{\partial V}{\partial x} + \frac{\partial^2 V}{\partial y^2} \right) + g_y
\]  

(2.2.3)

W-momentum

\[
\frac{\partial W}{\partial t} + U \frac{\partial W}{\partial x} + \frac{UW}{x} + V \frac{\partial W}{\partial y} = \nu \left( \frac{\partial^2 W}{\partial x^2} + \frac{1}{x} \frac{\partial W}{\partial x} + \frac{\partial^2 W}{\partial y^2} - \frac{W}{x^2} \right) + g_\theta
\]  

(2.2.4)

The coordinate system used is shown in figure 2. To transform the above equation into a conservative form (i.e. the divergence of momentum flux), for the convective members the following procedure is applied.
The convective portion of the $U$-momentum equation is,

\[ U \frac{\partial U}{\partial x} + W \frac{\partial U}{\partial y} \]

(2.2.2a)

By rearranging, the above equation becomes

\[ U \frac{\partial U}{\partial x} + U \frac{\partial U}{\partial x} - U \frac{\partial U}{\partial x} + \nabla \frac{\partial U}{\partial y} + \frac{\partial W}{\partial y} - U \frac{\partial V}{\partial y} - \frac{W^2}{x} \]

or

\[ \frac{\partial (U^2)}{\partial x} + \frac{\partial (UV)}{\partial y} - \frac{W^2}{x} \]

which can be reduced to,

\[ \frac{\partial (U^2)}{\partial x} + \frac{\partial (UV)}{\partial y} - U \left( \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} \right) - \frac{W^2}{x} \]  

(2.2.2b)

Substituting continuity equation of (2.2.1) into expression (2.2.2b), one obtains,

\[ \frac{\partial (U^2)}{\partial x} + \frac{\partial (UV)}{\partial y} + \frac{U^2 - W^2}{x} \]

and the $U$-momentum equation can be expressed as,

\[ \frac{\partial U}{\partial t} + \frac{\partial^2 (U^2)}{\partial x^2} + \frac{\partial (UV)}{\partial y} + \frac{(U^2 - W^2)}{x} = - \frac{\partial P}{\partial x} \]

\[ + \nabla \left( \frac{\partial^2 U}{\partial x^2} + \frac{1}{x} \frac{\partial U}{\partial x} + \frac{\partial^2 U}{\partial y^2} - \frac{U}{x^2} \right) + g_x \]

(2.2.5)

If the same technique is applied to the other $V$ and $W$ momentum equations, their conservative form may be written as\textsuperscript{15,16}.

**$V$ - momentum**

\[ \frac{\partial V}{\partial t} + \frac{\partial^2 (V^2)}{\partial x^2} + \frac{\partial (UV)}{\partial y} + \frac{V}{x} = - \frac{\partial P}{\partial y} + \nabla \left( \frac{\partial^2 V}{\partial x^2} + \frac{1}{x} \frac{\partial V}{\partial x} + \frac{\partial^2 V}{\partial y^2} \right) + g_y \]

(2.2.6)

**$W$ - momentum**

\[ \frac{\partial W}{\partial t} + \frac{\partial (WU)}{\partial x} + \frac{\partial (WV)}{\partial y} + 2 \frac{WU}{x} = \nabla \left( \frac{\partial^2 W}{\partial x^2} + \frac{1}{x} \frac{\partial W}{\partial x} + \frac{\partial^2 W}{\partial y^2} - \frac{W}{x^2} \right) + g_\theta \]

(2.2.7)
2.3 THE FLOW REGION AND GRID SYSTEM

Figure 3 shows how the flow region on a meridional plane is divided into rectangular cells. This flow region is surrounded by a layer of fictitious cells on all sides to incorporate the boundary conditions (BCs).

A cell is magnified in figure 4, which shows the location of each variable, \( P, U, V \) and \( W \). The pressure and tangential velocity are located at the center of the cell, and the radial and axial velocities positioned on the right (vertical) and top (horizontal) sides, respectively. Thus normal velocities (to the wall) lie directly on the physical boundaries of the domain, which is defined as the region enclosed by the boundaries, while the tangential velocities and pressures are placed at half cell intervals. This arrangement greatly simplifies the application of boundary conditions.
CHAPTER 3
SOLUTION PROCEDURE

3.1 THE FINITE DIFFERENCE EQUATIONS

Mathematically, the governing equations are parabolic (in time) and a marching solution procedure is adapted.

Starting from initial field values throughout the domain, a time-march process is used to advance the flow-field towards the final steady-state. The numerical method employed uses Forward-Time, Centered-Space (FTCS) difference scheme. The usual one-sided, first time derivatives and centered, second space derivatives are used in representing these equations. However, special techniques in computational fluid dynamics in the representation of the convective terms are required. A certain amount of upstream differencing is given to these terms (the donor cell approach) to remove the unconditional instability of the resulting algorithm in case that a very small viscosity is used.

The following are the difference equations representing the conservation of momentum in \( x \), \( y \) and \( \theta \) directions:

\[
U_{i,j}^{n+1} = U_{i,j}^n + \Delta t \left\{ \frac{1}{\Delta x} \left( P_{i,j}^n - P_{i+1,j}^n \right) + g_x - FUX \right\} \\
- \left( FUY - FUC + VISX \right) \\
V_{i,j} = V_{i,j}^n + \Delta t \left\{ \frac{1}{\Delta y} \left( P_{i,j}^n - P_{i,j+1}^n \right) + g_y - FVX - FVY \right\} \\
- \left( FVC + VISY \right) \\
W_{i,j} = W_{i,j}^n - \Delta t \left\{ FWX + FWY + FWC - VISZ \right\} \tag{3.1.1}
\]
where, \( F_{UX}, F_{UY}, F_{UC}, F_{VX}, F_{VY}, F_{VC}, F_{WX}, F_{WY} \) and \( F_{WC} \) are the convective fluxes while \( V_{ISX}, V_{ISY} \) and \( V_{ISZ} \) are the viscous fluxes (see Appendix A). Superscripts \( n \) and \( (\text{blank}) \) are used to denote values of time-level \( t \) and \( t + \Delta t \), respectively.

If the convective terms of these equations are to be evaluated with the central difference approximation and the viscosity is very small, instability will result. In order to alleviate this without resorting to a less accurate algorithm, the upstream differencing scheme must be applied. That is, if \( \phi \) is a general property and if the donor cell approach is used, see figure 5, then the following conditions must be satisfied:

\[
\begin{cases}
\frac{3\phi}{3x}|_{x_0} - \frac{\alpha\Delta x}{4} \frac{3^2\phi}{3x^2}|_{x_0} - o(\Delta x^2) \text{ if } \phi_i,j > \frac{\phi_{i+1,j} + \phi_{i-1,j}}{2} \\
\frac{3\phi}{3x}|_{x_0} + \frac{\alpha\Delta x}{4} \frac{3^2\phi}{3x^2}|_{x_0} - o(\Delta x^2) \text{ if } \phi_i,j < \frac{\phi_{i+1,j} + \phi_{i-1,j}}{2}
\end{cases}
\]

(3.1:2)

The coefficient \( \alpha \) is a constant taking a value between zero and one, and so giving the desired amount of upstream differencing in the convection terms. A value of zero gives merely central differencing code which is second-order accurate in \( \Delta x \), however numerical instability problems arise. A value of one gives full upstream differencing which, though introducing errors, is stable, provided the other stability criteria are satisfied.
Therefore,

\[ FUX = \frac{\partial U^2}{\partial x} \bigg|_{x_0} - \frac{\alpha \Delta x}{4} + \frac{\partial^2 U^2}{\partial x^2} \bigg|_{x_0} + o(\Delta x^2) \]

or,

\[ FUX = \frac{(U_{i+1,j} + U_{i,j})^2 - (U_{i-1,j} + U_{i,j})^2}{4\Delta x} \]

\[ - \frac{\alpha \Delta x}{4} \left( \frac{U_{i-1,j}^2 - 2U_{i,j}^2 + U_{i+1,j}^2}{\Delta x^2} \right) + o(\Delta x^2) \]

\[ = \frac{1}{4\Delta x} \left[ (U_{i+1,j} + U_{i,j})^2 - (U_{i-1,j} + U_{i,j})^2 \right. \]

\[ - \alpha \left\{ (U_{i-1,j} + U_{i,j})(U_{i-1,j} - U_{i,j}) - (U_{i,j} + U_{i+1,j})(U_{i,j} - U_{i+1,j}) \right\} \]

\[ + o(\Delta x^2) \]  \( (3.1.3) \)

To assure that,

\[ FUX = \begin{cases} 
\left| FUX \right|_{x_0 - \frac{\alpha \Delta x}{4}} & \text{if} \quad U_{i,j} \geq \frac{U_{i+1,j} + U_{i-1,j}}{2} \\
\left| FUX \right|_{x_0 + \frac{\alpha \Delta x}{4}} & \text{if} \quad U_{i,j} < \frac{U_{i+1,j} + U_{i-1,j}}{2} 
\end{cases} \]

Equation \((3.1.3)\) becomes:

\[ FUX = \frac{1}{4\Delta x} \left[ (U_{i+1,j} + U_{i,j})^2 + \alpha \left| U_{i,j} + U_{i+1,j} \right| (U_{i,j} - U_{i+1,j}) \right. \]

\[ - (U_{i-1,j} + U_{i,j})^2 - \alpha \left| U_{i-1,j} + U_{i,j} \right| (U_{i-1,j} - U_{i,j}) \]

\[ + o(\Delta x^2) \]  \( (3.1.4) \)
Following the same reasoning and to assure that:

\[
FUY = \begin{cases} 
  y_0 - \frac{\alpha u y}{4} & \text{if } U_{1,j} \geq \frac{U_{i+1,j} + U_{i-1,j}}{2} \\
  y_0 + \frac{\alpha u y}{4} & \text{if } U_{1,j} < \frac{U_{i+1,j} + U_{i-1,j}}{2}
\end{cases}
\]

then,

\[
FUY = \frac{1}{4\Delta y} \left[ (V_{i,j} + V_{i+1,j})(U_{i,j} + U_{i,j+1}) + \alpha | V_{i,j} + \\
V_{i+1,j} | (U_{i,j} - U_{i,j+1}) - (V_{i,j-1} + V_{i+1,j-1}) \\
(U_{i,j-1} + U_{i,j}) - \alpha | V_{i,j-1} + V_{i+1,j-1} | (U_{i,j-1} - U_{i,j}) \right] + o(\Delta y^2)
\]

(3.1.5)

The same technique is applied in order to approximate the rest of the convective terms of the equation (3.1.1) and they are defined in Appendix A.

3.2 PRESSURE CORRECTION EQUATIONS

Although equation (3.1.1) enables one forward time-step to be accomplished, the newly calculated velocities will not, in general, satisfy the continuity requirement, as expressed in central finite-difference form

\[
\frac{1}{\Delta x} (U_{i,j} - U_{i-1,j}) + \frac{1}{\Delta y} (V_{i,j} - V_{i,j-1}) + \\
\frac{1}{2\Delta x(1.5)} (U_{i,j} + U_{i-1,j}) = 0
\]

(3.2.1)

Terms here are evaluated at time-level \( t + \Delta t \).

This incompressibility constraint is imposed by iteratively adjusting the cell pressure. That is, if the divergence, \( \text{Div} \), of a cell
is positive (the left side of equation (3.2.1) is positive), there is a net mass-flow from that cell. This is corrected by reducing the cell pressure. On the other hand, if the divergence is negative, an increase in cell pressure is necessary.

When the cell pressure changes from \( P \) to \( P + \Delta P \) the velocity components on the four faces of the cell change. The amount changed is expressed as,

\[
U_{i,j} = U_{i,j} \text{ (OLD)} + \frac{\Delta t \Delta P}{\Delta x}
\]

\[
U_{i-1,j} = U_{i-1,j} \text{ (OLD)} - \frac{\Delta t \Delta P}{\Delta x}
\]

\[
V_{i,j} = V_{i,j} \text{ (OLD)} + \frac{\Delta t \Delta P}{\Delta y}
\]

\[
V_{i,j-1} = V_{i,j-1} \text{ (OLD)} - \frac{\Delta t \Delta P}{\Delta y}
\]

Where (OLD) means previous level of iteration. Substituting equation (3.2.2) into equation (3.2.1) one obtains,

\[
\frac{1}{\Delta x} \left( U_{i,j} \text{ (OLD)} - U_{i-1,j} \text{ (OLD)} \right) + \frac{1}{\Delta y} \left( V_{i,j} \text{ (OLD)} - V_{i,j-1} \text{ (OLD)} \right) + \frac{1}{2 \Delta x (1-1.5)^{-0.5}} \left( U_{i,j} \text{ (OLD)} + U_{i-1,j} \text{ (OLD)} \right) = - 2 \left( \frac{\Delta t \Delta P}{\Delta x^2} + \frac{\Delta t \Delta P}{\Delta y^2} \right)
\]

Since the left side equals the divergence of the previous iteration level (OLD), equation (3.2.3) becomes,

\[
\text{Div (OLD)} = - 2 \left( \frac{\Delta t \Delta P}{\Delta x^2} + \frac{\Delta t \Delta P}{\Delta y^2} \right)
\]

Then the amount of correction to the pressure is:

\[
\Delta P = - \text{Div (OLD) / (2\Delta t (1/\Delta x^2 + 1/\Delta y^2))}
\]

(3.3.4)
Pressure update iteration continues until the divergence of all the cells are less than some prescribed small positive quantity \( \epsilon \). An over-relaxation factor \( \omega \) near 1.8 often is applied to equation (3.2.4)

\[
\Delta p = - \omega \text{Div} (\text{OLD}) / (2\Delta t (1/\Delta x^2 + 1/\Delta y^2))
\]

in order to speed up the convergence of the pressure-iteration process.

3.3. BOUNDARY CONDITIONS

In the previous sections the finite difference equations (FDE's) approximating the governing partial differential equations (PDE's), are set up and solved by way of a time-march process applied to cells within the flow domain of interest. A single layer of fictitious cells are placed around the flow region thus utilizing the value on the boundary.

Rigid wall boundaries are defined in such a way as to coincide with cell boundaries. For interior normal velocity calculations, zero normal values on the rigid wall are assumed. Interior tangential (to the wall) velocity calculations use the fictitious values which are placed in the surrounding layer of complementary computational cells. Specification of these is after each time-step and after each sweep of the cells during the pressure correction iteration. The tangential velocity component has a vanishing gradient across a no-slip boundary, and this is achieved by setting the external values of the velocity equal to the negative of their immediate associated interior values, see figure 6. The free-slip boundary is met by setting the external tangential velocity value equal to their immediate associated interior values, as shown in figure 7.

Some care has to be taken in the selection of either no-slip or free-slip boundary conditions to assure a realistic picture of the flow-
field. For an actual fluid, no-slip condition implies the development of a boundary layer. The velocity increases from zero value at the rigid wall to the free stream value some distance from it. The boundary layer thickness may be large or small in comparison to the cell's dimension. As it can be seen from figure 8, a small value of boundary layer thickness $\delta$ relative to the cell's dimension, gives a bad approximation to the velocity profile and imposes an artificially large drag on the field. An estimation of the magnitude of the boundary layer thickness can be made utilizing the elementary boundary layer theory. According to simple theory on laminar flow, the boundary layer thickness is expressed as

$$\delta \sim \frac{L}{\sqrt{R_L}}$$

where:

$L = \text{length of the chamber}$

$R_L = \frac{L \bar{V}}{\nu}$

$\bar{V} = \text{average axial velocity within the chamber}$

If the displacement thickness $\delta^*$ is expressed as

$$\delta^* = \frac{3}{4} \delta$$

and if,

$$\delta^* < \frac{1}{4} \Delta y \text{ then the boundary layer is considered to be "thin".}$$

if,

$$\delta^* \geq \frac{1}{4} \Delta y \text{ then the boundary layer is "thick".}$$

Therefore, for a coarse grid, free-slip boundary conditions are appropriate for the tangential velocities. On the other hand, with a fine grid over the flow-field, or with a fine grid in the wall's neighborhood, no-slip boundary conditions are needed.
Specifications of normal velocities at an outflow boundary often pose a problem, as it can have a detrimental upstream influence. One might merely impose the normal gradient of continuative condition and set these values to their immediate upstream values as shown in figure 9. When primary interest is being focused on the final steady-state, a constant value may be added to each such extrapolated value. This will result in a more rapid convergence. This constant value is chosen so as to make the total outlet flux equal to the total inlet flux, thus satisfying the condition of continuity. Outlet boundary specification is imposed, only each time-step as computed via equation (3.2.1) and not after each pass through the mesh during the pressure iteration.

On the axis of symmetry, the usual zero normal velocity and free-slip axial velocity specifications are applicable; the swirl velocity is given a definite zero value via no-slip condition as shown in Fig. 10.

Inlet boundary conditions are satisfied by imposing a zero gradient on the radial and swirl velocity components, while the axial velocity components are forced to zero on the fictitious exterior cells as shown in figure 11.

3.4 STABILITY CONSIDERATIONS

Attempts to solve PDE's numerically using a finite difference method are not always successful. The reason is that the solution to the PDE's may be dominated from a monotonic or oscillatory error growth which will in no way resemble the solution expected from the original PDE's. To avoid this difficulty, stability considerations and appropriate restrictions have to be applied on the algorithm. Since a non-linear theoretical stability treatment is essentially non-existent for the present problem, the following simple heuristic method along with numerical experimentation was found to give very reasonable stability criteria.
The derived FDE’s link only those cells which have common boundaries. A fluid particle that propagates more than one cell for each time step cannot be monitored by the FDE’s. The algorithms, thereby, fail to be stable. To assure stability, the fluid particle must not be allowed to cross more than one cell for each time step. The worst cases that can exist in a flow-field are in those regions where the velocities assume their maximum values. Thus the following two inequalities must be satisfied,

\[ \Delta x > |U_{\text{MAX}} \Delta t| \quad \text{and} \quad \Delta y > |V_{\text{MAX}} \Delta t| \]

Solving, for \( \Delta t \), both inequalities,

\[ \Delta t \leq \frac{\Delta x}{|U_{\text{MAX}}|} \quad \text{and} \quad \Delta t \leq \frac{\Delta y}{|V_{\text{MAX}}|} \]

or,

\[ \Delta t \leq \min \left\{ \frac{\Delta x}{|U_{\text{MAX}}|} , \frac{\Delta y}{|V_{\text{MAX}}|} \right\} \quad (3.4.1) \]

Assume that the PDE for the general property \( \phi \) has the form:

\[ \frac{\partial \phi}{\partial t} + U \frac{\partial \phi}{\partial x} + V \frac{\partial \phi}{\partial y} = - \frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} \right) \quad (3.4.2) \]

Assume further that \( U \) and \( V \) are constants, then the FDE becomes,

\[ \frac{\phi_{i,j} - \phi_{i,j}^n}{\Delta t} = - U \frac{\phi_{i+1,j}^n - \phi_{i-1,j}^n}{2\Delta x} - V \frac{\phi_{i,j+1}^n - \phi_{i,j-1}^n}{2\Delta y} \]

\[ + \frac{\phi_{i+1,j}^n - 2\phi_{i,j}^n + \phi_{i-1,j}^n}{\Delta x^2} + \frac{\phi_{i,j+1}^n - 2\phi_{i,j}^n + \phi_{i,j-1}^n}{\Delta y^2} \]
or,
\[
\phi_{i,j}^{n+1} = \Delta t v \left( \frac{\phi_{i-1,j}^n + \phi_{i+1,j}^n}{\Delta x} + \frac{\phi_{i,j-1}^n + \phi_{i,j+1}^n}{\Delta y} \right) (p_{i,j+1}^n - p_{i,j}^n) \Delta t
\]
\[-\frac{\Delta t u}{2\Delta x} \left( \phi_{i+1,j}^n - \phi_{i-1,j}^n \right) - \frac{\Delta t v}{2\Delta y} \left( \phi_{i,j+1}^n - \phi_{i,j-1}^n \right)
\]
\[+ \left[ 1 - 2\Delta t v \left( \frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} \right) \right] \phi_{i,j}^n
\]

For stability according to Reference 18,
\[1 - 2\Delta t v \left( \frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} \right) > 0\]
therefore,
\[\nu \Delta t < \frac{1}{2} \left( \frac{\Delta x^2 \Delta y^2}{\Delta x^2 + \Delta y^2} \right) \quad (3.4.3)\]

Consider the equation
\[
\frac{\partial \phi}{\partial t} + U \frac{\partial \phi}{\partial x} = \nu \frac{\partial^2 \phi}{\partial x^2} \quad (3.4.4)
\]
where U is constant.

Expansion in Taylor's series about the point \((i\Delta x, n\Delta t)\) gives the donor cell equation.
\[
\frac{\partial^2 \phi}{\partial t^2} + \frac{\Delta t}{2} \frac{\partial^2 \phi}{\partial t \partial x} + U \frac{\partial^2 \phi}{\partial x^2} = \nu \frac{\partial^2 \phi}{\partial x^2} + \frac{\alpha U |\Delta x|}{2} \frac{\partial^2 \phi}{\partial x^2} + o(\Delta x^2, \Delta t^2) \quad (3.4.5)
\]

Taking the time derivative of equation (3.4.4) we have,
\[
\frac{\partial^2 \phi}{\partial t^2} = -U \frac{\partial^2 \phi}{\partial t \partial x} + \nu \frac{\partial^3 \phi}{\partial t \partial x^2}
\]
\[= -U \frac{\partial \phi}{\partial x} \left( -U \frac{\partial \phi}{\partial x} + \nu \frac{\partial^2 \phi}{\partial x^2} \right) + \nu \frac{\partial^2 \phi}{\partial x^2} \left( -U \frac{\partial \phi}{\partial x} + \nu \frac{\partial^2 \phi}{\partial x^2} \right)
\]
Neglecting terms higher than three

\[ \frac{\partial^2 \phi}{\partial t^2} = u^2 \frac{\partial^2 \phi}{\partial x^2} \] (3.4.6)

Substituting equation (3.4.6) into equation (3.4.5) one obtains

\[ \frac{\partial \phi}{\partial t} + u \frac{\partial \phi}{\partial x} = \left( \nu + \frac{a |U| \Delta x}{2} - \frac{\Delta t U^2}{2} \right) \frac{\partial^2 \phi}{\partial x^2} + o (\Delta x^2, \Delta x \Delta t, \Delta t^2) \] (3.4.7)

If we let,

\[ \nu_e = \nu + \frac{a |U| \Delta x}{2} - \frac{\Delta t U^2}{2} \]

Then,

\[ \frac{\partial \phi}{\partial t} + u \frac{\partial \phi}{\partial x} = \nu_e \frac{\partial^2 \phi}{\partial x^2} \] (3.4.8)

where \( \nu_e \) is known as the "effective viscosity coefficient".

Since any diffusion coefficient "smears out" uniformly any disturbance in the general property \( \phi \), \( \nu_e \) means that the coefficient tends to concentrate any small perturbation from a uniform \( \phi \) distribution (this is physically impossible). Therefore, for stability,

\[ \nu_e + \frac{a |U| \Delta t}{2} - \frac{\Delta t U^2}{2} > 0 \]

For high \( R_e \), the viscosity coefficient is numerically equal to zero, then

\[ \frac{a |U| \Delta x}{2} - \frac{\Delta t U^2}{2} > 0 \]

\[ \alpha > \left| \frac{U \Delta t}{\Delta x} \right| \] (3.4.9)
Therefore, equation (3.4.9) must be satisfied in order to gain stability.

The algorithm is stable for any inlet swirl strength equal or less than one, if all the mentioned restrictions are followed. For inlet swirl strength greater than one, the algorithm fails to be stable, owing to the fact that the tangential velocity component dominates the radial momentum equation. After a great deal of numerical experimentation it was concluded that for convergence, if $S$ is greater than one, $\Delta t$ must satisfy the following additional inequality:

$$\Delta t < \min \left( \frac{\Delta x}{|W_{\text{MAX}}|}, \frac{\Delta y}{|W_{\text{MAX}}|} \right)$$  \hspace{1cm} (3.4.10)

where $W_{\text{MAX}}$ can be taken as approximately

$$W_{\text{MAX}} = S \cdot W_{\text{IN}}$$

Therefore, to assure stability of the algorithm, all the above mentioned restrictions have to be met. A summary of the stability and convergence criteria is given as follows:

Having chosen the grid size, the time increment must be restricted in three ways, and a suitable amount of upstream differencing must be effected.

(i) Since the FDE's assume fluxes only between neighbouring cells, the fluid particles can only move through one cell in one time step. Thus for stability, $\Delta t$ must be less than (typically equal to 0.25 to 0.33 times) the minimum cell transit time taken over all cells:

$$\Delta t < \min \left( \frac{\Delta x}{U}, \frac{\Delta y}{V} \right)$$
(ii) When the kinematic viscosity is non-zero, momentum must not diffuse more than approximately one cell in one time step for which a linear analysis shows

\[ \Delta t < \frac{1}{2v} \left( \frac{\Delta x^2 \Delta y^2}{\Delta x^2 \Delta y^2} \right) \]

(iii) When \( S \) is greater than one, \( \Delta t \) must be

\[ \Delta t < \min \left( \frac{\Delta x}{W_{\text{MAX}}} , \frac{\Delta y}{W_{\text{MAX}}} \right) \]

where \( W_{\text{MAX}} = S \times W_{\text{IN}} \)

(iv) When the time step is so restricted, the required amount of upstream (donor cell) differencing must be achieved by choosing a value slightly greater than (typically 1.2 to 1.5 times) the larger of the right hand side members of

\[ 1 > \alpha > \max \left( \left| \frac{V a t}{\Delta x} \right| , \left| \frac{V a t}{\Delta y} \right| \right) \]

where the maximum is taken over all cells. If \( \alpha \) is chosen to be too large, stability is being achieved at the introduction of an unnecessarily large amount of diffusion, like truncation errors known as numerical smoothing.

3.5 COMPUTATIONAL PROCEDURE

The finite difference equations along with the boundary and initial conditions constitute the necessary elements in synthesizing an algorithm which gives solutions to the given problems. The computational procedure consists of the following steps:
(i) Set initial conditions, read necessary constants.
(ii) Update the velocity.
(iii) Set boundary conditions.
(iv) Correct the pressure of the velocity in order to satisfy cell continuity.
(v) March time one time-step and return to step (ii).

Repeat the process until steady state is achieved.

The pressure iteration procedure continues until the divergences of all the cells are less than $\varepsilon$. All the required listings for the computation program are given in Appendix B.
CHAPTER 4

RESULTS AND DISCUSSIONS

Two kinds of computations dealing with single- and multi-stable cyclone chambers are described. For both configurations, a computational mesh of 10 x 10 in the x- and y- directions was overlaid on the plane of interest, with a cell size of 0.0079 [0.026] and 0.0320 [0.105] m [ft.], respectively. The flow fields were marched through the required time steps to assure steady-state conditions. The computations were performed utilizing a CDC Cyber 174 computer.

4.1 SINGLE-SET INLET CYCLONE FLOW

Predictions were first made for a cyclone chamber with a single set of inlets located near the base. An inlet height 0.032 m [0.105 ft.] giving a mean inlet flow-rate of 6.748 x 10^{-5} m^3/sec [0.143 cfm], and an average outlet velocity of 1.280 m/sec [4.20 ft./sec] was used for most of the predictions. The chamber has an aspect ratio (L/D) equal to 2. Profiles of the velocity components were graphed for the radial stations Z_1, Z_2, Z_3, and Z_4, as shown in figure 12.

First, the effects of the inlet swirl strength were investigated. For the inlet, a flow-rate was kept constant at 6.748 x 10^{-5} m^3/sec [0.143 cfm]. Three different inlet swirl strengths (S), weak (S=0.1), medium (S=0.5) and strong (S=1.0) were applied. The tangential velocity profiles for the radial station Z_3 were shown for these three different swirl strengths.

The tangential velocity component, figure 13, resembles the Rankine profile with the forced portion of the vortex occurring in the proximity of the central axis. The fluid enhances its tangential

\[
* \frac{Z_n}{L} = \frac{Z_n}{L}
\]

Z_n = 0.187, 0.1437, 0.687 and 0.937 where n = 1, 2, 3 and 4.
velocity component while moving towards the center, and thus conserves it's angular momentum. Due to the viscosity present in the fluid, the tangential velocity does not evidently increase to infinity, as in the case of the ideal inviscid fluid flow. Instead, the velocity attains the maximum value in the neighborhood of the center axis, and then decays to zero through a forced vortex profile. The existence of viscosity also causes the velocity to undergo a smooth vortex mode transformation, and thus manifests a dual behavior. For large inlet swirl strength, a considerable velocity increase is observed especially close to the axis of symmetry, and an abrupt vortex transition is taking place. The variation of the tangential velocity is more moderate for a weak swirl strength, and a distinct mixed vortex region is evident.

The effects of the inlet flow-rate were also tested. Inlet velocities of 0.3048 m/sec [1.0 ft/sec], 0.6096 m/sec [2.0 ft/sec], and 0.9144 m/sec [3.0 ft/sec] giving flow rates of 6.466 x 10^{-5} m³/sec [9.137 cfm], respectively were applied keeping the rest of the parameters constant*.

The tangential and axial velocities were graphed for the radial station Z₃.

*Note that in order to keep the inlet Swirl Strength \( S = \frac{W_{IN}}{U_{IN}} \) constant, an increase of the inlet tangential velocity must be applied.
The tangential velocities in figure 14 show that the velocity increases proportionally with the inlet flow-rate. A sharp vortex mode transformation is taking place for high flow-rate, and a smoother profile is exhibited by the velocity for low inlet ones. The maximum velocity increases proportionally to the inlet flow-rate, and it is taking place always within the inner core of the vortex. In the outer flow region of the vortex, most of the momentum is in the x and \( \theta \) directions since the presence of the top plate restricts the development of the velocity in the axial direction, as indicated in figure 15. As the fluid moves towards the axis of symmetry, it begins to sense the downstream large axial pressure gradient due to the opening in the top plate. Therefore, the momentum from the x and \( \theta \) directions starts to flow in the axial direction, which is manifested with an increase in the \( v \)-velocity component in that region.

Three constant viscosity values were used:

\[
1.858 \times 10^{-5} [2.0 \times 10^{-4}], \quad 1.858 \times 10^{-4} [2.0 \times 10^{-3}] \quad \text{and} \quad 1.858 \times 10^{-3} [2.0 \times 10^{-2}] \text{m}^2/\text{sec} [\text{ft}^2/\text{sec}] \in \text{an attempt to study the viscosity effect.}
\]

Figure 16 shows that as the viscosity increases, the free vortex flow is shifted towards the region close to the wall with the limiting case for the viscosity being infinity, where there is no free vortex region. In other words, when \( \nu \to \infty \), the fluid is rotating as a solid body. As fluid "thins out", the forced vortex region is shifted towards the center of the symmetry with the limiting case of the fluid of no viscosity in which there is no force vortex region. For low viscosity, the axial velocity has a maximum near the axis of the chamber and then decays towards the cylindrical wall.
Figure 17 shows the effect of viscosity on axial velocities revealing that, when the position of the axial velocity is shifting towards the wall, there is an increase in viscosity. Large viscosities diffuse any sharp change of the property, thus giving a more uniform axial velocity profile across the chamber's diameter as compared with the case of lower viscosity.

The tangential, radial and axial velocity components are presented for several radial stations, and for the same cyclone chamber arrangement, to display a picture of the aerodynamic pattern produced.

The tangential velocity at station \( Z_1 \), as shown in figure 18, exhibits similar characteristics as those previously discussed. Velocity profiles for the radial stations \( Z_2 \) and \( Z_3 \) are not presented, since their shape and magnitude are almost identical to that of station \( Z_1 \). At \( Z_4 \), which is close to the central exit, the tangential velocity profile shown in figure 19 appeared to start with a defined value near the cylindrical wall and increased in magnitude as the flow moved towards the central axis following the law of angular momentum. At a distance, \( R/x = 0.675 \) where the exit starts, the tangential velocity adjusts itself to the outlet protruding wall and eventually reaches the no-slip condition at the "throats". Once the flow reaches inside the exit port, the velocity again increases from zero to a maximum value resembling that of the free vortex configuration, and then decays to zero in order to satisfy the zero tangential velocity condition at the axis of symmetry.

Careful study of axial velocity profile at various stations as shown in figure 20, figure 21, figure 22 and figure 23 indicates that as the fluid moves from the bottom plate to the central exit port, there is
a gradual shift of magnitude of axial velocity towards the center of the inner core region. The radial velocity generally exhibits a much smaller magnitude in comparison to the tangential and axial velocities except in Station $Z_1$ near the base plate as in figure 24. As fluid moves towards the central exit, magnitude of the radial velocity as shown in figure 25 becomes negligibly small.

4.2 MULTI-SET INLET CYCLONIC FLOW

The second configuration deals with the same system as previously discussed, except that inlets of one cell are now arranged near the top and the bottom plate, see figure 26.

Figure 27 shows a computer vector graph of $U$ and $V$ velocity components for such configurations. Inlet velocities of $U_{IN}$ near the top and $2U_{IN}$ near the bottom plate are applied. The outlet wall protruding inwards causes the fluid to move first downwards, and after joining the fluid coming from the bottom inlet port it is directed to the outlet.

Figure 28 depicts the tangential velocity for two stations, $Z_3$ and $Z_4$, for the same chamber as well as conditions.

Figure 29 shows a computer vector graph of $U$ and $V$ velocity components for the above geometric arrangement, but with applied inlet velocities of $2U_{IN}$ and $U_{IN}$ near the top and bottom plate respectively. The fluid coming to the chamber from the top inlet joins the rest of the fluid further down towards the bottom plate in a manner similar to that of the previous arrangement. For this inlet condition a lower magnitude of the tangential velocity is observed across the length of the chamber (Figure 30).
Focusing attention on the tangential velocity profile of station $Z_3$ near the exit, figure 31 shows the influence of the degree of inlet swirl strength on the tangential velocity development.
CHAPTER 5
CONCLUSIONS

A prediction procedure for axisymmetric swirling flows in cyclone chambers has been developed. Based on the Los Alamos 2-D SOLA ideas, the transient Navier-Stokes equations of an incompressible fluid are solved via their associated finite-difference equations directly in terms of the primitive pressure-velocity variables. The technique is kept simple in order to facilitate its usage by persons with less experience in computational fluid dynamics, and boundary conditions are simple to specify. Thus, the code represents a basic tool, to which user oriented sophistications can easily be added if necessary. Computations show the flow prediction within single- and multi-set of inlets cyclone chamber, indicating that an initial attempt to solve a highly complex vortex flow problem has been successful.
REFERENCES


Figure 1: Cyclone Chamber Schematic and Physical Dimensions
Figure 2: Coordinate System

Figure 3: General Mesh Arrangement
Figure 4: Arrangement of Finite Difference Variables in a Typical Cell.

Figure 5: Typical Marker and Cell Mesh Structure
Figure 6: Rigid, No-Slip Boundary Conditions.
Figure 7: Rigid, Free-Slip Boundary Conditions.
Figure 8: Numerical And Actual Velocity Distribution for Flows With Large Reynold's Numbers.
Figure 10: Boundary Condition On The Axis of Symmetry
Figure 11: Inlet Boundary Conditions
Figure 12: Schematic of a Single-Set of Inlets Cyclone Chamber and Arrangement of the Radial Stations.
Figure 13: Tangential Velocity Profiles at Radial Station Z,
for Different Inlet-Swirl Strengths.

*W*IN = 0.317 m/s (1.04 ft/s)
Figure 14: Tangential Velocity Profiles at Radial Station Zs for Different Inlet Flowrates
Figure 15: Axial Velocity Profiles at Radial Station $Z_1$ for Different Inlet Flowrates.
Figure 16: Tangential Velocity Profiles at Radial Station Z
for Different Constant Viscosities.
Figure 17: Axial Velocity Profiles at Radial Station $Z_s$ for Different Constant Viscosities.
Figure 18: Tangential velocity Distribution for the Radial Station \( Z_1 \).
Figure 19: Tangential Velocity Distribution for Z₄.
Figure 20: Axial Velocity profile for $Z_1$. 
Figure 21: Axial velocity Distribution for Z2.
Figure 22: Axial Velocity Profile for Z₃.
Figure 23: Axial velocity Profile for Z₄.
Figure 24: Radial Velocity Distribution for $Z_1$. 
Figure 25: Radial Velocity Profile for $Z_2$. 
Figure 26: Schematic of two Sets of Inlets (Near the Top and Base Plates)
Cyclone Chamber and Arrangements of the Radial Stations.
Figure 27: Computer Vector Graph for U and V Velocity Components with $S = 0.5$. 
Figure 28: Tangential Velocity Profiles with $S = 0.5$ and Inlet

Velocities of $U_{IN}$ and $2U_{IN}$ on Top and Bottom Respectively.
Figure 29: Computer Vector Graph for U and V Velocity Components with $S = 0.5$. 
Figure 30: Tangential Velocity Profiles with $s = 0.5$ and Inlet Velocities of $Z \cdot U_{IN}$ and $U_{IN}$ on the Top and Bottom Respectively.
Figure 31: Tangential Velocity Distribution for the Radial Station $Z_3$ for the Inlet Swirl Strengths of 0.5 and 1.0.
APPENDIX A
The 4 terms on the right of each of the equations (3.7.1) are defined by:

**U - equation**

\[
FUX = \frac{1}{4\Delta x} \left[ (U_{1,j} + U_{1+1,j})^2 + \alpha |U_{1,j} + U_{1+1,j}| (U_{1,j} - U_{1+1,j}) \\
- (U_{1-1,j} + U_{1,j})^2 - \alpha |U_{1-1,j} + U_{1,j}| (U_{1-1,j} - U_{1,j}) \right]
\]

\[
FUY = \frac{1}{4\Delta y} \left[ (V_{1,j} + V_{1+1,j}) (U_{1,j} + U_{1,j+1}) + \alpha |V_{1,j} + V_{1+1,j}|
(U_{1,j} + U_{1,j+1}) - (V_{1,j+1} + V_{1+1,j+1}) (U_{1,j+1} + U_{1,j}) \\
- \alpha |V_{1,j} + V_{1,j+1}| (U_{1,j} + U_{1,j+1}) \right]
\]

\[
FUC = \frac{1}{8\Delta x(1-1)} \left[ (U_{1,j} + U_{1+1,j})^2 + (U_{1-1,j} + U_{1,j})^2 \\
+ \alpha |U_{1,j} + U_{1+1,j}| (U_{1,j} - U_{1+1,j}) \\
+ \alpha |U_{1-1,j} + U_{1,j}| (U_{1-1,j} + U_{1,j}) \right] - \frac{1}{4\Delta x(1-1)}
\]

\[
W_{1,j} = \left(\frac{1}{\Delta x^2} \right) (U_{1+1,j} - 2U_{1,j} + U_{1-1,j}) + \frac{1}{\Delta y^2} (U_{1,j+1} - 2U_{1,j} + U_{1,j-1}) \\
+ \frac{1}{2\Delta x^2(1-1)} (U_{1+1,j} - 2U_{1,j} + U_{1-1,j}) - \frac{U_{1,j+1}}{\Delta x^2(1-1)^2}
\]
\[ \begin{align*}
V - \text{equation} \\
F VX &= \frac{1}{4\Delta x} \left[ (U_{1,j} + U_{1,j+1}) (V_{1,j} + V_{1+1,j}) \\
&+ \alpha |U_{1,j} + U_{1,j+1}| (V_{1,j} - V_{1+1,j}) - (U_{1-1,j} + U_{1-1,j+1}) \\
&\quad (V_{1-1,j} + V_{1,j}) - \alpha |U_{1-1,j} + U_{1-1,j+1}| (V_{1-1,j} - V_{1,j}) \right] \\
F VY &= \frac{1}{4\Delta y} \left[ (V_{1,j} + V_{1,j+1})^2 + \alpha |V_{1,j} + V_{1,j+1}| \\
&\quad (V_{1,j} - V_{1,j+1}) - (V_{1,j-1} + V_{1,j})^2 - \alpha |V_{1,j-1} + V_{1,j}| \\
&\quad (V_{1,j-1} - V_{1,j}) \right] \\
F VC &= \frac{1}{8\Delta x(1-1.5)} \left[ (U_{1,j} + U_{1,j+1}) (V_{1,j} + V_{1+1,j}) \\
&+ (U_{1-1,j} + U_{1-1,j+1}) (V_{i-1,j} + V_{i,j}) + \alpha |U_{1,j} + U_{1,j+1}| \\
&\quad (V_{i-1,j} - V_{i+1,j}) + \alpha |U_{1-1,j} + U_{1-1,j+1}| (V_{i-1,j} - V_{i,j}) \right] \\
V SY &= \nu \left[ \frac{1}{\Delta x^2} (V_{i+1,j} - 2V_{i,j} + V_{i-1,j}) + \frac{1}{\Delta y^2} (V_{i,j+1} - 2V_{i,j} + V_{i,j-1}) \\
&+ \frac{1}{2\Delta x^2(1-1.5)} (V_{i+1,j} - V_{i-1,j}) \right].
\end{align*} \]
$W$ - equation

\[
FWX = \frac{1}{2\Delta x} \left[ U_{i,j} (W_{i,j} + W_{i+1,j}) + \alpha |U_{i,j}| (W_{i,j} - W_{i+1,j})
- U_{i-1,j} (W_{i-1,j} + W_{i,j}) - \alpha \left|U_{i-1,j}\right| (W_{i-1,j} - W_{i,j}) \right]
\]

\[
FWY = \frac{1}{2\Delta y} \left[ V_{i,j} (W_{i,j} + W_{i,j+1}) + \alpha |V_{i,j}| (W_{i,j} - W_{i,j+1})
- V_{i,j-1} (W_{i,j-1} + W_{i,j}) - \alpha |V_{i,j-1}| (W_{i,j-1} - W_{i,j}) \right]
\]

\[
FWC = \frac{1}{2\Delta x (1-1.5)} \left[ U_{i,j} (W_{i,j} + W_{i+1,j}) + U_{i-1,j} (W_{i-1,j} + W_{i,j})
+ \alpha |U_{i,j}| (W_{i,j} - W_{i+1,j}) + \alpha |U_{i-1,j}| (W_{i-1,j} - W_{i,j}) \right]
\]

\[
VISZ = \nu \left[ \frac{1}{\Delta x^2} (W_{i+1,j} - 2W_{i,j} + W_{i-1,j}) + \frac{1}{\Delta y^2} (W_{i,j+1} - 2W_{i,j} + W_{i,j-1})
+ \frac{1}{2\Delta x (1-1.5)} (W_{i+1,j} - W_{i-1,j}) - \frac{W_{i,j}}{\Delta x^2 (1-1.5)^2} \right]
\]

Terms here are evaluated at time level $t$. 

PROGRAM CYCLONE COMPUTES THE ASSUMED 2-D AXISYMMETRIC SWIRLING FLOW WITHIN A CYCLONE CHAMBER.
THE DATA TO BE ENTERED IS,
  DELY IS THE MESH SIZE IN THE X-D
  DELY IS THE MESH SIZE IN THE Y-D
  IBAR NUMBER OF DIVISIONS IN THE X-D
  JBAR NUMBER OF DIVISIONS IN THE Y-D
  IOUT NUMBER OF COMPUTATIONAL CELLS FOR THE EXIT PORT
  ALPHA CONVERGENCE AND STABILITY PARAMETER TAKING A VALUE
  BETWEEN(0,1).
  DELT TIME INCREMENT
  MCYR NUMBER OF FORWARD IN TIME FRAMES THAT SHOULD BE TAKEN
  FOR STEADY STATE CONDITIONS
  LPR SELECTION PRINT INTERMEDIATE FLOWFIELODS VALUES
  UINITL INLET RADIAL VELOCITY
  WINITL INLET TANGENTIAL VELOCITY

INTEGER CYCLE,THRHS
REAL NU
DIMENSION U(15,15),V(15,15),W(15,15),P(15,15),UN(15,15),VN(15,15),
WNN(15,15)

C PARAMETER SETTING
DATA EPSI,6XVY,CYL,OMG
+/5.0E-3,0.0,0.0,1.0,1.7,
DZRO=1.0

C GEOMETRIC PARAMETERS
DELY=0.026
DELY=0.105
JBAR=8
IBAR=8
JINT=2
JINB=2
IOUT=5
PI=3.14159

C FLUID DYNAMIC PARAMETERS
NU=2.0E-4

C CONVERGENCE AND ACCURACY PARAMETERS
ALPHA=1.0
DELT=0.0014
MCYR=2000

C PRINTING INSTRUCTIONS
LPR=300
IWRITE=0

C BOUNDARY CONDITION INSTRUCTIONS
C INLET VELOCITIES
UINITL=-2.08
WINITL=1.04
SURA=WINITL/UINITL
PRINT 9001,UNITL,WINITL,JINT,JINB,SWRAI
9001 FORMAT(1X,* UNITL = *,E14.4/,*WINITL = *,E14.4/,* JINT = *,12
+,* JINB = *,12/,* SWRAI = *,E14.4/) END
LSTEP=LPR
HEIGT=JBAR*DELY

C

JINBM1=JINB-1
RLARGE=(IBAR)*DELY
AREA(N)=2*(IBAR)*DELY*(JINT-JINBM1)*DELY*PI
AREAOUT=((IOUT-1)*DELY)**2*PI
AREACH=((IBAR)*DELY)**2*PI
AREAAT=AREAIN/AREAOUT
VOUT=UNITL*AREAAT

C REYNOLDS NUMBER BASED ON CHAMBERS DIAMETER AND AVERAGE CH. VELOCITY.
VCHAMB=VOUT*AREAOUT/AREACH
RENUM=VCHAMB*RLARGE/NU
PRINT 91,RLARGE,NU,AREAIN,AREAOUT,AREACH,AREAAT,VOUT,VCHAMB,

1
RENUM
C

IMAX = IBAR+2
JMAX = JBAR+2
IM1 = IBAR+1
JM1 = JBAR+1
IM2 = IBAR
JM2 = JBAR
JTHR=(JMAX+1)-(JINT-JINB)
THRH=JMAX-JTHR
JTHRM1=JTHR-1
RDY=1./DELY
KBDY=1./DELY
DETA=MH/(2.*DELY*(RDY**2 + KBDY**2))

C INITIALIZATION

C

T = 0
ITEX=0
CYCLE=0

C GUESS INITIAL VELOCITIES
DO 560 I=1,IMAX
DO 560 J=1,JMAX
U(I,J) = 0.
V(I,J) = 0.
W(I,J) = 0.
560 CONTINUE

C

ASSIGN 5000 TO KRET
GO TO 2000
1000 CONTINUE
ITER=0
FLG=1.0
ASSIGN 3000 TO KRET
APPLY MUNENSA EQUATIONS FOR TIME

CALL TIMESP(DELX,DELY,DELT,P,CYL,ALPHA,OX,OY,NU,WU,WV,WN,
                +U,V,W,IM1,JM1,ROX,RDY).

2000 CONTINUE

---

GENERAL BOUNDARY CONDITIONS

DO 2200 J=1,JMAX

BOUNDARY CONDITIONS ON LEFT

U(1,J)=0.0
V(1,J)=V(2,J)
W(1,J)=W(2,J)

BOUNDARY CONDITIONS ON RIGHT

IF(J.LE.JINT.AND.J.GE.JINB) GO TO 2200
U(IM1,J)=0.0
V(IMAX,J)=V(IM1,J)
W(IMAX,J)=W(IM1,J)

2200 CONTINUE

DO 2500 I=1,IMAX

BOUNDARY CONDITIONS ON TOP

IF(I.LE.IDOUT) GO TO 2400
U(I,1)=0.0
V(I,JM1)=U(I,JM1)
W(I,JM1)=W(I,JM1)

2400 CONTINUE

BOUNDARY CONDITIONS ON BOTTOM

V(I,1)=0.0,
U(I,1)=U(I,2)
W(I,1)=W(I,2)

2500 CONTINUE

SPECIAL BOUNDARY CONDITIONS

EXIT THROAT WALL

V(IDOUT+1,JTHR1)=0.0
DO 2810 J=JTHR,JMAX
U(IDOUT+1,J)=0.0
W(IDOUT+1,J)=0.0
V(IDOUT+1,J)=0.0

2810 CONTINUE
OUTLET BOUNDARY CONDITIONS

COMPUTATION OF THE IN AND OUT FLUXES

FLUXIN=0,

DO 2811 J=JNB,JINT

V(IMAX,J)=0.

U(IMAX,J)=UNITIL

U(IM1,J)=UNITIL

W(IMAX,J)=WUNITL

FLUXIN=FLUXIN-2.*PI*IRAR*DELY*DELX*U(IM1,J)

2811 CONTINUE

FLUXOUT=3.14159*DELX**2*V(2,JM2)

DO 6113 I=3,IOUT

FLUXOUT=FLUXOUT+2.*3.14159*(FLOAT(I)-1.5)*DELX**2*V(I,JM2)

IF(ITER. EQ. 0) GO TO 2813

VINC=(FLUXIN-FLUXOUT)/AREAOUT

DO 2817 I=2,IOUT

V(I,JM1)=V(I,JM2)+VINC

V(I,JMAX)=V(I,JM1)

U(I,JMAX)=U(I,JM1)

2817 CONTINUE

2813 CONTINUE

PRESSURE ITERATION AND P, U, V

GO TO KRET (3000,5000)

3000 CONTINUE.

IF (FLG.EQ.0) GOTO 4000

ITER=ITER+1

STORIT=ITER

IF(ITCR.LT.900) GOTO 3050

IF(CYCLE.LT.20) GOTO 4000

TERMINATION CONDITION

T=1E+10

GOTO 5000.

3050

FLG=0.0

CHECK IF CONVERGENCE HAS BEEN REACHED

SUMD=0.0

DO 3500 J=2,JM1

DO 3500 I=2,IM1

D=RD*X*(U(I,J)-U(I-1,J)) + RY*(V(I,J)-V(I,J-1)) + CYL*(U(I,J)

1 + U(I-1,J))/2.*DELX**6*(FLOAT(I)-1.5))

IF(ABS(D/DZRO).GE.EPSI) FLG=1.0

DELP = -BETAX*F

P(I,J)=P(I,J)+DELP*P

U(I,J)=U(I,J)+DELT*RD*X*DELP

U(I-1,J)=U(I-1,J)-DELT*RD*X*DELP

V(I,J)=V(I,J)+DELT*RDY*DELP

V(I,J-1)=V(I,J-1)-DELT*RDY*DELP

SUMD=SUMD+ABS(D)

3500 CONTINUE

CHECKPRINTS DURING PRESSURE CYCLE
IWRITE=0
IF(ITER.LE.2) IWRITE=1
IF(CYCLE.GT.30.AND.CYCLE.LT.MCYR) IWRITE=0
IF(IWRITE.EQ.1) GO TO 5152

C RETURN FROM PRINTING SECTION
3501 CONTINUE
IWRITE=0
C
GO TO 2000
4000 CONTINUE.
5000 CONTINUE.
C
--- INTERMEDIATE PRINTING ---
IF(CYCLE.GE. MCYR-5) GO TO 5152
KATA=CYCLE/LSTEP
IF(KATA.EQ.1) LSTEP=LSTEP+1FR
IF(KATA.EQ.0) GO TO 5152
IF(CYCLE.GT.2) GO TO 5251
5152 CONTINUE.
CALL PRINT(ITER,T,CYCLE,UN,WEIGHT,JMAX,IMAX)
SUH=0.0
SUMV=0.0
SUMW=0.0
DO 6100 I=2,IM1
DO 6100 J=2,JM1
SUMU=SUMU+ABS(UN(I,J)-U(I,J))
SUMV=SUMV+ABS(VN(I,J)-V(I,J))
SUMW=SUMW+ABS(WN(I,J)-W(I,J))
6100 CONTINUE
PRINT 90
PRINT 91,UN,UN,WEIGHT,JMAX,IMAX
5251 CONTINUE
C RETURN TO PRESSURE ITERATION
C CYCLE IF THESE WERE ONLY
C CHECK PRINTS
IF(IWRITE.EQ.1) GO TO 3501
C
-------- REPACKAGING -------
DO 6101 I=1,IMAX
DO 6101 J=1,JM1
UN(I,J)=U(I,J)
VN(I,J)=V(I,J)
WN(I,J)=W(I,J)
6101 CONTINUE
C COMputation of IN and OUT Fluxes
FLUXIN=0.0
DO 6110 J=JINT,JINT
FLUXIN=FLUXIN-2.*PI*IBAR*DELY*DELY*U(IM1,J)
FLUXOUT=3.14159*DELY**2*V(JM1,J)
6110 DO 6111 I=3,IM1
FLUXOUT=FLUXOUT+2.*3.14159*(I-1.5)*DELY**2*V(I,JM1)
FLUXRAT=FLUXIN/FLUXOUT
PRINT 91,UN,WEIGHT,JMAX,IMAX
C
C ADVANCE TIME AND CYCLE
C
T=T+DELT
IF(T.GT.MCYR*DELT) GO TO 6500
CYCLE=CYCLE+1
GOTO 1000
6500 CONTINUE
900 CONTINUE

C VELCITY GRAPHS
CALL PLOT(U-V,I MAX,JMAX)

C
STOP
90 FORMAT(/A4,X,UMON,9X,VMON,7X,PRESS ITER,
14X,*SUMU*,10X,*SUMV*,10X,*SUMW*,10X,*SUMD*/)
91 FORMAT(8El4.4)
100 FORMAT(1X,8El1.4)
END

SUBROUTINE TIMESTEP(DELX,DELY,DELT,F,CYL,ALPHA,GX,GY,NU,UN,UN,WN,
+U,V,W,IM1,JM1,ROX,ROD)

C THIS SUBROUTINE COMPUTES THE VALUES
C OF THE VELOCITY COMPONENTS FOR
C TIME FRAME T + DT
C
REAL NU
DIMENSION U(15,15),V(15,15),W(15,15),P(15,15),UN(15,15),VN(15,15)
+WN(15,15)

DO 1100 I = 2,IM1
DO 1100 J = 2,JM1

FUX=(UN(I,J)+UN(I+1,J)+(UN(I,J)+UN(I+1,J))+ALPHA*ABS(UN(I,J)+UN(I+1,J))
+UN(I+1,J)+UN(I,J))/UN(I,J)
2-ALPHA*ABS(UN(I,J)+UN(I,J)+UN(I,J))/UN(I,J)
FUY=(UN(I,J)+UN(I,J)+UN(I,J)+UN(I,J))/UN(I,J)
1+ALPHA*ABS(UN(I,J)+UN(I,J))/UN(I,J)
2-UN(I,J-1)+UN(I,J)=UN(I,J)
3-ALPHA*ABS(UN(I,J)-UN(I,J)+UN(I,J))/UN(I,J)
FUC=CYL*UN(I,J)+UN(I,J))/UN(I,J)
2+ALPHA*ABS(UN(I,J)+UN(I,J))/UN(I,J)
3+ALPHA*ABS(UN(I,J)+UN(I,J))/UN(I,J)
4/(8.*DELX*FLOAT(I-1))

FUX=(UN(I,J)+UN(I,J+1)+(UN(I,J)+UN(I,J+1))+#ALPHA*ABS(UN(I,J)+UN(I,J+1))
+UN(I,J)+UN(I,J+1))/UN(I,J)
2-ALPHA*ABS(UN(I,J)+UN(I,J+1))+UN(I,J))/UN(I,J)
FUY=(UN(I,J)+UN(I,J)+UN(I,J))/UN(I,J)
2+ALPHA*ABS(UN(I,J)-UN(I,J)+UN(I,J))/UN(I,J)
4/(8.*DELX*FLOAT(I-1))

VISX=NU*((UN(I+1,J)-2.*UN(I,J)+UN(I-1,J))/DELX**2+1.
+UN(I,J+1)-2.*UN(I,J)+UN(I,J-1))/DELX**2
- 71 -

2 FLJ = SYM(J+1)*UN(J+1,J-1)/((2*DELT*FLJ*FLOAT(I,J+1))**2)
3 J = J+1
4 CONTINUE
5 ENDDO
6 RETURN
7 END

C
C SUBROUTINE PRINT PRINTS THE U, V, W AND FIELD VALUES
C
C DIMENSION U(15,15), V(15,15), W(15,15), F(15,15)
C INTEGER CYCLE
C
C WRITE(*,3,*), ITER, T, CYCLE
C DO 7001 J=1,JMAX
C JMM = JMAX-J+1
C WRITE(*,47) (U(I,JMM), I=1,1MAX)
C 7001 CONTINUE
C DO 7002 J=1,JMAX
C JMM = JMAX-J+1
C WRITE(*,47) (V(I,JMM), I=1,1MAX)
C 7002 CONTINUE
C IF(SWRL NE.1) GO TO 7014
C WRITE(*,53)
C DO 7003 J=1,JMAX
C JMM = JMAX-J+1
C WRITE(*,47) (W(I,JMM), I=1,1MAX)
C 7003 CONTINUE
C 7014 CONTINUE
C WRITE(*,51)
C DO 7004 J=1,JMAX
C JMM = JMAX-J+1
C WRITE(*,47) (F(I,JMM), I=1,1MAX)
C 7004 CONTINUE
C FORMAT(12(1E11.4))
C FORMAT(12(1E11.4))
FORMAT(///,2X,8H V-FIELD,/)  
FORMAT(///,2X,8H W-IELD,/)  
FORMAT(6X,SHITEK=,I5,9X,SHTIME=,1PE12.5,10X,6HCYCLE=,I4)
RETURN
END

SUBROUTINE PLOT (U,V,IMAX,JMAX)

C=====================================================================================================
C  SUBROUTINE PLOT GRAPHES THE U, V VELOCITIES COMPONENTS IN VECTORIAL FORM
C================================================================================
DIMENSION V(15,30),U(15,30),VJ(15,30),UJ(15,30)
WRITE(60,25)
25 FORMAT(10X,*PLTL*)
   JM1=JMAX-1
   IM1=IMAX-1

DO 1 J=2, JM1
DO 1 I=2, IM1
   VJ(I,J)=(V(I,J)+V(I,J-1))/2*100
   UJ(I,J)=(U(I,J)+U(I-1,J))/2*100
1 CONTINUE
   NEWDELX=10000/IM1-20
   NEWDELY=10000/JM1-20

DO 731 J=1, IM1
DO 731 J=1, JM1
   INCXY=(J-1)*NEWDELY
   INCXY=(I-1)*NEWDELX
   WRITE(60,105) INCXY,INCY
105 FORMAT(5X,I4,5X,I4,*.**,*)
   IVELX=INCXY+UJ(I,J)
   IVELY=INCRY+VJ(I,J)
   WRITE(60,106) IVELX,IVELY
106 FORMAT(5X,I4,5X,I4)
731 CONTINUE
   WRITE(60,26)
26 FORMAT(10X,*PLTL*)
RETURN
END