ABSTRACT

A LABORATORY INVESTIGATION OF THE NEAR-SURFACE VELOCITIES IN TORNADO-LIKE VORTICES.

By Simon Patrick Wayne

The goal of this thesis is to provide a detailed examination of the lowest region of a tornado-like vortex. The lowest region of the vortex has not been previously studied in great detail. This thesis focuses on the total, the vertical, the tangential, and the radial velocity components of this lowest layer.
A LABORATORY INVESTIGATION OF THE NEAR-SURFACE VELOCITIES IN TORNADO-LIKE VORTICES.

A Thesis

Submitted to the
Faculty of Miami University
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Table of Contents

Chapter 1  Introduction and Statement of the Research Problem

1.1 Introduction  
1.2 Definitions  
1.3 Vortex Structure  
1.4 Statistics  
1.5 Techniques of Measurement  
1.6 Laboratory Modeling of Tornado-like Vortices  
1.7 Statement of Problem  

Chapter 2  Tornado-like Vortex Models

2.1 Introduction  
2.2 Rankine-Combined Vortex  
2.3 Burgers-Rott Model  

Chapter 3  Experimental Procedure

3.1 Apparatus  
3.2 Sensing Techniques  
3.3 Calibration of Sensor  
3.4 Data collection  
3.5 Experimental difficulty  

Chapter 4  Analytical Procedure

4.1 Data Reduction  
4.2 The Analytical Method  

Chapter 5  Results and Presentation of Data

5.1 Presentation of Total Velocity Data  
5.2 Curve Fits for $w_{max}$  
5.3 Velocity Components  
5.3.1 Vertical Velocity Data Profiles  
5.3.2 Tangential Velocity Data Profiles  
5.3.3 Layer-Averaged Radial Velocity Data Profiles
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4</td>
<td>Ratio of $v_{\text{max}}/w_{\text{max}}$</td>
<td>58</td>
</tr>
<tr>
<td>5.5</td>
<td>Core Radius</td>
<td>59</td>
</tr>
<tr>
<td>Chapter 6</td>
<td><strong>Discussion of Results and Suggestions for Future Research</strong></td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td>Research Objectives and Past Work on Tornado-Like Vortices</td>
<td>60</td>
</tr>
<tr>
<td>6.2</td>
<td>Summary of Results</td>
<td>60</td>
</tr>
<tr>
<td>6.3</td>
<td>Uncertainties in Data Collection</td>
<td>63</td>
</tr>
<tr>
<td>6.4</td>
<td>Suggestion for Future Work</td>
<td>63</td>
</tr>
</tbody>
</table>

**Bibliography**  

65
List of Tables

Table 3.1 Difference in MUTVC and TVC used by Baker. 15
Table 3.2 Voltage to Swirl Ratio 16
Table 5.1 Swirl Ratio to $z_0$ Values 35
Table 5.2 Peak Vertical Velocities (m/s) 2-10mm and for S1-S5 58
Table 5.3 Peak Tangential Velocities (m/s) 2-10mm and for S1-S5 58
Table 5.4 $v_{max}/w_{max}$ for each swirl 59
Table 5.5 Core Radii 59
Table 5.6 Average Core Radii 60
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1</td>
<td>Thunderstorm Cross Section Showing Location of Mesocyclone</td>
<td>2</td>
</tr>
<tr>
<td>Figure 1.2</td>
<td>Tornado Made Visible by Lightning</td>
<td>3</td>
</tr>
<tr>
<td>Figure 1.3</td>
<td>Tornado Vortex Regions</td>
<td>4</td>
</tr>
<tr>
<td>Figure 1.4</td>
<td>Tornado Suction Marks</td>
<td>6</td>
</tr>
<tr>
<td>Figure 1.5</td>
<td>MUTVC</td>
<td>7</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>MUTVC Vane Structure</td>
<td>15</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>MUTVC</td>
<td>16</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>Sensor Diagram</td>
<td>17</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>Averaged Velocity Data $S=0.37$ for $Z=6\text{mm}$</td>
<td>21</td>
</tr>
<tr>
<td>Figure 4.2</td>
<td>Reaveraged Velocity Data $S=0.37$ for $Z=6\text{mm}$</td>
<td>22</td>
</tr>
<tr>
<td>Figure 4.3</td>
<td>Flux at ground level</td>
<td>26</td>
</tr>
<tr>
<td>Figure 4.4</td>
<td>Flux for cylinder not at ground level</td>
<td>26</td>
</tr>
<tr>
<td>Figure 5.1</td>
<td>Total Velocity (m/s) v.s. Radius from Center (cm) for $S=0.235$</td>
<td>29</td>
</tr>
<tr>
<td>Figure 5.2</td>
<td>Total Velocity (m/s) v.s. Radius from Center (cm) for $S=0.235$ (0-10\text{mm})</td>
<td>30</td>
</tr>
<tr>
<td>Figure 5.3</td>
<td>Total Velocity (m/s) v.s. Radius from Center (cm) for $S=0.28$</td>
<td>31</td>
</tr>
<tr>
<td>Figure 5.4</td>
<td>Total Velocity (m/s) v.s. Radius from Center (cm) for $S=0.37$</td>
<td>32</td>
</tr>
<tr>
<td>Figure 5.5</td>
<td>Total Velocity (m/s) v.s. Radius from Center (cm) for $S=0.39$</td>
<td>33</td>
</tr>
<tr>
<td>Figure 5.6</td>
<td>Total Velocity (m/s) v.s. Radius from Center (cm) for $S=0.40$</td>
<td>34</td>
</tr>
<tr>
<td>Figure 5.7</td>
<td>Height for each Swirl v.s. $W_{\text{max}}$</td>
<td>37</td>
</tr>
<tr>
<td>Figure 5.8</td>
<td>Velocity Peak Values v.s. Probe Scanning Height</td>
<td>38</td>
</tr>
<tr>
<td>Figure 5.9</td>
<td>Velocity Peak Values v.s. Probe Scanning Height</td>
<td>39</td>
</tr>
<tr>
<td>Figure 5.10</td>
<td>Vertical Velocity ($S=0.235$)</td>
<td>41</td>
</tr>
<tr>
<td>Figure 5.11</td>
<td>Vertical Velocity ($S=0.28$)</td>
<td>42</td>
</tr>
<tr>
<td>Figure 5.12</td>
<td>Vertical Velocity ($S=0.37$)</td>
<td>43</td>
</tr>
<tr>
<td>Figure 5.13</td>
<td>Vertical Velocity ($S=0.39$)</td>
<td>44</td>
</tr>
<tr>
<td>Figure 5.14</td>
<td>Vertical Velocity ($S=0.40$)</td>
<td>45</td>
</tr>
<tr>
<td>Figure 5.15</td>
<td>Tangential Velocity ($S=0.235$)</td>
<td>47</td>
</tr>
<tr>
<td>Figure 5.16</td>
<td>Tangential Velocity ($S=0.28$)</td>
<td>48</td>
</tr>
<tr>
<td>Figure 5.17</td>
<td>Tangential Velocity ($S=0.37$)</td>
<td>49</td>
</tr>
<tr>
<td>Figure 5.18</td>
<td>Tangential Velocity (S=0.39)</td>
<td>50</td>
</tr>
<tr>
<td>Figure 5.19</td>
<td>Tangential Velocity (S=0.40)</td>
<td>51</td>
</tr>
<tr>
<td>Figure 5.20</td>
<td>Layer-Averaged Radial Velocity (S=0.235)</td>
<td>53</td>
</tr>
<tr>
<td>Figure 5.21</td>
<td>Layer-Averaged Radial Velocity (S=0.235)</td>
<td>54</td>
</tr>
<tr>
<td>Figure 5.22</td>
<td>Layer-Averaged Radial Velocity (S=0.235)</td>
<td>55</td>
</tr>
<tr>
<td>Figure 5.23</td>
<td>Layer-Averaged Radial Velocity (S=0.235)</td>
<td>56</td>
</tr>
<tr>
<td>Figure 5.24</td>
<td>Layer-Averaged Radial Velocity (S=0.235)</td>
<td>57</td>
</tr>
</tbody>
</table>
Chapter 1  Introduction and Statement of the Research Problem

1.1  Introduction

Tornadoes are naturally occurring phenomena which can have devastating impacts on society. Tornado research has been difficult in the past due to the unpredictability of when and where a tornado will occur. Even when airspeed or pressure measurement devices could be placed in the path of an oncoming tornado in many cases they were lost or destroyed or the tornadoes did not pass sufficiently close to yield useful data. There is also no accurate way to tell if the devices which were able to collect data were in fact recording the maximum values. Over the last three decades the Doppler radar technique has been developed and deployed with greater success than previous methods, but this still requires further refinement (Lund, D. E., J. T. Snow, 1993).

Laboratory modeling of tornado-like vortices represents another option to actually chasing tornadoes, and allows the experimentalist to create a vortex in the relative safety of a laboratory setting, and with at least the promise of obtaining repeatable results. The modeling approach certainly resolves the issue of when and where a tornado will occur, and allows for constraints to be placed on the vortex that could not duplicated in an actual tornado. Tornado-like vortex modeling allows one a better insight into the airflow dynamics of tornado-like vortices than could be accomplished by studying actual tornadoes due to the lack of control of the variables in such situations (Church, C. R., J.T. Snow, 1993). Laboratory modeling does however have its own unique set of difficulties. It is difficult to construct a tornado chamber large enough to produce a vortex of any great size. The vortices produced do not remain in a fixed positions, and but wander constantly, and it is only after many trials that a representative data set is obtained. Conditions in the chamber may also vary slightly depending on outside weather conditions (such as wind and temperature), despite the most determined efforts to isolate chamber conditions from outside conditions.

The efforts of this research focus on the part of a tornado most likely to cause damage to societal infrastructure, namely the lowest few meters of the tornado column and in the vicinity of the vortex core. The corresponding region to be studied in the laboratory vortex is the region within 10 mm of the surface and also close to its axis of rotation. This is a region which has not been previously investigated in detail.
1.2 Definitions

The tornado phenomenon is generally defined as a narrow column of rotating air extending from a cumuliform cloud to the ground. In the event that the vortex does not reach the ground it may be referred to as a funnel cloud. Tornadoes usually form in the rotating portion of a thunderstorm, technically referred to as a mesocyclone. The mesocyclone typically has a diameter of a few kilometers and contains a strong updraft through the thunderstorm. A mesocyclone may last on the order of hours, and could potentially spawn several tornadoes in its lifespan. The tornadoes created will most often have a relatively short lifespan in comparison to the parent mesocyclone itself. A mesocyclone is not always necessary for the formation of a tornado, and not all mesocyclones produce tornadoes but their formation is far more likely to occur in the presence of the mesocyclone.

![Thunderstorm Cross Section Showing Location of Mesocyclone](Image Source: www.met.tamu.edu/.../Severedir/torn-dev-full.jpg)

Naturally forming tornadoes vary greatly in their visual appearance and have a high degree of structural variability. Various factors contribute to this variability, such as the availability of visualizing materials (atmospheric condensation depending on moisture levels, and dust and debris), degree of swirl (defined later) and the physical
nature of the underlying surface (rough or smooth). Some tornadoes appear relatively thin (a few meters in diameter), others may have diameters of several hundred meters, and the larger ones may contain multiple suction vortices that circulate about a common axis. Damage paths also can vary from a few meters to more than one kilometer in width, making it difficult to assess core widths if the tornadoes occurred at night and were not observed. Different tornadoes will of course also have different ranges of wind speed. Wind speeds for tornadoes are often difficult to verify, and in many cases are highly educated guesses based on damage to surrounding landmarks and structures as with the Fujita intensity scales.

There are also other types of vortex phenomena. Waterspouts (tornadoes over water), dust devils, and fire whirls (whirlwinds associated with forest fires), share similar characteristics with tornadoes, although they are generally less intense.

Figure 1.2 Tornado Made Visible by Lightning

1.3 Vortex Structure

As observed in nature as well as in the laboratory, tornado-like vortices have two distinct regions separated by a transition zone known as the Vortex Breakdown (VBD). The lowest region is said to be one-celled, and the upper region downstream of the VBD is two-celled.
The one-cell layer of the vortex extends from the surface (the ground or chamber floor) to the VBD. The two-cell layer extends from the VBD to a point at the top where the vortex loses shape and structural identity. The height at which the VBD occurs is dependent on the amount of swirl in the vortex. The higher the amount of swirl the closer the VBD will be to the surface. The one-cell region of a vortex has a narrow laminar core with a single centralized vertical air flow, the peak vertical velocity being along the axis of rotation.

The two-cell region of the vortex is much broader and contains a turbulent core with less vertical movement of air near the axis, with most of the upflow being in a ring surrounding the axis. If the amount of swirl is sufficiently high, the entire vortex column may be two-celled and may contain multiple (2 or more) subsidiary suction vortices.

Figure 1.3  Tornado Vortex Regions
1.4 **Tornado Statistics**

Tornadoes are most common in the United States due to geographical constructs of the country. Although tornadoes occur in other countries they do so with much less frequency. Conditions conducive to the formation of tornadic thunderstorms are large areas of flatlands downstream of a North-South mountain chain with an ample supply of moisture to the south. Such background features allow for the rapid development of large scale mid-latitude cyclones in which tornadic thunderstorms are likely to develop at certain times of the year. These conditions are found usually during spring and summer over The Great Plains of the central United States, with the Gulf of Mexico serving as the primary moisture source. On average there are nine hundred tornadoes a year in this country. Most tornadoes are small and cause little if any damage. Three percent of tornadoes cause massive damage to social infrastructure and monetarily cost about 200 million dollars a year (Galway, 1975). The death U.S. toll is around 100 people per year.

1.5 **Field Measurement Techniques**

As mentioned earlier measuring wind speeds in actual tornadoes is a difficult process. This difficulty arises from being able to put a sensor in the path of the tornado, being able to later retrieve it and knowing exactly where the tornado went relative to the sensor. There are a few other methods worth mentioning.

Photogrammetry is a method of estimating tornado wind speeds using moving film or more recently video camera (Carver III, B. R., 1997). Such data has become more abundant in the last few years thanks to the popularity of small digital cameras and phones with video recording technology. Photogrammetry has it limits. These limits are partly due to frame rate, and picture clarity and resolution. But one must also have objects of relative size for comparison to the size of the tornado, know the distance of the camera to the tornado at the time of filming, and even know the path of the tornado (Golden, 1976).

Another method used to determine wind speeds in particularly large tornadoes is to examine suction marks left behind after the tornado goes through. Other estimating techniques include looking at the damage done to buildings, in relation to a building’s
supposed resistance to certain wind speeds. The greater damage to a building the higher the winds that caused the damage.

Figure 1.4  Tornado Suction Marks
(image Source: www.nhn.ou.edu/~feldt/pictures.html)

Perhaps the method most likely to yield data with the smallest uncertainties is through the use of mobile Doppler radar. These have been developed with increased degrees of refinement, are deployed in chasing storm systems that are likely to produce tornadoes. By using two Doppler radar setups simultaneously it is possible to resolve a two dimensional horizontal cross section of a tornado, and hence determine its three velocity components. By employing several slightly different microwave frequencies each radar unit it is feasible to scan the tornado column simultaneously at several different elevations, thereby obtaining a more complete picture of the vortex break structure at several levels. This technique is presently under development. In order to view the region of the tornado closest to the ground it is necessary to position the radar very close to the tornado, and this is a major operational difficulty.
1.6 Laboratory Modeling of Tornado-like Vortices

A Tornado Vortex Chamber (TVC) is an apparatus designed to simulate a tornado on a much smaller scale. The tornado-like vortices created in a TVC exhibit the characteristics of an actual tornado. This allows for the nature of air flows to be studied on the small scale and then applied to the large scale, in accordance with the long-established engineering practice of wind tunnel modeling.

Figure 1.5 MUTVC
Most TVCs in existence today are based on the Ward type model developed in the 1960’s (needs to be cited). The Ward type TVC simulator contains an updraft region that represents the updraft in the mesocyclone region of a thunderstorm. The numerically small aspect ratio (inflow depth to updraft diameter $a<1$) in the TVC is also similar to that found under the mesocyclone. The original Ward type model used a rotating mesh system to create swirl. The MUTVC uses a vane system developed by Dr. Church to create swirl.

Measurements in the MUTVC are performed using either pressure sensors connected to the chamber floor, or with a hot-film anemometer sensor that is swept through the core of a vortex on an arm that swings back and forth and passes through the core at a speed of 0.28 m/s.

The method of taking measurements with the hot-film anemometer does have its limitations. The process involves setting the sensor at a set height above the chamber floor. A horizontal laser sheet illuminates a cross section of the vortices made visible with smoke. The radial position of the sensor is adjusted in order to sweep it through the center of the vortex. A difficulty lies in the inherent randomness of the position of the vortex. The constant movement of the vortex makes it difficult to cause the sensor to track through the exact center of the vortex. This requires many sweeps with the anemometer, and then several peaks that have met certain selection criteria are averaged. The selection criteria consist of taking the most prominent and symmetric peaks from the collected data.

1.7 Statement of Problem

A characteristic of swirling tornado-like flows is that the rotation has the effect of enabling high flow velocities (in all three component directions) to be present very close to the surface. Consequently, in the Earth’s biosphere the destruction can be considerable, and to an extent that depends on flow parameters such as degree of swirl and flow rate. The research objective here is to study in the laboratory the corresponding region of flow in model 1-cell tornado-like vortices, focusing primarily on the lowest centimeter of the flow and in the vicinity of the vortex core. Data collection consists of making lateral sweeps with a single hot film air speed sensor at closely spaced height intervals (2-4-6-8-
10mm) for increasing degrees of swirl. This uses the same general approach employed by Kosiba (2002) but now with greater spatial resolution, concentrating on what is perhaps the most elusive part of the vortex to be treated experimentally. Analysis is to be done following the technique developed by Beer (2006). This technique makes it possible to use single sensor data to systematically develop profiles for each of the three component directions, although with certain limitations.
Chapter 2  Tornado-like Vortex Models

2.1  Introduction

For an analytical model to accurately represent the structure of vortex flows it needs to satisfactorily take into account the properties of the fluids, namely density and viscosity, and characteristics of the flow, such as degree of swirl and turbulence, surface roughness, flow geometry and flow rate. The Navier–Stokes equations can provide non-linear solutions, but even these are inadequate in certain areas, such as not taking account of turbulent stresses or being able to explicitly describe the surface boundary effects. One cannot expect to derive from theory mathematical functions that successfully describe the structure of vortex flows. However following sections presents two mathematical models which, in spite of their substantial shortcomings, capture some of the essence of vortex structure.

Vorticity is defined as the local rate of spin of a fluid particle about a given axis. Thus vertical vorticity ($\zeta$) is associated with spin about a vertical axis, and the core of a vortex is the region containing highly concentrated vertical vorticity. In cylindrical polar coordinates, the radial, tangential and vertical velocity components ($u$, $v$, and $w$ respectively) are

$$u = \frac{dr}{dt}, \quad v = r \frac{d\theta}{dt}, \quad w = \frac{dz}{dt}$$

Vertical vorticity is equal to the curl of the horizontal velocity vector $V = u + v$, i.e.

$$\zeta = \nabla \times V$$

and with axial symmetry we also have $\zeta = \frac{v}{r} + \frac{\partial v}{\partial r}$.

2.2  Rankine-Combined Vortex

The Rankine combined vortex is a simple one-dimensional model. The Rankine model assumes an adiabatic homogeneous inviscid fluid for the tornado vortex. The Rankine model introduced in 1882 by Rankine, where

$$u = w = 0$$

$$v = \frac{\Gamma}{2\pi r} \quad \text{for} \ r > r_c,$$

$$v = \frac{\Gamma}{2\pi} \frac{r}{r_c^2} \quad \text{for} \ r \leq r_c,$$
For the condition of \( r = r_c \): \( v_{\text{max}} = \frac{\Gamma}{2\pi r_c} \)

Where \( \Gamma \) is the circulation of the vortex, \( v \) is the tangential velocity component. From the Euler’s equations:

\[
-\frac{1}{\rho} \frac{\partial p}{\partial r} = u \frac{\partial u}{\partial r} + \frac{v}{r} \frac{\partial u}{\partial \theta} - \frac{v^2}{r} \]

\[
-\frac{1}{\rho} \frac{\partial p}{r \partial \theta} = u \frac{\partial v}{\partial r} + \frac{v}{r} \frac{\partial v}{\partial \theta} + \frac{vu}{r}
\]

the hydrostatic equation simplifies to the cyclostraphic balance equation (Davies-Jones 1976):

\[
\frac{\partial P}{\partial r} = \frac{\rho v^2}{r}
\]

And the hydrostatic balance,

\[
\frac{\partial P}{\partial z} = -\rho g
\]

The maximum pressure deficit between “infinity” and the vortex center is:

\( \Delta p_{\text{max}} = (p_\infty - p_0) = \rho v^2 \)

Advantages of the Rankine-combined vortex are that it provides an elementary representation of rotational velocities in a vortex and relates pressures to velocities. Disadvantages of this model are that it is one-dimensional, nor does it predict core size, and it lacks variation with height or swirl. It also fails to address characteristics of the surface.

### 2.3 Burger-Rott Vortex

Another often used model for a single-cell vortex is the Burgers-Rott model.

\[
u = -ar
\]

\[
v = \frac{\Gamma}{2\pi r} \left[ 1 - e^{-\frac{ar^2}{2\eta}} \right]
\]

where \( \eta \) is the kinematic viscosity.

\[
w = 2az
\]
\[ p(r, z) = p(0,0) + \rho \int_0^r \frac{\nu}{\rho} dr - \frac{\rho a^2}{2} (r^2 + 4z^2) \]

where \( a \) is the horizontal convergence constant i.e. the negative of the radial velocity gradient (Davies-Jones 1976). For the TVC, at a volumetric flow rate of .38 m\(^3\)/s, \( a = \) 1.00 s\(^{-1}\). (Note that this \( a \) is not related to the aspect ratio.)

The Burgers-Rott model has an advantage over the Rankine-combined vortex in that there is no discontinuity for \( r = r_c \). The Burgers-Rott also includes viscosity as a determining factor in core size. For the Burgers-Rott model \( r_c \) is

\[ r_c = 1.12 \sqrt{\frac{2\eta}{a}} \]

And the maximum tangential velocity is

\[ v_{\text{max}} = \frac{.072\Gamma}{2\pi r_c} \]

This allows for a pressure deficit of

\[ \Delta p_{\text{max}} = 1.68 \rho v^2 \]

Although the model seems to be three-dimensional, it is in actuality only a one-dimensional model pasted on the velocity components (\( u, w \)) of the background flow. Another shortcoming is that does not predict variation of core diameter with height or swirl, nor does it take into account properties of the underlying surface.

A positive aspect is that, unlike the Rankine model the Burgers-Rott model provides for an estimate of core radius as a function of circulation (\( \Gamma \)) and the kinematic viscosity (\( \eta \)). For this experiment it can be determined that the expected core radius for the TVC is approximately 6mm. This is of the same magnitude as Beer’s values as shown in Table 4.2 (p.124) of his thesis. However the Burgers-Rott model does not take into account variations of core radius with swirl, height and surface roughness found by Beer and shown in his table.
Chapter 3  Experimental Procedure

3.1  Apparatus

The Miami University Tornado Vortex Chamber (TVC) models a tornado forming along the centerline of a mesocyclone. The design of the chamber is such that the vortex created is geometrically and dynamically similar to an actual tornado.

The TVC has four distinct regions; 1) the confluence region, where the flow is entirely horizontal. 2) the convergence region, where the flow turns from horizontal to vertical. 3) the convection region, where flow is entirely vertical and 4) the divergence region, where the vertical flux becomes entirely horizontal and is exhausted through a series of twelve fans located at the top of the chamber. The TVC is built over an internal viewing space (closed circuit TV) where the observer can view the vortex along a vertical axis through the vortex.

The TVC is designed to minimize turbulence and airflow from outside the chamber using a set of filters around the chamber sides. Upflow is achieved with the use of the twelve fans mounted to the top of the chamber, and the fans can be adjusted to control updraft flow rates. Around the circumference of the chamber another set of 6 fans cause an airflow across the convex surface of 12 curved vanes which give the inflow air a tangential component. These fans in conjunction with the vanes create varying degrees of swirl, according to the DC voltage applied to the fans. The swirl angle ($\theta$) is defined as the arctangent of the tangential component divided by the radial component of the airflow in the confluent region, i.e. $\theta = \tan^{-1}\left(\frac{V}{u}\right)$. 

\[ \frac{V}{u} \]
Other key factors in the experimental design are as follows: A raised chamber floor to allow access though a crawl space the underworkings of the chamber. A glass plate at the center of the chamber floor allows for viewing the vortex with the closed circuit camera. The camera is mounted to allow for focusing, and to observe the sensor sweeps through the vortex. The vortex is fed a small amount of smoke to make the vortex visible, and a particular thin layer can be illuminated using a narrow angle laser sheet. The laser sheet also illuminates the tip of the sensor as it passes through the vortex. This enables the mechanical sensor arm to be correctly positioned for optimum results. Table 3.1 Shows differences in the Miami University TVC (MUTVC) and the TVC used by Baker.
Table 3.1 Difference in MUTVC and TVC used by Baker.

<table>
<thead>
<tr>
<th></th>
<th>Wayne</th>
<th>Baker</th>
</tr>
</thead>
<tbody>
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<td>0.406</td>
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<td>Inflow depth</td>
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<td>0.406</td>
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<tr>
<td>Volume flow rate (m$^3$/s)</td>
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<td>0.47</td>
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<td>Mean vertical velocity (m/s)</td>
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<td>Horizontal convergence factor (sec$^{-1}$)</td>
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3.2 Measurement Techniques

In order for data to be collected from a vortex a constant temperature hot-film anemometer was employed. The hot film sensor was attached to an arm that moved the sensor through a chosen level of the vortex. The arm was a 6mm diameter stainless steel rod inclined at a 45 degree angle to the vertical and designed for minimal interaction with vortex upflow and also the vortex core. The sensor mounted to the arm sweeps back and
forth and passes through the vortex center at 0.28m/s. A small quantity of smoke is introduced into the chamber in order to make a cross section of the vortex visible to laser light. To acquire a representative velocity profile it was necessary to average many velocity profiles.

Figure 3.3   Sensor Diagram

3.3     Calibration of Sensor

The hot film anemometer is calibrated using a wind tunnel in the laboratory developed specifically for this purpose, and providing a range of speeds of 1-11m/s. The hot film sensor must first be set to the correct temperature using a bridge circuit with a variable resistance in series with the sensor. The bridge circuit allows for the proper voltage to be applied to the circuit. Air flow over the sensor draws away thermal energy, and the supply current, which maintains a constant sensor temperature, provides the signal that is a function of the flow speed. The sensor was placed in a wind tunnel and calibrated by varying the air speed in the wind tunnel. About 40 data points were collected in calibrating the sensor over a range of air speeds from 1-11m/s in the tunnel. These velocities were then matched to the sensor voltages and a unique curve fit for each sensor was then found.
The wind tunnel itself had been originally calibrated using a miniature (3mm diameter) Pitot-static tube connected to a Validyne DP-103 pressure transducer. The sensitivity of the transducer was such that it provided output voltage of 1.000 volts for 423.3 Pa difference between the total and static ports. From Bernoulli’s equation

$$\Delta p = \frac{1}{2} \rho v^2$$

(for $\rho = 1.15 \text{kg/m}^3$), it follows that accurate airspeed measurements of 1m/s or less cannot be made with this system. i.e. for $V=1\text{m/s}$ the Validyne output is only about 0.001 volts, which is the resolution limit of the pressure sensing system.

### 3.4 Data collection

The MUTVC allows for research to be conducted with multiple swirl ratios over a variety of heights. The swirl ratios of 0.235, 0.28, 0.37, 0.39, and 0.40 were employed for the collection of data. This range of swirls created one-cell vortices that ranged from a low intensity vortex where the VBD was situated close to the top of the experimental chamber to the most intense case where the VBD was within a couple of millimeters to the floor. At each of these swirl ratios velocity profiles were obtained at levels of 2, 4, 6, 8, and 10 millimeters. For the lowest swirl ratio case ($S = 0.235$) an additional data set at 10, 20, 30, 40, and 50mm was also obtained. Table 3.6.1 below shows the relationship between the DC voltages applied to the 6 fans and the swirl ratios obtained when the chamber volume flow rate was set at 0.38 m$^3$/s.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Swirl Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 V</td>
<td>0.235</td>
</tr>
<tr>
<td>16 V</td>
<td>0.28</td>
</tr>
<tr>
<td>18 V</td>
<td>0.37</td>
</tr>
<tr>
<td>20 V</td>
<td>0.39</td>
</tr>
<tr>
<td>22 V</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Table 3.2
The actual taking of data consisted of many sensor sweeps through the vortex, with the sensor properly elevated using the laser sheet to check vertical height above the chamber floor. The voltage across the sensor were output into a Labview program through a Daq card and converted to an Excel xls file. Each file would show approximately 15-20 profiles. Viable profiles would then be selected and combined through the averaging process with other viable profiles. A “viable” profile was one that had a certain maximum value to indicate it had passed through the vortex center, and was quite symmetrical. In many cases a data file might contain no profiles of any significance and occasionally a file would contain 5 or 6 profiles that were quite representative of the vortex structure. For some of the higher swirl measurements at the upper limit of the vertical distance (8-10mm) only 10 profiles out of many data sets would be considered representative profiles. The higher the swirl ratio the more the vortex would tend to wander; this made measurements at the higher swirls more difficult then measurements at the lower end swirls. For each new height measured the sensor arm had to be adjusted with the use of the laser sheet and the camera in the crawl space. The measurement process while sometimes long and laborious but did after many trials provide a representative set of data for the various swirls and heights.

3.5 Experimental difficulty

Difficulties in acquiring representative data were such that considerably more time was needed than originally expected. This was due in part to the vortex not being stationary for any appreciated amount of time. The constant position change of the vortex made it almost impossible to ever find a perfect profile. In addition, even under the most ideal of conditions, given the inherent unsteadiness of the vortex flow one would not expect to see the same identical profile on successive passes. This led to averaging several profiles in the data analysis process. In the process of acquiring a usable data set three previously acquired data sets had been critically examined and discarded. Each had typically taken about a month to acquire as the data collection technique was being improved. Even in the final data set it was clear that the sensor passed through the center of the vortex on only a fraction of occasions. Another issue to be mentioned is the fragility of the sensor. The hot-film sensor used a length of 20 μm
diameter metallized quartz filament mounted between two stainless steel prongs. On more than one occasion a sensor would break. This required recalibrating a new sensor. On other occasions the sensor broke due to having too much voltage across it and burning off the conducting film (from improper resistance across the bridge circuit), or from scraping the chamber floor during some of the lower level measurements. Measurements at the 2mm level required having the sensor swing back and forth extremely close to the chamber floor.
Chapter 4  Analytical Procedure

4.1 Data Reduction

With approximately 60,000 data points per run with 30 runs per level for one given swirl, the amount of data accumulated quickly. In most cases the data profiles used were never absolutely symmetrical. An averaging technique was employed on about the 15 of the best (i.e. most representative) profiles for each swirl at a given height. An example of the averaged data is shown in Figure 4.1 below, with the horizontal scale stretched to emphasize the typical asymmetry. Once the profiles were averaged in this way, the data was further averaged left to right about the maximum velocity data point. This process provided a symmetric velocity profile for each swirl and height as shown in Figure 4.1.2. This set of averaged symmetric velocity profiles were then used to extract the velocity components.

Figure 4.1
Since the single velocity sensor used here provided only a single stream of data, the method devised depends on additional information and certain assumptions made concerning vortex structure. This is the same method as was adopted by Beer (2006). The uncertainties are significantly greater than in Baker’s (1981) study in which he derived the technique for determining the velocity components independently. However, the present approach is considerably less laborious and enables, in a reasonable amount of time, the development of a more complete picture of how 1-cell vortex intensity varies with the degree of swirl. Also, within this same time frame, vortex structure can be examined at several narrowly spaced heights. In the final analysis, as in Beer’s work, profiles were obtained for the vertical and tangential velocity components, but for the radial component only average values were obtainable for each layer. In this study each layer has the same thickness of 2mm, which made it possible to compare the average radial velocities in adjacent layers.
### 4.2 Analytical Method

Analysis of the collected data is based on the assumption of a Lorentzian form for the vertical velocity profile. The following points provide a rationale for attempting to extract more than one velocity component from a single channel of data:

1) Boundary conditions: on the centerline of the vortex the radial and tangential components are both zero, and the velocity vector is entirely in the vertical ($u = v = 0$, $w = w_{\text{max}}$ at $r = 0$).

2) In the region close to the centerline: $u \approx 0$, $v > 0$ and $w < w_{\text{max}}$. The radial component in this region is small, and can be considered negligible also the orientation of the sensor makes it insensitive to motion in the radial direction. In modeling the flow near the centerline (and only in this region) the tangential velocity was taken as increasing linearly with radius, i.e. $v = kr$.

3) It is expected that the time-averaged vertical velocity profile is symmetrical about the centerline. Taking the average of several similar appearing profiles obtained under the same steady flow conditions is equivalent to a time average. Different functional forms were considered for the symmetrical vertical velocity profile, namely Gaussian, Jet and Lorentzian as shown below

**Gaussian Model:**

$$\frac{w}{w_{\text{max}}} = e^{-\left(\frac{r}{\eta}\right)^2}$$  \hspace{1cm} \text{Equation 4.1}

**Jet Profile:**

$$\frac{w}{w_{\text{max}}} = \frac{4}{\left(e^{-\left(\frac{r}{\eta}\right)} + e^{-\left(\frac{r}{\eta}\right)}\right)^2}$$  \hspace{1cm} \text{Equation 4.2}
Lorentzian: \[ \frac{w}{w_{\text{max}}} = \frac{1}{1 + \left(\frac{r}{r_0}\right)^2} \]  

Equation 4.3

With \( r \) being the radial distance from the vortex center, and \( r_0 \) being a derived scaling value for each swirl and height combination. For small values of \( \frac{r}{r_0} \), all functions have the same form (Lorentzian). For large values of \( \frac{r}{r_0} \), the Lorentzian profile is broader than the other two. Beer showed that Baker’s data for the vertical velocity profiles (which he was able to measure directly) closely fitted a Lorentzian profile.

To summarize, in the vortex model for flow close to the centerline the velocity components are as follows:

\[ u = 0, \ v = kr, \]  
\[ \text{and} \quad \frac{w}{w_{\text{max}}} = \frac{1}{1 + \left(\frac{r}{r_0}\right)^2} \]

The \( r_0 \) value is a radial scaling parameter that was determined by selecting pairs of data points near \( r = 0 \) and solving simultaneously for \( r_0 \). For each swirl and height a value for \( r_0 \) was determined which was then assumed to apply to all values of \( r \). Thus the vertical velocity profile could be determined entirely from the measured values \( w_{\text{max}} \) and derived quantity \( r_0 \). The velocity \( (V) \) measured by the sensor is as \( V = \sqrt{v^2 + w^2} \) and the expression applies over a large range of range of radii, no longer only close to the centerline. Having measured the \( V \) profile with the sensor and having derived the \( w \) profile analytically, the tangential profile can be determined from above equation. The layer-averaged radial velocity was derived in part using the function for \( w \), which has been assumed to be Lorentzian. The derivation is as follows:
Consider a ring at some height $z$ above the floor, to have radius $r$ less than $r_c$ (and to be axially centered with the vortex). The ring has a certain width (dr), and the vertical velocity $w_r$ through ring will be less than $w_{max}$.

\[
w_r = \frac{w_{max}^2}{1 + \left(\frac{r}{r_0}\right)^2}
\]

Let \( x = \frac{r}{r_0} \) (a dimensionless radius)

And \( w_r = \frac{w_{max}}{1 + x^2} \) \hspace{1cm} \text{Equation 4.4}

If \( r = r_0x \) then \( dr = r_0dx \) \hspace{1cm} \text{Equations 4.5 and 4.6 respectively}

To find the vertical flux through the ring using differential form;

\[
dF_v = 2\pi w_r r dr
\]

\text{Equation 4.7}

Substitute in equations 4.5 and 4.6 and rewrite equation 4.7 as;

\[
dF_v = 2\pi (r_0x)(r_0dx)w_r
\]

\text{Equation 4.8}

Then substitute equation 4.4 and solve for

\[
dF_v = \frac{2\pi w_{max}^2 x}{(1 + x^2)} dx
\]

\text{Equation 4.9}

The integration of equation 4.9 show the total vertical flux between \( r \) and 0 to be:

\[
F_v = \pi w_{max} r_0^2 \ln(1 + x^2)
\]

\text{Equation 4.10}

Using conservation of mass this vertical flux is equal to the horizontal flux through the sides of a cylinder of depth $z$ and radius $r$. Thus the horizontal flux for the cylinder is

\[
F_H = 2\pi zu = 2\pi r_0zu
\]

\text{Equation 4.11}

Where $u$ is the average radial velocity between $z$ and 0.

And from conservation of flux it follows that:

\[
2\pi r_0zu = \pi w_{max} r_0^2 \ln(1 + x^2)
\]

\text{Equation 4.12}

or

\[
u = r_0 w_{max} \ln(1 + x^2) \quad \frac{2xz}{2xz}
\]

\text{Equation 4.13}
Using the above equation 4.13 it is now possible to solve for the radial inflow velocities of each layer, 0-2mm, 2-4mm, 4-6mm, 6-8mm, and 8-10mm.

![Figure 4.3](image1.png) **Figure 4.3** Flux at ground level

![Figure 4.4](image2.png) **Figure 4.4** Flux for cylinder not at ground level

Figures 4.3 and 4.4 demonstrate the difference in airflow for the ground level and levels above the ground level.
Chapter 5    Results and Presentation of Data

5.1    Presentation of Total Velocity Data

Figures 5.1 – 5.6 present the reduced total velocity data. For the most part each graph represents a nested set of profiles, although total velocities in some cases do overlap (example Figure 5.5). This can be attributed to the general unsteadiness of the vortex, and that the measurement levels are only 2mm apart. The figures are presented as only half of the total profile, but the profiles are symmetric about the velocity axis (y-axis). This allows for a larger graph to be presented on the page in order to provide clearer detail.

Figure 5.1 and 5.2 together display results for 0 – 50mm above the chamber floor for a swirl ratio of 0.235. Figure 5.1 is for the first 10mm above the floor and shows an increase in the total velocity maxima for each increase in the height z above the floor. Figure 5.2 is for the 10 – 50mm levels. Notice in Figure 5.1 that the change in the total velocity maximum decreases accordingly with each change in height, and this trend continues through Figure 5.2 where there is little increase between the 20 – 50mm levels which all have velocity maxima close to 6.5m/s. These two figures combined also demonstrate a increase in the profile width with an increase of height.

Figures 5.1, 5.3, 5.4, 5.5 and 5.6 concentrate on the lowest 10mm above the chamber floor with swirl ratios of 0.235, 0.28, 0.37, 0.39, and 0.40 respectively. This collection of data forms the basis for most of the findings of this study. From the five sets mentioned above the vertical, tangential, and layer-averaged radial velocities are all derived. These five sets also offer insight into the basic structure of the tornado-like vortices. Each figure focuses on the levels of 2mm, 4mm, 6mm, 8mm, and 10mm. Generally each increase height will have a corresponding increase in the maximum value of the total velocity, in some cases there is little difference in the total velocity maximum between one level and the next. This is attributed to the vortex breakdown region (VBD) being so close to floor and being unstable (i.e. rapidly moving up and down), especially for the higher swirls.

It is a conclusion of this research that the total velocity maxima always increase with an increase of the swirl ratio for the lowest 10mm, provide the VBD is above the 10mm level. As an example if one looks at the 2mm level as the swirl increases through
the five swirl ratios for this study, it will be noticed that the total velocity maxima increase from 3.064m/s – 5.366m/s – 8.222m/s – 9.315m/s – 10.999m/s respectively with increases in swirl. This trend continues for each of the levels measured.

It may also be concluded from the data presented in Figures 5.1 – 5.6 that increasing the swirl decreases the width of the profile.

As the swirl ratio is increased the vortex breakdown region (VBD) becomes closer to the surface, and more agitated. For this reason Figure 5.5 does not include the 10mm level, and Figure 5.6 only includes the 2mm level. This implies that the VBD for a swirl ratio of 0.39 as in Figure 5.5 is less than 10mm, but higher than 8mm. In Figure 5.6 with a swirl 0.40 there is an implication that here the VBD is between 2mm and 4mm. Also for a swirl of 0.235 the VBD must be above 50mm or else Figure 5.2 would present two-cell velocity data. The remaining figures 5.3 and 5.4 do not provide an indication of the VBD height except to say it is above 10mm.

In Figure 5.6 there are two data sets for the same 2mm level. This is because one set is an average set, and the other is the actual data from the highest representative peak. The average data for this figure was difficult to collect and hence very few representative peaks could be found for the average. The reason for this is that most of the time the flow was two-celled at the 2mm level.
Figure 5.1
Figure 5.2
Figure 5.3

Total Velocity (m/s) v.s. Radius from Center (cm) for $S=0.28$
Figure 5.4

Total Velocity (m/s) v.s. Radius from Center (cm) for S=0.37

Velocity (m/s)

Radius from Center (cm)
Figure 5.5
Figure 5.6

Total Velocity (m/s) v.s. Radius from Center (cm) for S=0.40

- 2mm Averaged Data
- 2mm Highest Peak
5.2 Curve Fits for $w_{\max}$

Figures 5.7, 5.8, and 5.9 present the curve fits for $w_{\max}$. Figure 5.7 deals with a new curve found in the process of collecting data for this research. Figures 5.8 and 5.9 use Excel’s curve fitting functions to predict $w_{\max}$.

The curve fit function for Figure 5.7 is a logarithmic fit using the empirical equation:

$$w_{\max} = 1.09 \ln \left( \frac{z}{z_0} \right)$$

Equation 5.1

where $z$ is the vertical distance above the floor, and $z_0$ is a constant related to swirl.

<table>
<thead>
<tr>
<th>Swirl</th>
<th>$z_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.235</td>
<td>0.0800</td>
</tr>
<tr>
<td>0.28</td>
<td>0.0100</td>
</tr>
<tr>
<td>0.37</td>
<td>0.0011</td>
</tr>
<tr>
<td>0.39</td>
<td>0.0003</td>
</tr>
<tr>
<td>0.40</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

Table 5.1

The data is overlapped by the curve fit for Figure 5.7. One can see that the logarithmic fit predicts the $w_{\max}$ for $S = 0.235$ up to 50mm fairly well, and similarly predicts the $w_{\max}$ values for the next three swirl ratios. The $S = 0.40$ having only one point cannot be shown graphically, but the assigned value for $z_0$ provides a value for $w_{\max}$ that is consistent with the measurements.

The remaining two figures used Excel to determine the appropriate curve fits. For Figure 5.8 the smallest and the largest swirl ratios are the only two presented. This gives an idea of the maximum and minimum inflow depths of the chamber. For the lower swirl case, since $w_{\max}$ continues to increase with height in the range 0-50mm, there is radial inflow into the core throughout this depth. In the highest swirl case, since $w_{\max}$ does not increase above the 2mm level, this implies that all of the radial inflow into the core depth occurs in the 0-2mm layer. Figure 5.9 displays the data for vertical velocity maxima with height for all five swirl ratios. The curve fits of both figures are in the form of $y = A e^{Bx}$ where A and B are constants, x is the vertical velocity in meters/second, and y is in units.
of millimeters. These fits also give a good approximation to the vertical velocity maxima for each swirl.
Figure 5.7

Height for each Swirl vs Wmax

Vertical Velocity (m/s) vs Height above chamber floor (mm)

Log fit S1=0.235
Log fit S2=0.28
Log fit S3=0.37
Log fit S4=0.39
Log fit S5=0.40

S1=0.235 Data Set
S2=0.28 Data Set
S3=0.35 Data Set
S4=0.39 Data Set
S5=0.40 Data Set
Figure 5.8

Velocity Peak Values vs Probe Scanning Height

$y = 0.1e^{0.8913x}$

$S1 = 0.235$

$S5 = 0.40$

Expon. ($S1 = 0.235$)

Linear ($S5 = 0.40$)
Figure 5.9

Velocity Peak Values vs Probe Scanning Height

\[ y = 0.0439e^{0.7082x} \]  
\[ y = 0.0022e^{0.8494x} \]

\[ y = 0.2213e^{0.7017x} \]
\[ y = 0.008e^{0.6042x} \]

- S1 = 0.235
- S2 = 0.28
- S3 = 0.37
- S4 = 0.39
- S5 = 0.40

Exponential equations graphed with corresponding data points.
5.3 Velocity Components

This section deals with the data presented in Figures 5.10 – 5.24. Figures 5.10 - 5.14 are for the vertical velocity components, Figures 5.15 – 5.19 deal with the tangential velocity components, and Figures 5.20 – 5.24 display the layer averaged radial components.

5.3.1 Vertical Velocity Data Profiles

Figures 5.10 – 5.14 present the graphs of the vertical velocity vs radial distance for the swirl ratios of 0.235, 0.28, 0.37, 0.39, and 0.40. Each graph represent vertical velocity profiles determined for the heights of 2mm, 4mm, 6mm, 8mm, and 10mm for each of the five swirl ratios. The vertical velocity graphs are Lorentzian in shape, and shows the vertical velocity from the vortex center out to a radial distance of about 2cm, where the vertical velocities have become very small. Each increase in probe measurement height corresponded to an increase in the $w_{\text{max}}$ value, the increases corresponding identically with the previously presented increases in maximum total velocity values. This is because at the vortex center the vertical velocity component and total velocity are the same. There are other similarities between the vertical and total velocity data. Both show an increase in maximum values with an increase in swirl and shows a decrease in the profile width with height. They also show that the change in maximum values for any consecutive two levels generally decreases with height. A difference between the two however is that the profile width for the vertical velocity seems to change little with an increase in swirl, and may in fact be constant for any particular height regardless of swirl.

The vertical velocity data, while generally being in nested sets does sometime have some overlap in maximum profile values. With the profiles being Lorentzian, this means that entire profiles overlap such as in Figure 5.11 for the 4mm, 6mm, and 8mm data. Also Figures 5.13 and 5.14 do not show all five levels of sampling due to the previously mentioned reasons associated with the position of the VBD.
Figure 5.10

Vertical Velocity ($S=0.235$)

Radial Distance (cm)

Velocity (m/s)
Figure 5.11

Vertical Velocity (S=0.28)

Radial Distance (cm)

Vertical Velocity (m/s)

2mm 4mm 6mm 8mm 10mm
Figure 5.12
Figure 5.13

Vertical Velocity (S=0.39)

Radial Distance (cm)

Vertical Velocity (m/s)
Figure 5.14

Vertical Velocity (S=.40)

Radial Distance (cm)

Vertical Velocity (m/s)
5.3.2 Tangential Velocity Data Profiles

The tangential velocity data profiles presented in Figures 5.15 – 5.19 are for the levels of 2mm, 4mm, 6mm, 8mm, and 10mm for each of the five swirl ratios. The tangential velocity at the 2mm level for \( S = 0.235 \) (Figure 5.15) increases from \( z = 0 \) to some maximum value and then falls off gradually with increasing radial distance. As either the height or the swirl ratio increase the sharpness of the profiles increase. With each increase of height or swirl ratio there is a corresponding increase in the maximum tangential velocity. It should be noted that this is the case for the lowest layers of the vortex, and in each case at some higher level, depending on the degree of swirl, tangential velocities will no longer increase (as shown by Kosiba). From this data it cannot be determined if the core radius (the distance from the center of the vortex to \( v_{\text{max}} \)) increase or decreases with height, but the data does show that generally the core radius decreases with an increase in the swirl ratio.

The 10mm level is not included in Figure 5.18 and only the 2mm level is included in Figure 5.19. In both cases this is due to the previously mentioned issues with the VBD. It should be noted that the maximum tangential velocity for the entire set of data occurs at the 8mm level in Figure 5.18, which suggests an upper limit for the tangential velocity. Also in Figure 5.19 the average tangential profile for the 2mm level is very close to the tangential profile derived from the highest representative peak found in the total velocity data of Figure 5.6.
Figure 5.15: Tangential Velocity (S=0.235)
Figure 5.16
Figure 5.17

Tangential Velocity (S=0.37)

Radial Distance (cm)

Tangential Velocity (m/s)
Figure 5.18

Tangential Velocity (S=0.39)

Radial Distance (cm)

Tangential Velocity (m/s)

2mm | 4mm | 6mm | 8mm
Figure 5.19: Tangential Velocity (S=0.40) vs Radial Distance (cm) and Radial Velocity (m/s).

2mm for highest peak of S = 0.40.
5.3.3 **Layer-Averaged Radial Velocity Data Profiles**

Figures 5.20 – 5.24 are for the layer averaged radial velocity data profiles within each 2mm layer. Within the lowest (0-2mm) layer, since $u = 0$ at $z = 0$, the peak values of radial velocity ($u_{\text{max}}$) must be greater than the layer-averaged value.

Figures 5.20-5.22 show that the layer-averaged radial velocity increases with swirl and Figures 5.23 and 5.24 show the layer-averaged radial velocity decreasing with an increase in the swirl ratio.

The data shows conclusively that the greatest inflow of air occurs at the layer just above the surface, in the case of these data sets the 0-2mm layer. The 0-2mm layer in some cases has more inflow than the next closest layer (2-4mm) by an order of magnitude (Figure 5.22 for example).
Figure 5.20

Layer Averaged Radial Velocity ($S=0.235$)
Figure 5.21

Layer Averaged Radial Velocity (S=0.28)

Radial Distance (cm)

Radial Velocity (m/s)

0-2mm
2-4mm
4-6mm
6-8mm
8-10mm
Figure 5.22

Layer Averaged Radial Velocity (S=0.37)
Figure 5.23

Layer Averaged Radial Velocity (S=0.39)
Layer Averaged Radial Velocity ($S = 0.40$)

- 0-2mm
- 0-2mm (for highest peak of $S = 0.40$)

Figure 5.24
5.4 Ratio of $v_{\text{max}}/w_{\text{max}}$

Tables 5.2 and 5.3 present summaries of the maximum vertical and tangential velocities. Table 5.2 shows the $w_{\text{max}}$ increases with both height and swirl, and Table 5.3 gives peak values for the tangential velocity a functions of both swirl and height. In each case there is a general trend for the tangential velocity to increase with increases in height and swirl.

Tables 5.4 gives the ratio of \( \frac{v_{\text{max}}}{w_{\text{max}}} \) for each height and swirl combination.

Taking the average of all of these values gives \( \left( \frac{v_{\text{max}}}{w_{\text{max}}} \right)_{\text{average}} = 0.664 \), with a standard deviation of $\sigma = 0.053$.

<table>
<thead>
<tr>
<th></th>
<th>S = 0.235</th>
<th>S = 0.28</th>
<th>S = 0.37</th>
<th>S = 0.39</th>
<th>S = 0.40</th>
</tr>
</thead>
<tbody>
<tr>
<td>2mm</td>
<td>3.064</td>
<td>5.366</td>
<td>8.222</td>
<td>9.315</td>
<td>10.999</td>
</tr>
<tr>
<td>4mm</td>
<td>4.271</td>
<td>6.925</td>
<td>8.729</td>
<td>10.965</td>
<td></td>
</tr>
<tr>
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<td>4.913</td>
<td>7.002</td>
<td>9.410</td>
<td>10.989</td>
<td></td>
</tr>
<tr>
<td>8mm</td>
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<td>6.971</td>
<td>9.766</td>
<td>11.030</td>
<td></td>
</tr>
<tr>
<td>10mm</td>
<td>5.336</td>
<td>7.661</td>
<td>10.064</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2 Peak Vertical Velocities (m/s) 2-10mm and for S1-S5

<table>
<thead>
<tr>
<th></th>
<th>S = 0.235</th>
<th>S = 0.28</th>
<th>S = 0.37</th>
<th>S = 0.39</th>
<th>S = 0.40</th>
</tr>
</thead>
<tbody>
<tr>
<td>2mm</td>
<td>2.122</td>
<td>3.504</td>
<td>5.119</td>
<td>6.590</td>
<td>6.322</td>
</tr>
<tr>
<td>4mm</td>
<td>2.933</td>
<td>4.134</td>
<td>5.556</td>
<td>8.000</td>
<td></td>
</tr>
<tr>
<td>6mm</td>
<td>3.374</td>
<td>4.547</td>
<td>5.870</td>
<td>7.848</td>
<td></td>
</tr>
<tr>
<td>8mm</td>
<td>3.617</td>
<td>4.744</td>
<td>6.809</td>
<td>7.826</td>
<td></td>
</tr>
<tr>
<td>10mm</td>
<td>3.878</td>
<td>5.394</td>
<td>6.929</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.3 Peak Tangential Velocities (m/s) 2-10mm and for S1-S5
The core radius (the radius at which the tangential velocity becomes maximum) generally decreases with the increase of the swirl ratio. The exception to that in the data occurs for the core radius of 0.56cm corresponding to 4mm with a swirl ratio of S = 0.28. This is most likely an anomaly in the data. It is difficult to detect a systematic trend in the core radius as a function of height within the 0-10mm layer. This could be attributed to the relative flatness of the tangential velocity profiles around the peak values, combined with experimental uncertainty.

Table 5.5 Core Radii
### Table 5.6 Average Core Radii

<table>
<thead>
<tr>
<th>Swirl</th>
<th>Average Core Radius</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.235</td>
<td>0.546</td>
<td>0.104</td>
</tr>
<tr>
<td>0.28</td>
<td>0.474</td>
<td>0.057</td>
</tr>
<tr>
<td>0.37</td>
<td>0.395</td>
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<tr>
<td>0.39</td>
<td>0.326</td>
<td>0.024</td>
</tr>
<tr>
<td>0.40</td>
<td>0.196</td>
<td></td>
</tr>
</tbody>
</table>

**Chapter 6 Discussion of Results and Suggestions for Future Research**

### 6.1 Research Objectives and Past Work on Tornado-Like Vortices

The research presented has focused primarily on the lowest region of the tornado vortex (0 – 10mm) in the TVC at Miami University. This is the region corresponding to the flow structure of an actual tornado at close to ground level. This region has been looked at by past researchers, but not in as much detail as here. Baker concentrated on the lowest 15mm of tornado-like vortices, but only for a single swirl ratio. (Baker’s data collection method was far more labor intensive which hindered the scope of his work.) Kosiba acquired data for a much larger range of levels, and Beer analyzed the data, but the resolution close to the ground was not as great as in this research.

### 6.2 Summary of Results

**Total Velocity Data:** The total velocity is dependent on height and swirl ratio, and will increase with an increase of height or swirl ratio. The velocity profile width will increase with an increase in height for at least 0 -50mm above the floor. The total velocity profile width will decrease with increasing swirl. The higher the swirl ratio the lower the vortex breakdown region will occur.

**Curve fits for $w_{\text{max}}$:** The relationship between the maximum (on-axis) vertical velocity ($w_{\text{max}}$) and height ($z$) above the floor has been presented in two ways: $w_{\text{max}}$ vs $z$ and $z$ vs $w_{\text{max}}$. In both cases a logarithmic function fits the data within the limits of error. The data could then be represented by the functions
\[ w_{\text{max}} = 1.09 \ln \left( \frac{z}{z_0} \right) \text{ or } z = Ae^{Bw_{\text{max}}} \]

where \( z_0 \) or \( A \) and \( B \) are constants that depend on the swirl ratio \( S \). In Figures 5.7 and 5.9 there can be no curve fit listed for the single 2mm \( S = 0.40 \) data point, a reasonable curve fit for this point that is consistent with the other data in this set would be 
\[
z = 0.002e^{6.28w_{\text{max}}}.
\]

**Velocity Components:**

**Vertical Velocity Data Profiles:** Both increases in height or swirl ratio cause an increase in maximum values of the vertical velocity. As the swirl ratio increases the profile width decreases, while the profile width changes little depending on the height above the floor.

**Tangential Velocity Profiles:** Tangential velocity maxima increase with increases of both height or swirl ratio. The data is inconclusive about how the core radius changes with height, but the core radius does decrease as the swirl ratio increases.

**Layer-Averaged Radial Velocity Profiles:** The layer-averaged radial velocities are greatest in the 0-2mm layer for all swirl ratios. This directly implies that the greatest radial inflow occurs in the 0-2mm layer. In Figure 5.20 – 5.22 the radial velocity increases with swirl in the 0-2mm layer, and in Figures 5.23 and 5.24, (the highest swirl cases) the layer-average velocity is somewhat reduced. There are a number of explanations for this result. One explanation is that the layer-average is not close to the maximum radial velocity, and is thus giving a poor representation of the actual air flow of a tornado-like vortex. Another possibility is that the radial velocity begins to decrease in magnitude for swirls above the \( S = 0.28 \). Since the greatest fluctuations in the flow and the greatest uncertainties in the flow measurements occur at highest swirls, another possibility is that the data at these highest swirls is not of sufficient quality to enable a definitive conclusion on this trend in the radial velocity results.
Comparison with Beer’s Findings: Beer’s study found that vertical velocity increases with swirl. The findings of this project concur with this result. Both studies also found an increase in vertical velocity with height for the lowest levels. The vertical velocity was also found to be greater in magnitude than either the tangential or radial velocities at a particular height or swirl.

Both Beer’s study and this study determined that the tangential velocity increases with increasing swirl, and also that increases with increasing height in the lower levels of the chamber, keeping in mind that this study focused primarily on the lowest 10mm. Another point of agreement is that the maximum tangential velocity components while always lower in magnitude than the maximum vertical velocity is higher than the layer averaged radial velocity. However, since the maximum radial velocity, which is located within the 0-2mm layer, must be larger than the layer-averaged value, the maximum radial components must be of similar magnitudes to the maximum tangential velocity components.

Beer concluded that the maximum radial velocity will always occur in the lowest layers, but given the unequal thickness of the layer that he was dealing with, a direct comparison of the average radial velocities in adjacent layers could not be made. In the present study, with layers of equal thickness, this could be done, and for the most part, each successive higher layer shows a decrease in the radial inflow as compared with the layers immediately below it.

The core radius was also found to decrease with an increase in swirl for both studies, or that the width of the vortex at any given height seems to decrease with increasing swirl. This is also consistent with visual observations of the smoke filled core.

Ratios of $v_{\text{max}}/w_{\text{max}}$: The average value for the ratio of \( \frac{v_{\text{max}}}{w_{\text{max}}} \) average = 0.664 with a standard deviation of $\sigma = .053$. These values in Table 5.3 are close to those found by Baker. The average of the ratio for Baker’s values are \( \frac{v_{\text{max}}}{w_{\text{max}}} \) average = 0.543 with $\sigma = 0.032$. In some respects Baker’s ratio may be more accurate than the one found in this research. Baker’s research approach was much more laborious than that of the research
approach employed for this project, and he measured the vertical and tangential velocity components directly, without assuming a profile for the vertical velocity. This significantly reduced the amount of analysis Baker was capable of doing, but gave him better accuracy in his results. The approach for this project gave a greater quantity of data, but at the expense of accuracy.

**Core Radius Data:** Core radius decreases with an increase in the swirl ratio. It appears that the scanning levels are to close together and tangential velocity profiles too flat to determine a systematic trend for the core radius variation with height in the 0-10mm layer.

### 6.3 Uncertainties in Data Collection

Tornado vortex research for the lowest layers has appreciable error associated with the measurement. Close to the chamber floor the flow is unsteady and unpredictable. The vortex moves about the chamber floor in all directions, and the vortex breakdown region is not at a constant level for the higher swirls for any substantial amount of time, i.e. there is fluctuation in the vortex strength. Errors are random and systematic. Random error was addressed through the selection and averaging of representative profiles. Here standard deviations were in the range of 3-10% of the average values. Standard deviations were sufficiently small to enable some systematic trends to be found in the results. Sensor calibration errors and dimensional errors were small. However, overall uncertainties in the absolute values of the derived quantities may be high due to the assumed vertical velocity profile. This assumption is certainly true close to the core, but may not be true as the radial distance from the center increases. The accuracy of this research entirely hinges upon this assumption being true. Overall it is estimated that in the lower swirl cases uncertainties in the derived values are typically 5-10% and in the high swirl cases are typically 15-20%. In some cases these errors are large enough to prevent definitive conclusions from being made.

### 6.4 Suggestion for Future Work

The most important region of study of tornadoes vortices is the region most closely corresponding to ground level for an actual tornado. The lowest sampling level,
being 2mm when the chamber depth is 280mm, corresponds to the height of buildings and trees under a severe thunderstorm. The spatial interval of 2mm is still not adequate to determine all aspects of the flow. This interval is pushing the limits of the chamber, and perhaps even in some cases exceeding the limits of the chamber. An issue is the small size of the vortex core in relation to the chamber size, i.e. the one-cell core radius is on the order of 1% of the updraft radius. Greater spatial resolution is required in order to explore every detail of vortex flows, which would require construction of a much larger experimental chamber, not merely doubling the size but contemplating a size 5-10 times as large. This however would be very expensive to implement.

Tornado vortex chambers in the future need to be much larger in size than current chambers (something on the order of the Astrodome would be ideal). Also the types of measurement devices could stand an upgrade. A smaller version of the Doppler radar employed in studying larger tornadoes would be a great benefit, and this would finally eliminate the question of whether or not the sensor interfered with the vortex flow.

In studying tornado-like vortices the primary variables that affect vortex structure and strength are flow rate, swirl ratio, and ground roughness. The primary quantities to be determined are the velocity components in three-dimensional spaces as a function of these variables, as well as turbulence intensity static pressure and representations of the vortex structure through flow visualization. All of these have been attempted in the past using small chambers. The main focus of future research is not so much finding new things to measure, but to continue to pursue the same types of measurements with greater accuracy and resolution.
Bibliography


