

LABORATORY MEASUREMENTS OF VELOCITY PROFILES IN SIMULATED TORNADO-LIKE VORTICES

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 received January 10, 2001

ABSTRACT

Axial vertical velocity measurements of simulated super-critical tornado-like vortices were made in the Miami University Tornado Vortex Chamber (TVC). Improvements to the Miami TVC tornado generation mechanisms and data acquisition methods aided in the attainment of data with spatial resolution never before achieved in the study of simulated vortices. Axial vertical velocity measurements are presented as a function of super-critical vortex height for varying swirl ratio, and are referred to as velocity profiles. The data suggest a strong correlation between super-critical inner core region diameter and swirl ratio, as well as an apparent breakdown of super-critical structure well below vortex breakdown (vortex bubbling).

INTRODUCTION

In the last twenty-five years, several research teams and individuals have had notable success in simulating tornado-like vortex flows in the laboratory¹. Figure 1 shows a photo of a simulated vortex in the Miami Tornado Vortex Chamber (TVC). The laboratory environment provides a degree of experimental precision, control and repeatability for making measurements on vortices that is nearly impossible in nature. The atmospheric factors that are involved in creating an actual tornado in a thunderstorm environment (dynamic, thermodynamic and micro-physical) are usually simplified or omitted in a laboratory simulation. Despite this, the utilization of laboratory generated vortices is a powerful tool in understanding the dynamics of a tornado.

Obtaining accurate data for vertical velocities along the height of a tornado's rotational axis, the axial vertical

velocity, has had a history of eluding interested researchers, both in and out of the laboratory. Methods have been proposed to measure pressure deficits in actual tornado core regions. However, none of these ideas have been realized nor have met with success. Scientists in the

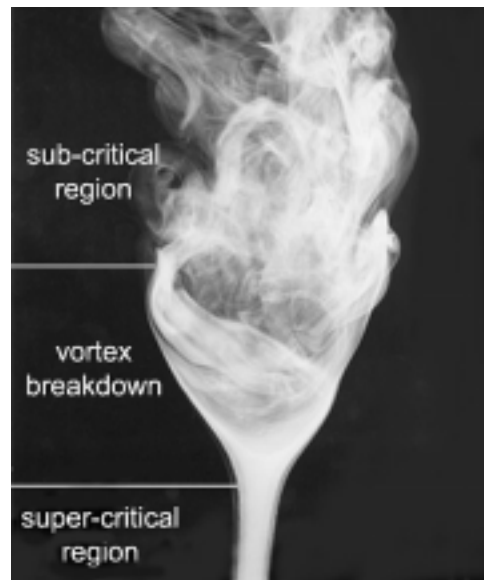


Figure 1

Photograph of a simulated vortex in the Miami TVC. Tornado-like vortices display three distinct dynamic regions: a tightly structured super-critical region; the vortex breakdown bubble; the turbulent sub-critical region.

David graduated in December 2000 with a degree in engineering. His research began in the fall of his junior year, and culminated with an Undergraduate Summer Scholars grant in the summer of 2000. David currently works as an electrical engineer in Chicago, IL, and plans to attend graduate school in applied physics in the fall of 2002. He spends most of his free time playing music or designing high fidelity audio systems.

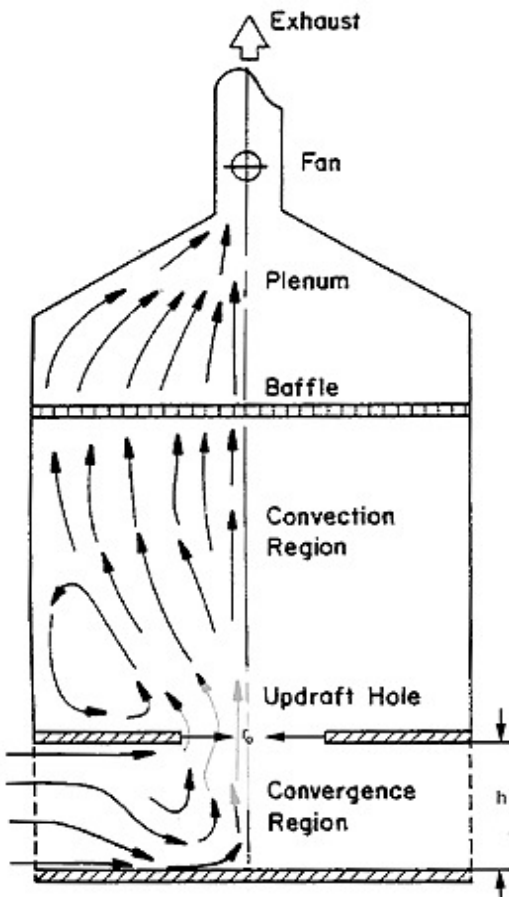


Figure 2

Schematic layout of a Ward type Tornado Vortex Chamber (TVC). The arrows mark the direction of the air flow.

laboratory have made notable progress, but the instrumentation used to probe the vortex axis was often obtrusive, and/or offered poor spatial resolution.

Due to the significant down scaling in vortex size necessary in laboratory modeling, most simulated vortex research provide highly general results, analyzing large flow fields rather than internal core dynamics. Improving the spatial resolution of airflow measurements to uncover the complex inner structure of a tornado is the driving force behind the research at the Miami TVC. Since velocity gradients in the core region are large over very small length scales, and the axis of a vortex does not maintain a completely static position with respect to the ground, the core structure is experimentally elusive.

MIAMI TVC AND RECENT IMPROVEMENTS

The best apparatus² for modeling tornadoes in a laboratory was the TVC designed by N.B. Ward.³ Ward type TVCs have been constructed at Purdue University, University of Oklahoma, Kyoto University and Miami University. The basic concept of the TVC is to provide

initial vorticity and subsequent circulation to a radial inflow that converge and ascend due to an exhaust fan mounted on top of the chamber. A cylindrical baffle is placed above the convection region to straighten and scale the size of the vortex. Figure 2 shows a cross-sectional view of a Ward type TVC. A more complete discussion of Ward type TVCs and their variants can be found elsewhere.¹

The first Ward type chambers used rotating mesh screens to provide the initial vorticity and circulation. In later chambers, the screens were replaced by arrays of steel vanes of specific chord and curvature that guided the radial inflow into a circulatory pattern. The vane method was very successful, and has since been the standard in TVC design. An important quantity in the Ward type TVC is the swirl ratio, S : the ratio of the tangential velocity, v_t , at the edge of the updraft radius to the mean vertical velocity through the updraft hole, w_o . In TVCs that uses vanes, S is defined as:

$$S = \frac{\tan(\theta)}{2a}, \quad (1)$$

where θ is the angle of inflow with respect to the radial and a is the aspect ratio defined as:

$$a = \frac{h}{r_o}, \quad (2)$$

where h is the inflow depth and r_o is the updraft radius. The swirl ratio dictates much of the vortex dynamics and morphology, and thus is usually varied often in simulated tornado research.

To change swirl ratios in a TVC using vanes, the metal plates have to be added or removed according to chord and curvature. This becomes a tedious process, and gives the researcher relatively limited control over swirl. A system of fans, as shown in Figure 3, feeding into vane-guided discharge columns installed in regular intervals around the perimeter of convergence region in the Miami TVC has

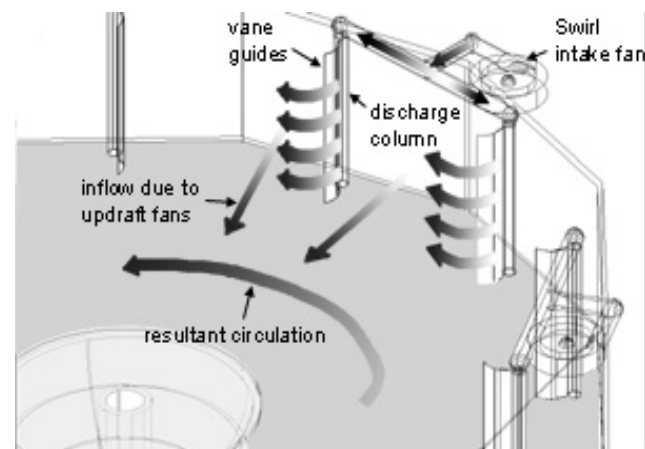


Figure 3

Overhead view of the discharge/vane-guide system. The shaded region is the chamber floor. The arrows mark the direction of the flow of the air.

improved the control over swirl. An array of six fans provide air flow to twelve discharge columns whose four-inch-chord vane-guides smooth the convergence of radial flow caused by the exhaust fans and the tangential flow of the discharge columns.

For most experiments conducted in a TVC, a vortex with static axial position is ideal. The vane-guide configuration provides less vortex wander (the random motions of the axial position of the vortex about the chamber floor due to turbulence in the convergence region) than the discharge columns alone. The fan/discharge column system does not seem to compromise any vortex position stability when compared to previous vane configurations. Using the discharge column system, the swirl in the Miami TVC can be changed by manipulating the output of a regulated power source wired in parallel with the system fan array. The swirl is then given by a combination of Equation 1, the swirl due to the vanes, and the swirl created by the discharge columns.

The height of vortex breakdown (VBD) and swirl are related. As the swirl is increased, the VBD descends to the chamber floor. This relationship is direct and fairly linear, so the swirl created by the new vane-guided discharge column system could be calibrated by comparing VBD heights in previous data sets with VBD heights in the modified chamber.^{4,5}

In addition to the physical improvements to the TVC, an entirely new data acquisition system was installed. Hot-film probes in conjunction with a constant-temperature anemometer have been the most accurate and affordable way to probe the flow velocities in a simulated vortex. These small, unobtrusive probes could capture a quasi-instantaneous “snapshot” of axial or tangential flow velocities by sweeping through the vortex core.⁵

Highly crucial to the validity of these snapshots is how many times per second the output of the anemometer is sampled. Since the dimensions of the vortices studied are so small, the distance the probe travels between samples must be significantly smaller to provide accurate spatial resolution. To do this, either the sampling rate must increase, or the speed at which the probe sweeps must decrease. Since decreasing the probe sweep speed would reduce the chance of a clean swipe through the core region due to vortex wander, a system that would greatly increase the sampling rate was installed.

A high speed data acquisition board⁶ was installed to take data from the constant temperature anemometer and transfer it to a personal computer via software written in LabVIEW™ specialized for the Miami TVC. This setup allowed sampling rates of over 2000 per second to be achieved, exceeding the sampling rates used in earlier hot film work by several orders of magnitude. All data reported in this research were obtained at a sampling speed of 1000 samples per second, providing spatial resolution of

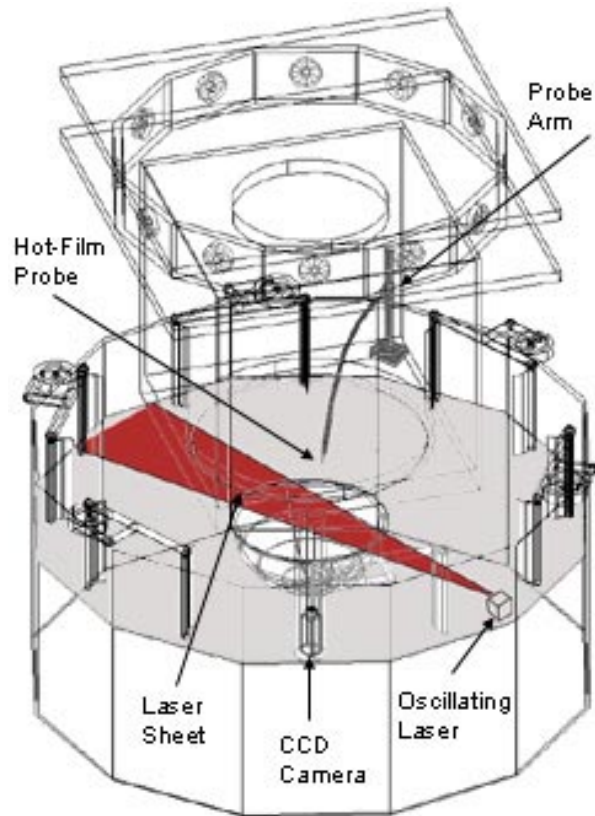


Figure 4

Overhead diagram of the vortex probing system in the Miami TVC. The light gray area is the chamber floor. The laser sheet is shown in a darker gray.

about 125 samples per centimeter.

EXPERIMENTAL PROCEDURE

The velocity measurements made by hot-film probe/constant temperature anemometer systems in this study were preceded by an extensive calibration process of all apparatus used to ensure an unprecedented level of accuracy. Each probe used was calibrated in a low flow wind tunnel in which stable flow velocities could be produced by applying a range of voltages to the tunnel fan motor. Tunnel flow velocity as a function of applied fan motor voltage was calibrated previously^{5,7} However significant renovation of the wind tunnel was undertaken in preparation for this research, so recalibration was necessary.

The most accurate way to calibrate the low flow tunnel was to insert a Pitot-static tube into the mid-tunnel flow measure a differential pressure between atmospheric pressure and the pressure deficit created by the flow through the tunnel. The pressure difference was converted to a proportional voltage using a wet-wet differential pressure transducer, which in turn was calibrated with a micromanometer.⁸ The differential pressure Δp , was converted to a velocity, v , using an expression derived

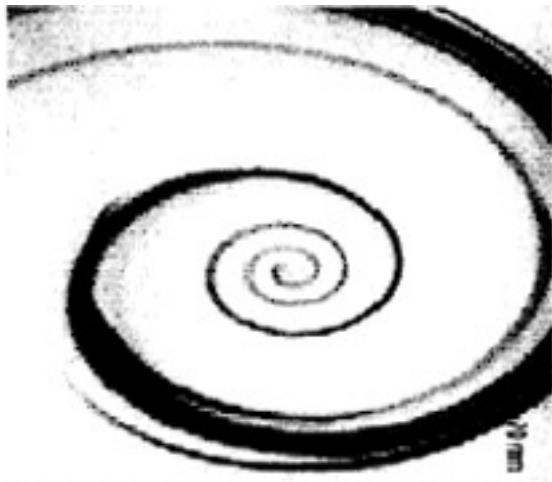


Figure 5

Digital display frame from CCD camera mounted in the TVC's crawl space. A laser sheet is created to illuminate smoke within the chamber and create a white to black contrast ratio. Colors in this picture have been inverted (black regions contain smoke).

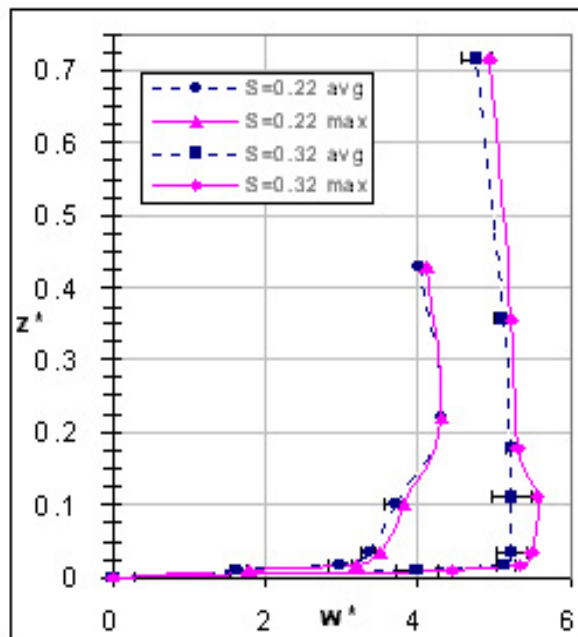
from Bernoulli's equation:

$$\Delta p = \frac{1}{2} \rho v^2, \tag{3}$$

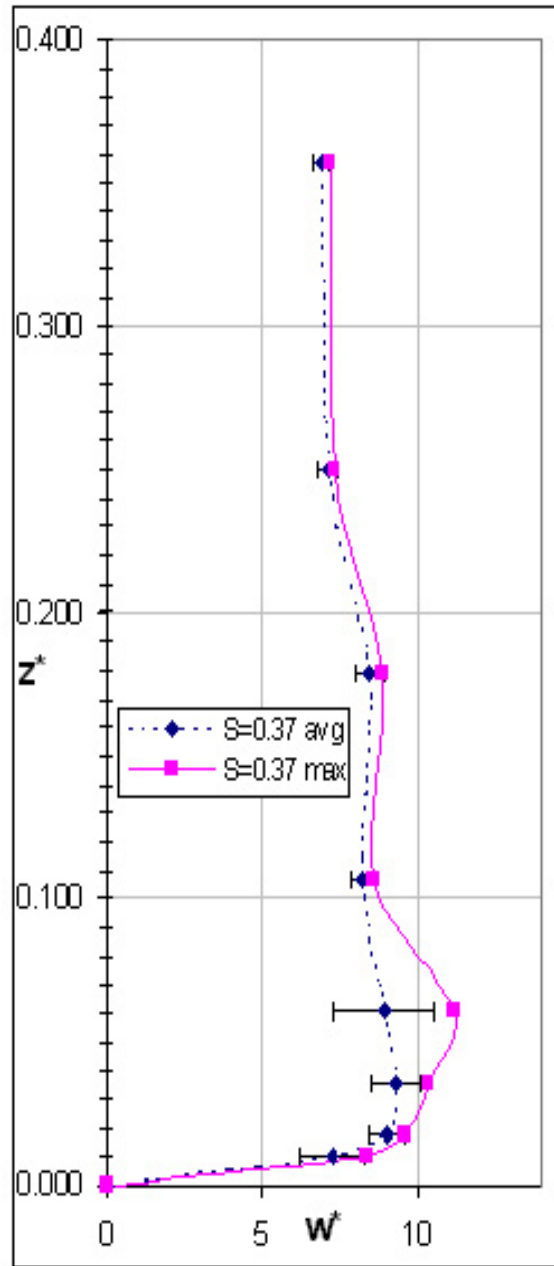
where ρ is the density of air.

Of the four principle TVC parameters (swirl ratio, volume flow rate, probe height, and updraft hole radius), only swirl ratio and probe height were varied during the course

of this research. The updraft hole radius was fixed at 0.255 meters and the volume flow rate through the hole was set at $0.386 \text{ m}^3\text{s}^{-1}$. A larger updraft radius has the advantage of creating a larger vortex cores. However, the smaller updraft hole has the benefit of reducing vortex wander. Calibration of the hot film probes showed large error bars at low wind speeds (below 1 m/s), so the volume flow rate in the TVC was selected so the average velocity through the updraft hole was about 2 m/s. This assured all wind speeds measured would be within the most accurate



(a)



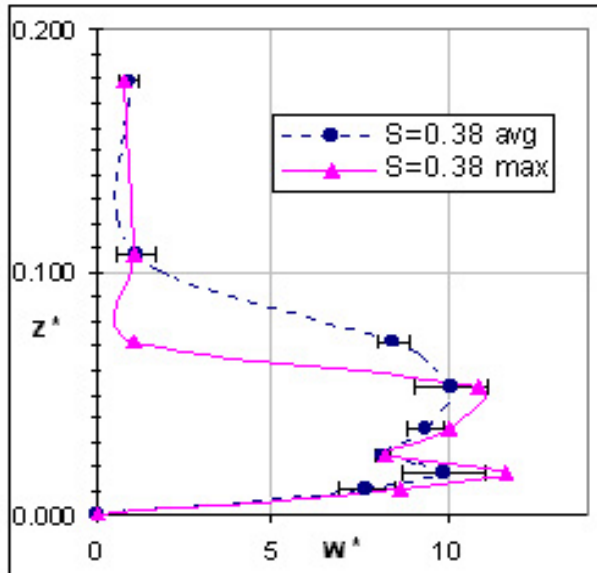
(b)

Figure 6

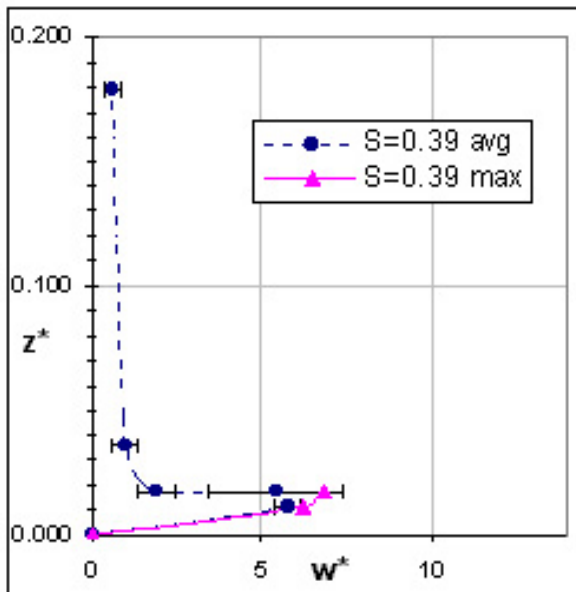
Axial vertical velocity profile of vortices created with swirl ratio of: (a) $S=0.22$ and $S=0.32$. (b) $S=0.37$. The diamond shaped points are average values and the triangular points are maximum values

region of probe calibration.

The hot film probe was attached to a variable height, rotating mounting arm shown in Figure 4. The rotating mechanism was attached above the updraft radius. The mounting arm descends at a 45-degree angle into the convergence region, sweeping out a 15 cm arc through the vertical axis of the chamber. If the axial position of the vortex with respect to the chamber floor does not change, the 15 cm arc would always intersect the core region,



(c)



(d)

Figure 6

Axial vertical velocity profile of vortices created with swirl ratio of (c) $S=0.38$ and (d) $= 0.39$. The diamond shaped points are average values and the triangular points are maximum values

requiring only one sweep of the probe arm to obtain a vertical velocity snapshot. However, due to vortex wander, many sweeps are usually necessary to obtain just a few accurate vertical velocity snapshots.

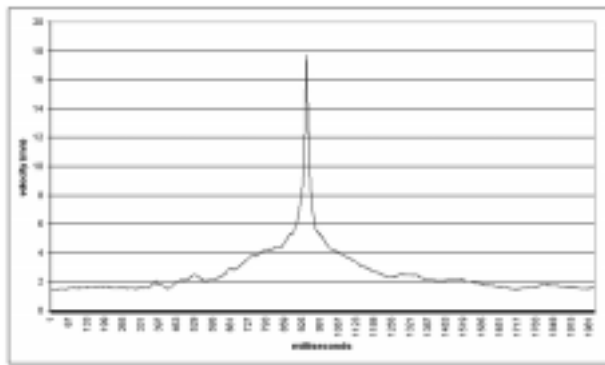
To determine which of the sweeps actually trace the hot-film probe across a diameter of the vortex core, a digital video system was installed to monitor the axial motion of the vortex. A CCD camera mounted in the crawl space beneath the TVC floor can be focused on variable heights along the axis of the convection region through a glass aperture. For visualization purposes, smoke is introduced through the chamber floor. A small diode laser apparatus mounted near the perimeter of the convergence region can be aimed at different heights across the center of the TVC floor. The laser beam apparatus oscillates the horizontal position of the laser beam parallel to the chamber floor at roughly 60 Hz creating the effect of a “laser sheet” (see Figure 4). This thin illuminated surface highlights the smoke particles in a cross-section of the vortex core, providing a nearly white to black contrast ratio between the vortex and background, maximizing the effectiveness of video analysis. Figure 5 is an example of the video analysis. By adjusting the laser sheet to shine across the same cross-sectional plane as the probe is sweeping, visual confirmation of the path of the probe through the vortex core can be obtained.

All data taken during this research is catalogued with digital video recordings of the vortex-probe interaction. This enables each data set to be reviewed on digital slow motion and frame-by-frame video, to determine if the probe actually did make a clean sweep through the core region. In a given data acquisition run of fifteen core sweeps, only two to four sweeps were reliable data.

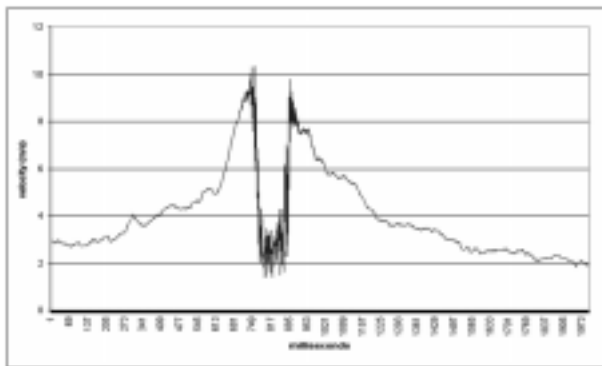
This data acquisition process was repeated at different probe heights for super-critical vortex flows of varying swirl ratios. For each probe height at each swirl ratio, roughly 100 sweeps through the core region were attempted and analyzed. This experimental procedure, coupled with the increased acquisition rates, allow the data from this research to be presented with a level of confidence that has not been matched in the field of simulated vortex study.

RESULTS AND DISCUSSION

Axial vertical velocity profiles of vortices created at five different swirl ratios, 0.22, 0.32, 0.37, 0.38 and 0.39 were acquired. The results, shown in Figure 6, are presented as both average (dotted line), and maximum (solid line) non-dimensional height, z^* , versus non-dimensional axial vertical velocity, w^* . Error bars represent the standard deviation of the average non-dimensional velocity at a particular height. The non-dimensionalized height is calculated by dividing the probe height by the inflow depth, and dividing the resulting velocities by the average velocity through the updraft hole. Data in this form lend themselves to easy comparison to data taken in other



(a)



(b)

Figure 7

Example of an axial vertical velocity snapshot in (a) the super-critical region and (b) in vortex breakdown or vortex bubbling

TVCs with different physical geometries and updraft flow rates.

The super-critical region of the vortex was probed up to the height of vortex breakdown (VBD). This breakdown is a transition from a relatively smooth super-critical flow to a highly turbulent, sub-critical flow. Velocity measurements above the VBD are highly erratic and do not lend themselves to all but the most general modeling. In Figure 6(d), the steep decline of vertical velocity along the vortex axis is a signature of vortex breakdown. The maximum vertical velocities diverge from the vortex axis and trace around the surface of a bubble of nearly stagnant air. A more complete discussion of VBD structure can be found elsewhere.¹

Axial vertical velocity snapshots taken in the vortex core appear in Figure 7. The sampling frequency of data acquisition was fixed at 1 kHz, so the core velocity could be measured once every millisecond. If the velocity of the probe arm remained constant, each sample would represent about 1 mm across the probe sweep path. Unfortunately, the probe arm travel velocity is not completely predictable. Useful spatial approximations can be made by converting the sample period to a distance. But for this research, it is more accurate to plot axial vertical velocity versus time in milliseconds as displayed in Figure 7.

The hot-film probes used are not directionally sensitive, so with the current data acquisition apparatus, the ascending walls of the spikes cannot be resolved into vertical and tangential velocity components. The maximum value of these spikes, however, represents a region of the central vortex core that is known to possess a one-dimensional vertical flow along the vortex axis. Due to the inability to resolve velocity components, interpolations of inner core radii could not be attempted with confidence. The spike width was notably less than the spike widths of data taken at the Miami TVC with smaller data sampling rates, implying greater spatial resolution.

The sharp peak seen in Figure 7(a) is characteristic of the super-critical flow. The column of rapidly ascending air is surrounded by a more slowly ascending rotating “pipe.” This structure is lost during vortex breakdown, and the flow creates a double peak signature (see Figure 7(b)) with a turbulent trough between the two velocity maximums. The height of the VBD remains somewhat constant for given TVC flow and geometry arrangements and can be visually recognized through the viewing window in the TVC.

During data collection of the $S = 0.22$ and $S = 0.32$ vortices, the VBD was visually confirmed as being more than 1 meter and 0.5 meters off the chamber floor respectively, yet at low probe heights the hot-film would pick up a velocity signature that resembled that of VBD. Upon closer video analysis, it was found that the super-critical region occasionally underwent a structure breakdown, or super-critical bubbling, that would propagate up the super-critical region. This bubble would ultimately “burst” once it approached the VBD, and often significantly altered the height of the larger breakdown. The $S = 0.22$ and $S = 0.32$ data sets showed no evidence of vortex bubbling under an axial height of 20 mm, which suggests that the super-critical region near the surface is more stable than the region near the VBD.

In addition to the apparent structural instability in the upper super-critical region, there was an apparent instability in axial vertical velocities in the super-critical region of high swirl vortices. The low swirl flows ($S = 0.22$ and $S = 0.32$), had very well behaved vertical velocity profiles, so much so that they could nearly be represented by an exponential or even piece-wise linear function. As the swirl was increased, the vortices’ vertical axial velocities began to be less consistent at any given height. As seen in Figure 6(d), the velocity profiles begin to develop bulges near the surface and large uncertainty. The standard deviation of velocities in the core region increases markedly with increasing swirl ratio. Upon close examination of the peaks recorded at higher swirl ratios, it was realized that the physical dimensions of the inner core region were shrinking with increased swirl.

The velocities in the steep peak regions of high swirl

vortices varied by nearly a meter per second between points, implying that the actual inner core diameter was comparable to the diameter of a human hair, less than 1/125 of a centimeter. The average standard deviations of axial vertical velocities rose sharply with swirl because the inner core became increasingly more difficult to probe due to its minute size.

SUMMARY AND SUGGESTIONS FOR FURTHER RESEARCH

The precision and accuracy of the data produced in this research is probably the best that can be achieved with the hot-film/constant temperature anemometer system at the given sampling rate. Although the physical dimensions of these probes are very small, the inner core region proved to be several orders of magnitude smaller in high swirl vortices. In fact, the data obtained show that the diameter of the inner core region contracts drastically as the swirl ratio increases. Data acquisition methods that enable constant monitoring of the vortex core, such as an improved version of laser Doppler velocimetry⁹ would enhance spatial resolution. When compared to hot film sensors, laser systems are expensive, complex and, on this scale of measurement, have a relatively large sampling volume. Using higher sampling rates in a hot-film anemometer system may also provide the resolution necessary to capture peak axial vertical velocity values of high swirl super-critical vortices. The Miami TVC computer acquisition system is currently set up to take data at up to 20,000 samples per second. This research suggests that further study with film sensors in comparable sized vortices employing sampling frequencies of 2000 samples per second and above should be done. Sacrificing vortex stability by using a larger updraft hole would increase the size of the vortex core and could improve the spatial resolution.

In tornados, axial vertical velocity, in principle is the most straight forward measurement because of its one-dimensional nature. This is not the case even a fraction of a millimeter off the axis of the vortex, where the tangential component of the velocity rapidly becomes significant. For off-axis measurements, more than one sensor used simultaneously is needed to resolve vertical and tangential velocity components. A new probe arm that accommodates two mutually perpendicular hot film sensors is needed to resolve the two components of velocity. Such device would reveal much more about the core dynamics and structure as well as a more accurate determination of the core radius.

ACKNOWLEDGMENTS

The author would like to thank the Miami University OAST and the Undergraduate Summer Scholars Program for providing grant support. He acknowledges Dr. Christopher Church for providing all the apparatus and overseeing the research. Dr. Michael Pechan and Lynn Johnson provided technical expertise in implementing the data acquisition system. He acknowledges the collaboration of Karen Kosiba in the calibration process, the data acquisition and analysis.

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