15.1 A TRANSLATING TORNADO SIMULATOR FOR ENGINEERING TESTS: COMPARISON OF RADAR, NUMERICAL MODEL, AND SIMULATOR WINDS

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1. INTRODUCTION

A simulator has been designed at Iowa State University that produces the largest translating tornado in the country (with respect to a ground plane) for wind tunnel model testing of the interaction of tornado-like vortices with the built environment. The simulator also has an option that allows it to produce a microburst.

Simulating tornados in laboratory environments is not a new concept. Many laboratory simulator designs have been based on the pioneering work of Ward (1972) and were built for meteorological purposes to understand the parameters influencing tornado formation. The Ward simulator essentially consisted of a fan providing an updraft at the top of a cylinder above a test area and guide vanes and rotating screens around the test area to provide angular momentum to converging flow. Subsequent efforts—based on the Ward model —at Purdue University (Church et al., 1977, 1979), the University of Oklahoma (Leslie, 1977; Jischke & Light, 1983; Diamond and Wilkins, 1984) and that of Davies-Jones (1976) employed various means to improve the similarity between laboratory simulations and full-scale tornado events. Ted Fujita had his own version of a laboratory simulator with rotating cups inside a duct at the top. Some efforts have already been made to place building and structure models in tornado simulators to quantify tornado loads. The design of many simulators makes such efforts difficult—for example, some simulators have holes in the ground plane right where a building model would need to be. In spite of this, Chang (1971), and Jischke & Light (1983), among others, modified the basic Ward design and added a small building model with pressure taps. These efforts found mean surface pressures to be significantly higher (3-5 times in swirling, tornado-like vortices than in straight-line boundary layer flows. This suggests that when estimating tornado-induced wind loads on structures, it is not sufficient to use a conventional wind tunnel running with tornado wind velocities. It is for this reason that the new translating tornado simulator was developed at ISU. In the following report, the design of the simulator will be discussed, along with some comparisons of measurements taken in the simulator with radar observations and numerical modeling results.

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2. DESIGN OF SIMULATOR

Planning for a moving tornado simulator began in 1997, and five different design concepts were tested between 2001 and 2003. The final prototype design is based loosely on observations during the VORTEX project that suggested a rear-flank-downdraft (RFD) nearly encircles the region of low-level enhanced vorticity around the time of tornadogenesis at the surface. This idea of how many tornadoes might form in the atmosphere provided a framework that would allow a translating tornado to be created in the laboratory. Figure 1 shows the simulator in action, with dry ice being supplied to visualize the vortex. Figure 2 is a schematic depicting the structure and dimensions of the simulator when used to produce either a tornado or a microburst. A circular duct 18 feet in diameter and 11 feet high is suspended from a 5 ton track crane so that it can move along a 34 foot ground plane. Within this 1 foot wide duct, a downdraft is simulated and some vorticity is imparted to this flow through the use of vanes at th e top. This downdraft diverges upon hitting the ground, and a sizeable portion of the flow moves inward beneath a large fan (maximum flow rate of 125,000 cfm) that acts as an updraft. The vorticity present in the low-level inflow is stretched beneath the updraft, forming a tornado that travels along the ground plane as the entire fan/downdraft-producing mechanism translates. This design permits a maximum tornado diameter of 4 ft., with a maximum tangential velocity with the 4 ft diameter core being 60 miles per hour. The maximum swirl ratio achievable is 1.0, and the translation speed of the vortex can reach up to 2 ft/sec. The vortex height can vary from 4 to 8 feet by adjusting the ground plane upward or downward. In the path of the vortex, models of structures scaled to 1/150 and 1/300 are placed so that measurements can be made of the pressures/loads on them.

Figure 1: Tornado simulator with vortex highlighted through the use of dry ice.

3. RADAR OBSERVATIONS OF NEAR-GROUND WINDS

To validate the reasonableness of the simulated winds within the vortex, observations from the Spencer South Dakota tornado of May 30, 1998 were used. These observations were collected by the Doppler on Wheels radars and some discussion of this particular tornado can be found in Wurman (2002). Radar observations were input into an axisymmetric model constrained by the radar data to eliminate some higher wavenumber perturbations such as multiple vortices. The radar constrained model incorporates the tornado wind field components of axisymmetric rotation and translation. The model domain covered a 2 km by 2 km area with 10 m horizontal grid spacing. The swirl ratio was believed to be relatively low (.5 or so) at the time these observations were made and was primarily a single-cell vortex. In addition to these data, a least squares minimization of the Doppler velocity observations was applied to estimate the azimuthally averaged (axisymmetric) radial and tangential wind speed components in 40 m wide annuli at successive 20 m intervals moving out from the tornado center. These estimates are tornado-relative and do not include the translation speed. Figure 3 shows the average tangential velocity as a function of radius for several height levels above ground. Note that the winds at the lowest elevation (20 m) are the strongest anywhere within the lowest kilometer. In addition, the radius of maximum winds is smaller at the lowest two heights (around 100 m) and then becomes wider (200 m) and relatively constant with height above roughly 70 m. The radial component of the flow is shown in Figure 4. The radial flow tends to be strongest relatively far from the center of the vortex, in the .5-1 km band. The radial inflow is strongest at the lowest elevation no matter what radial distance at which the observation is taken.

4. NUMERICAL SIMULATIONS

Because radar observations are unable to be made within the lowest 20-50 meters of the ground due to beam angle and obstructions, a CFD model was used to get an idea of wind in the lowest levels of the troposphere. For this purpose, Fluent was used. Tests were primarily made using a domain that represented the controlled laboratory simulator. However, one test was performed where the radar data within the lowest 900 m of the ground were assumed to represent inflow conditions in the domain. Figure 5 shows the tangential velocity from the numerical model. The model generally simulates the radar observations well, with the strongest winds in the lowest 50 m of the ground. The peak winds are about 10% smaller than observed. Although the numerical model does show a hint of a smaller radius of maximum winds for the lowest elevations, the difference is not as pronounced as in the radar observations, and the radii are larger than observed, especially at the lowest levels. The simulated radial flow (Figure 6) has peak magnitudes relatively close to the radar observations, although for small radial distances the flow is overestimated near the ground. The simulations indicate relatively constant low-level radial inflow for all radii greater than or equal to 300 m. Radar found this to be the case only for radii of 600 m or more. In addition, the simulated results indicate too deep a layer of inflow, with not enough outflow aloft. However, in general, taking into account the fact that the true depth of the inflow layer for the actual tornado is unknown, Fluent does a reasonably good job of simulating the Spencer tornado. The numerical model has been used to simulate flow based on measurements taken in a smaller model laboratory simulator on which the design of the large simulator was based. Tangential and radial velocity profiles for these simulations are shown in Figure 7. This simulator was scaled 1:4.5 compared to the large simulator,

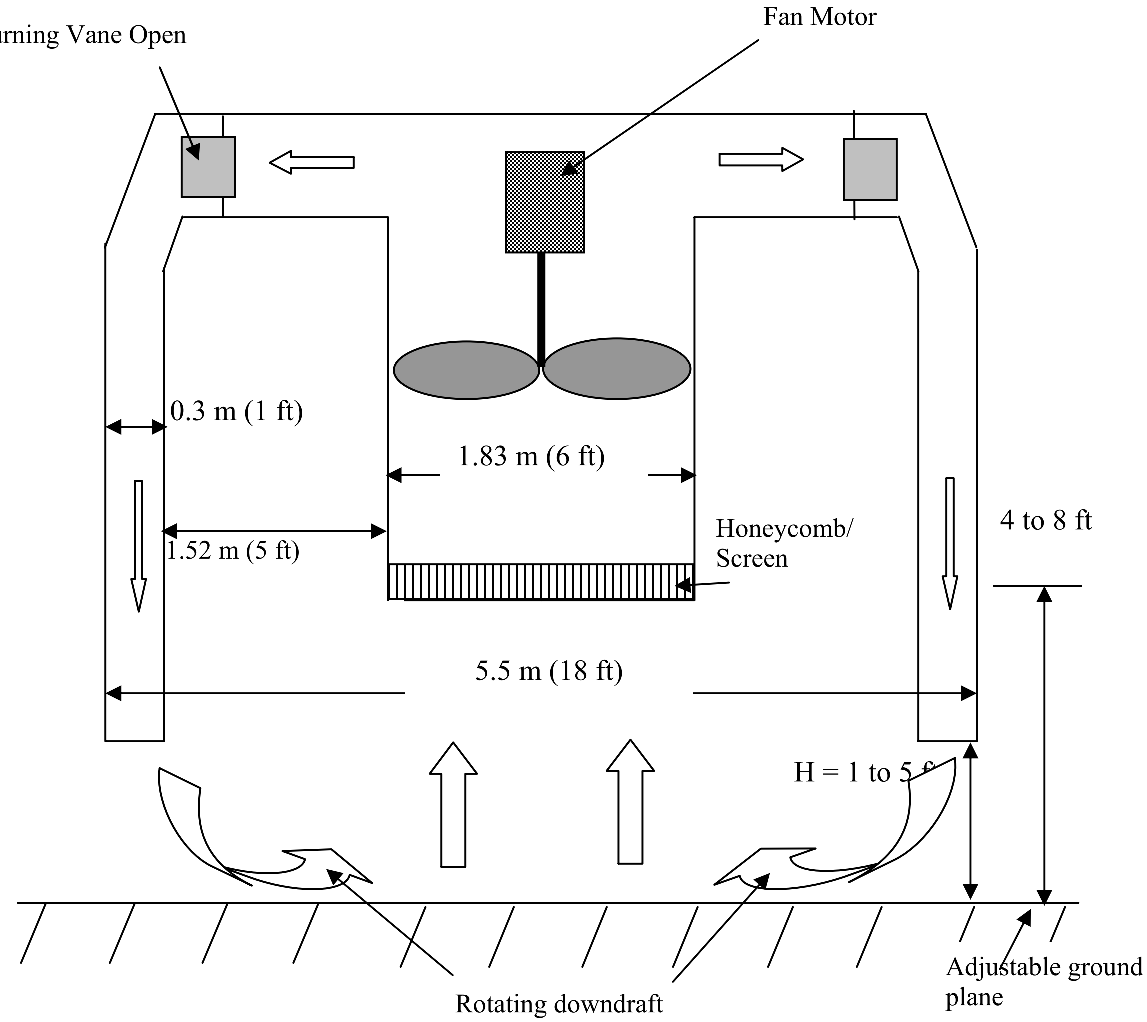


Figure 2: Schematic of tornado simulator showing dimensions of simulator

and had a maximum fan flow rate a factor of 53 less than that of the large simulator. Figure 7 shows relatively weak tangential flow in the vortex with a vertical orientation (radius of maximum flow constant with height). The radial velocity plot was created assuming a moving ground plane to represent the effects of tornado translation. Qualitatively both the tangential and radial velocity profiles resemble the observations, and even moreso the simulations based on the radar data. The simulated wind speeds, however, are significantly less than those measured in the laboratory simulator, which are discussed in the next section. Fluent will be used in the future to simulate the vortex present in the large simulator, once velocity measurements are collected that can be used as inflow conditions. Sensitivity tests will also be performed to determine the impact on the vortex from assumptions about surface roughness.

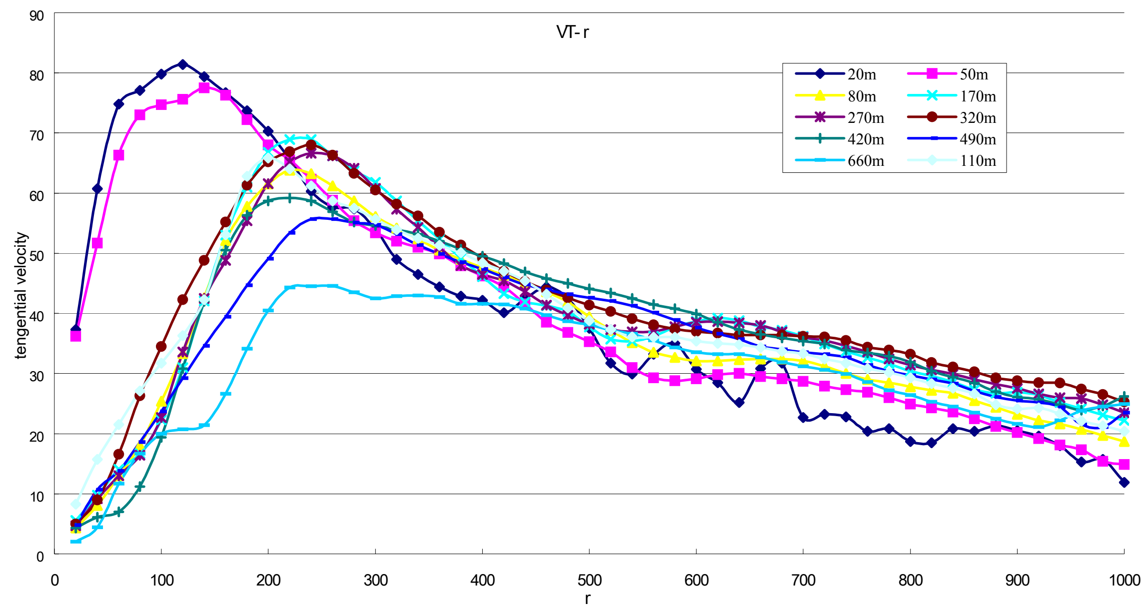


Figure 3: Radar-observed tangential velocity profiles in m/s (averaged azimuthally) as a function of radial distance (meters). Different colored curves show profiles at different elevations (m) above ground.

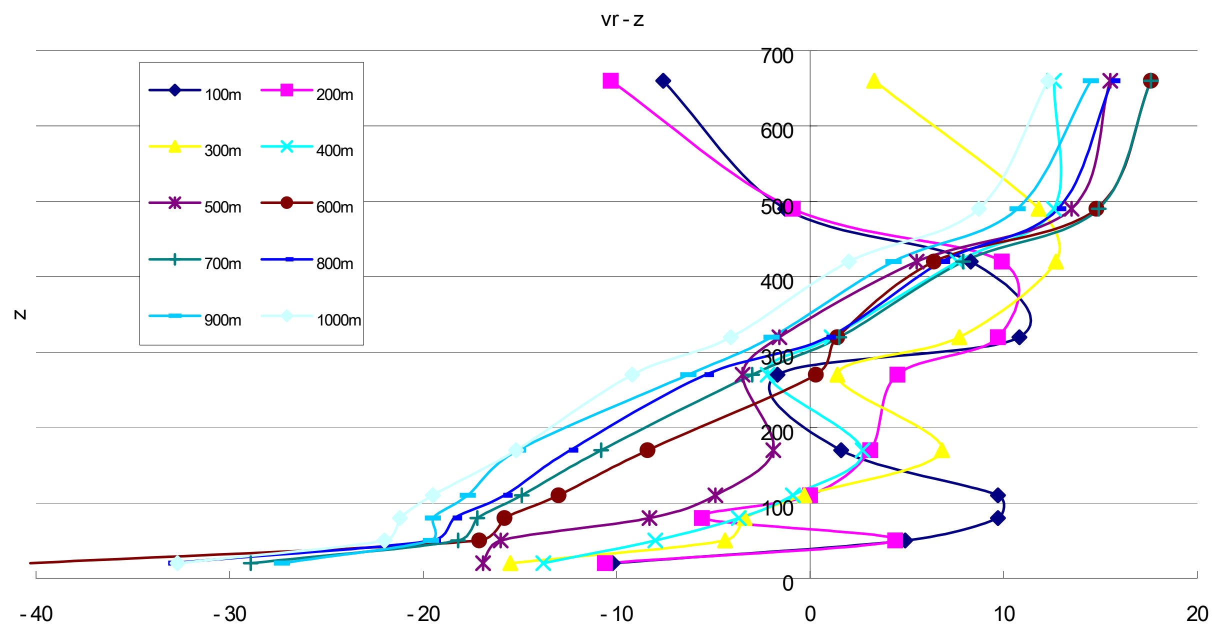


Figure 4: Radar-observed radial velocity profile (m/s) averaged azimuthally as a function of height (in meters). Different curves refer to different radial distances (m) from the center of the vortex.

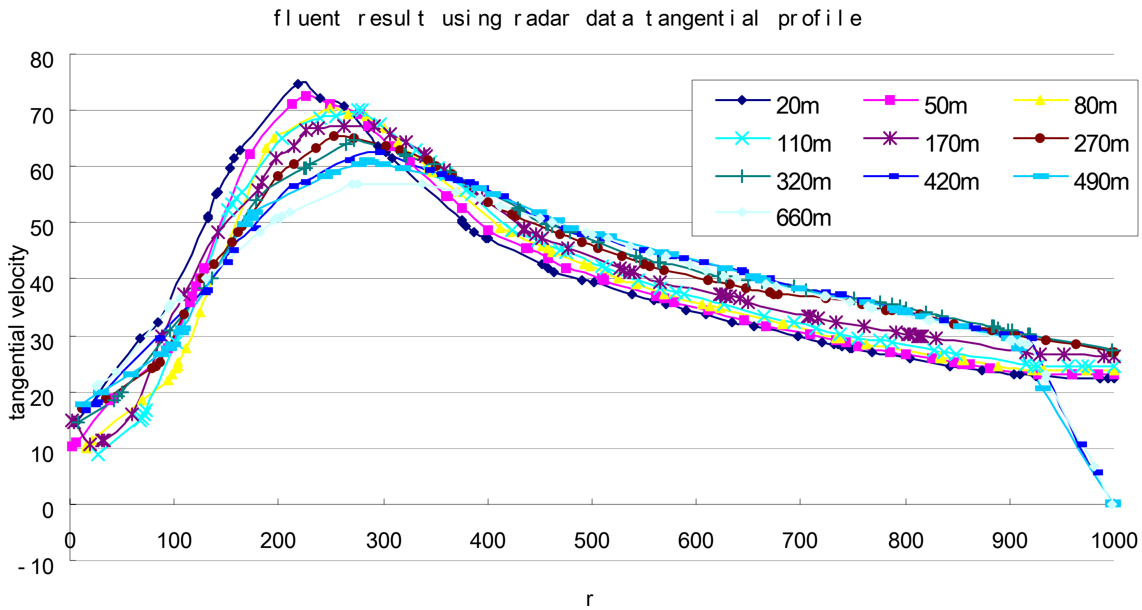


Figure 5: Numerically-simulated tangential wind profile (m/s) averaged azimuthally as a function of radial distance (in m), using radar data in the lowest 900 m as inflow conditions in the model. Different curves refer to different distances (m) above the ground.

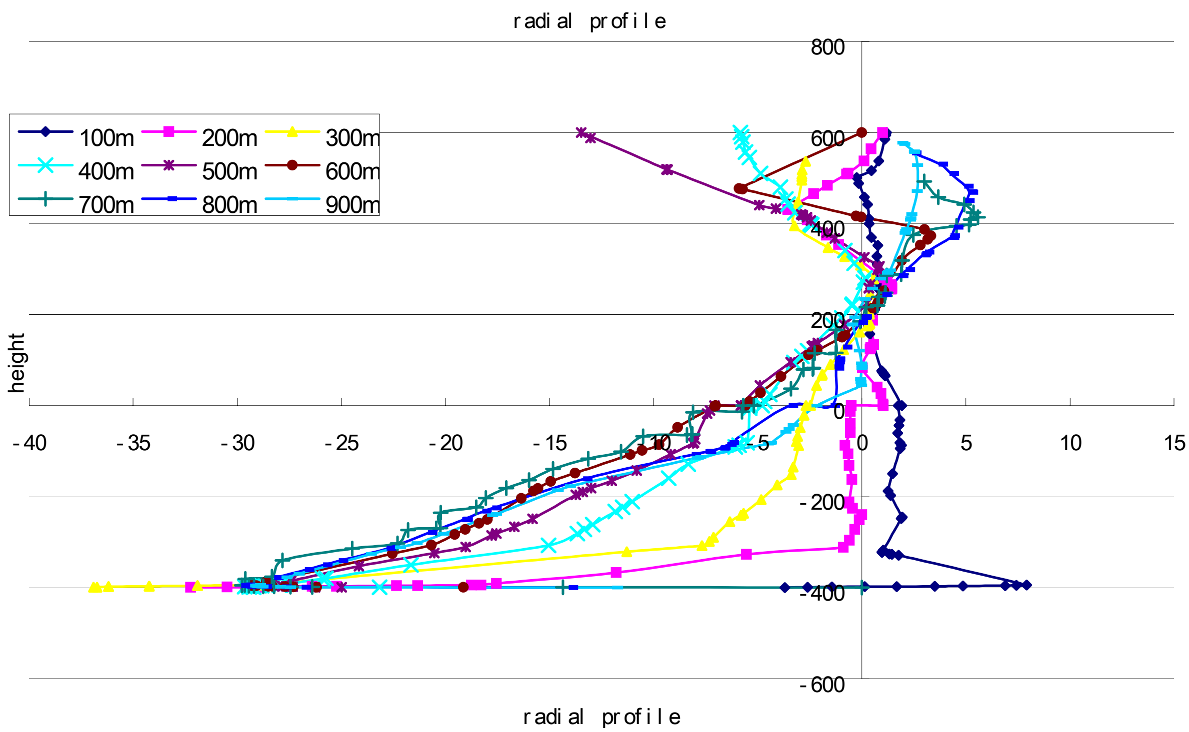
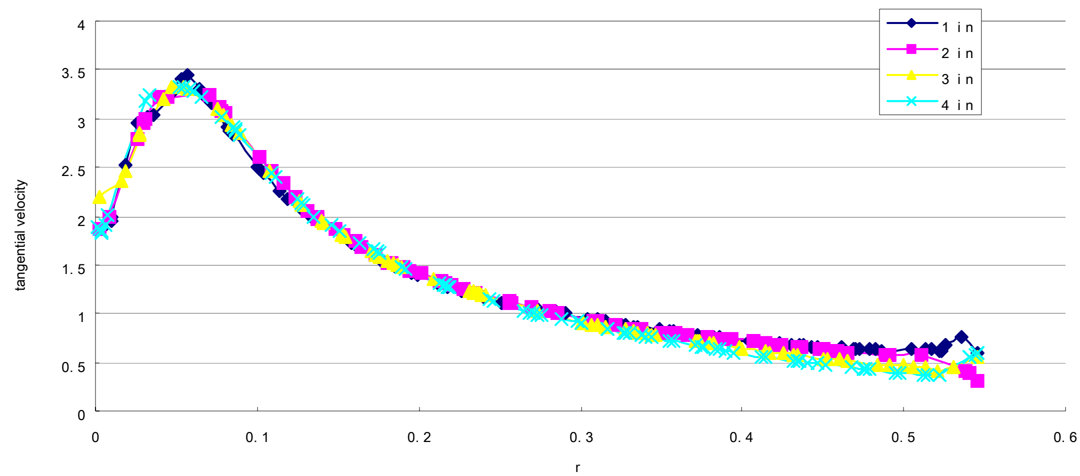


Figure 6: Numerically-simulated radial inflow profiles (m/s) averaged azimuthally as a function of height (in m), using same assumptions as in Fig. 5. Different curves refer to different radial distances (m) from center of vortex. Vertical scale is not relative to the ground; ground height is shown as –400 m.



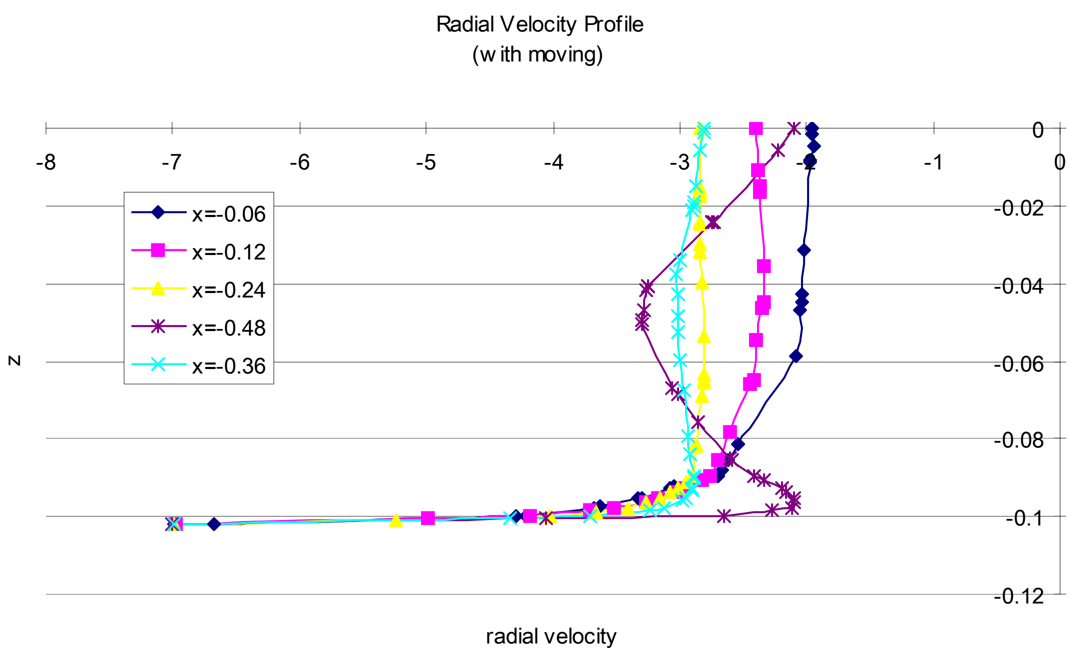


Figure 7: Tangential (top) and radial (bottom) velocity profiles (m/s) simulated using inflow data provided from a smaller laboratory model. Radial distance in top figure and height in bottom are in meters.

5. LABORATORY SIMULATOR RESULTS

Much data was collected from a smaller model laboratory simulator prior to spring 2004. Figure 8 shows the tangential velocity profile as a function of radial distance at a height of 3 inches above ground for laboratory tests using several different vane angles and a height of the downdraft duct of 4 inches above the ground. Simulations were found to be somewhat sensitive to both this height and the vane angle. Maximum tangential flow was found for vane angles around 70 degrees. Peak tangential velocities in this figure are just over 10 m/s, substantially larger than the Fluent results for this case. It is believed that a failure to include the vertical component of the flow in the inflow conditions may account for some of the discrepancy. The inflow conditions were measured rather close to the downdraft duct, where it is likely a substantial vertical component was present. Note that although the peak tangential velocity increases as vane angle increases (such that the low-level inflow has more tangential flow and less radial component), the radius of maximum wind expands as the vane angle increases.

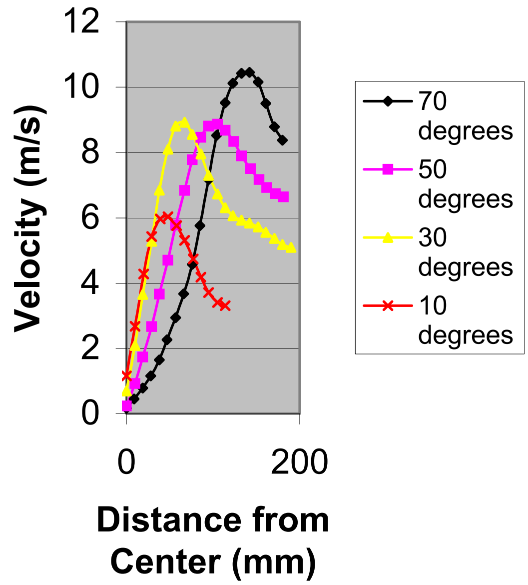


Figure 8: Tangential velocity profiles from small model laboratory simulator as a function of radial distance. Curves indicate different vane angles used to impart vorticity (red=10 degrees, yellow=30, pink =50, black =70).

Measurements are ongoing at present within the large tornado laboratory simulator. These results will be presented at the conference. Preliminary pressure measurements indicate a pressure drop of nearly 9 mb within the vortex when the fan is operating at full power. The pressure profile qualitatively resembles that obtained within an F4 tornado that passed directly over a portable probe near Manchester, South Dakota in June 2003 (T. Samaras, personal communication). Making normal assumptions about pressure deficit and corresponding vortex winds, the 9 mb drop would correspond to peak flow of slightly over 60 miles per hour, roughly what was predicted based on results from the smaller model. The calculated swirl ratio in this case was .57 based on the core radius, but would be roughly 1.0 based upon the radius of the updraft itself.

6. SUMMARY

A simulator that creates a moving tornado vortex has been designed to produce a large enough vortex to allow engineering studies. The laboratory results are being compared with radar observations and numerical simulations to validate the realism of the laboratory tornado.

7. ACKNOWLEDGEMENTS

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