Velocity Measurements in a Laboratory Tornado Simulator and their comparison with Numerical and Full-Scale Data

by

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ABSTRACT
A laboratory tornado simulator that can generate a translating vortex has been built for the purpose of studying the interaction of a tornado-like vortex with the built environment such as individual buildings or suburban and urban complexes. The simulator, mounted on a crane to impart translation, operates like a closed-return wind tunnel with an open test section. It has two concentric ducts to circulate the flow between the inside duct that houses the 1.83-m diameter fan and the outside duct with 5.5 m outer diameter and 4.88 m inside diameter to create a tornado-like vortex whose diameter can reach 1.22 m and tangential velocity can reach 33 m/s. Since the primary purpose of the simulator is to assess the wind-induced loads on engineered structures, it is important to validate the wind field of the simulated tornado with full-scale data. Doppler on Wheels radar data from the Spencer, South Dakota tornado of 1998 was used for this purpose. Numerical simulations were also performed with Fluent software for assessing the near-ground flow field (less than 50 m) since the Doppler radar data may not be very accurate at those heights. Analyses of the radar data show peak tangential winds occurring at the lowest scan, roughly 20 m above ground level, with a vortex whose core radius increases between 120 m and 200 m above ground, and remains relatively constant above that level. Numerical model data based on the dimensions of the laboratory simulator and laboratory inflow data are generally consistent with the laboratory and radar observations despite some differences.

KEYWORDS: tornado laboratory simulation; flow measurement and comparison; Doppler radar data; tornado-like vortex CFD simulation.

1.0 INTRODUCTION

Building wind tunnels with advanced capabilities will aid research efforts to understand the complex fluid structure interaction problems encountered in wind engineering design. Computer simulations currently are inadequate for design calculations because of the complexity of the fluid dynamics problems involved. Wind tunnels remain an integral component of the design process for wind sensitive structures.

Tornadoes are vortices with significant tangential, radial and vertical velocity

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components. Therefore, the flow field in a tornado is much different from the straight-line boundary-layer wind. A simulator has been designed at Iowa State University (ISU) that produces a translating tornado (with respect to a ground plane) for wind tunnel model testing with a geometric scale of 1/100 to 1/500 to study the interaction of tornado-like vortices with the built environment such as individual buildings or suburban and urban complexes. The simulator also has an option that allows it to produce a translating microburst.

According to Wind Hazard Reduction Coalition statistics, each year 800-1000 tornados occur in the U.S. and cause 80 deaths, 1500 injuries, and $850 million worth of damage on an average. Although mostly associated with the region in the central states which extends from Texas to North Dakota and Nebraska to Ohio, often referred to as "tornado alley," tornados have occurred in all fifty states and also occur in coastal regions as hurricanes make landfall. In spite of causing significant losses, tornados have received little attention from wind engineers. Statistics show that 90% of all recorded tornados are rated F2 or less (Bluestein and Golden, 1993) on the Fujita Scale—that is, they involve wind speeds less than 157 mph (1/4th Fastest Mile or 161 mph 3-sec gust). It may be economically feasible to design low-rise residential and commercial buildings to resist F2 tornados. It can be also argued that certain essential facilities such as power plants, schools, hospitals, and airports should be designed for tornados of F3 or higher intensity. Any such design work, however, requires accurate information about the nature of the wind loads on structures due to tornados.

Determining tornado-induced wind loads is difficult for two reasons—because quantifying wind velocity magnitudes in tornados is difficult and because simulating tornados in a laboratory while measuring wind pressures on structures is non-trivial and has not been attempted systematically. With the latest instruments, equipment, and computing facilities, it is now possible to pursue these goals through fieldwork and through numerical and laboratory simulation.

2.0 BACKGROUND

2.1 Wind Field Measurements

Beyond the use of storm damage, recent advances in field measurements have greatly enhanced current knowledge of tornados and the supercells that spawn them. For example, the VORTEX project (which stands for "Verification of the Origins of Rotation in Tornadoes Experiment") (Rasmussen et al., 1994) was an effort to use advanced remote sensing equipment to conduct field measurements of tornados and tornadic storms.

One particular piece of field equipment that has proved to be useful is the "Doppler on Wheels" system (DOW). DOW systems measure wind velocities directly during a storm from single or multiple truck-based radars (e.g., Wurman, 1998, Wurman & Gill, 2000). In more recent years two DOW radars have been deployed in a pattern to allow dual-Doppler analysis. The DOW radars have been upgraded to include a 2.33 m dish, with a 0.9 degree beam width. In a violent tornado in South Dakota, one of the radars was deployed within 1.7 km of the tornado, so that wind data were collected with resolution of 30 m x 30 m x 38 m (Wurman 1998). These wind observations from radar are both supporting existing theories, and in some cases, raising questions about the previous views of tornado behavior. For example, Doppler measurements are finding that the decay rate of the wind does not follow a Rankine curve, as is often assumed (Wurman & Gill 2000).

2.2 Numerical Simulation

Because of prior difficulties in collecting small-scale observations within and near a tornado, numerical simulations of tornadic flow have been performed as a tool to improve understanding of tornado dynamics, small-scale flow characteristics, and possible genesis. The models most directly relevant to the near ground flow field of interest in this study have simulated tornados with domains focused in the area of the tornado rather than including the entire storm (e.g., Lewellen et al., 1997; Lewellen et al. 2000). As will be seen, this general approach to the simulation is similar to that of the laboratory and numerical simulations in this study.

2.3 Laboratory Simulation

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. These laboratory simulations were aimed at greater understanding of the tornado vortex itself. However, numerical simulation has overtaken physical simulation as the tool of choice for tornado studies—both because of cost and because of versatility. While both laboratory and numerical simulation efforts have revealed a great deal about tornado structure (Lewellen, 1993), physical simulation of tornados for the purpose of studying the tornado may no longer be useful. For the purpose of quantifying tornadic wind loads on structures, however, physical simulation is a necessity.

Some efforts have already been made to place building and structure models in tornado simulators to quantify tornado loads. The design of these simulators made 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), and Bienkiewicz & Dudhia (1993) 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. The description of this simulator along with comparisons of velocity measurements taken in the simulator with radar observations and numerical modeling results are presented in this paper.

3. CURRENT WORK

3.1 Radar Observations of Near-Ground Winds

To validate 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 discussion of this particular tornado can be found in Wurman (2002), Wurman & Alexander (2005) and Alexander & Wurman (2005). 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 20 m horizontal grid spacing. The swirl ratio was believed to be relatively low (0.5 or so) at the time these observations were made. The tornado 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 5 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 flow tends to be strongest relatively far from the center of the vortex, in the 0.5 to 1 km band. The radial inflow is strongest at the lowest elevation for all radial distances observed. The temporal average of the tangential velocities at 40 m elevation for two instances that are approximately three minutes apart are also plotted in Figure 5 (40 m Avg). This plot shows that the maximum tangential velocity when averaged is less than the instantaneous value at the 50 m elevation and the radius of the core is more than the corresponding value at 50 m. The temporal average shows that a range of length and velocity scales can be used to compare the laboratory and full-scale data.

3.2 Laboratory Tornado Simulation

Planning for a moving tornado simulator at ISU began in 2000, 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.

The final design of the laboratory simulator at ISU is unique in comparison to other simulators constructed in the past due to efforts to replicate nature as much as possible. In this design, a tornado-producing thunderstorm is simulated by producing a strong region of updraft, surrounded by a spinning tube of air that descends toward the ground plane. This spinning air that is created by adjustable turning vanes at the top of the simulator simulates the RFD. This design might allow testing of theories that buoyancy of the RFD plays a big role in determining tornado intensity and longevity (Markowski et al., 2002) by manipulating the temperature of the down-flow. One of the most revolutionary features of this simulator is that it is able to produce a translating vortex. The down-flow duct shelters the vortex from the stagnant outside air, while a large enough gap exists at the bottom of the simulator to allow it to pass over building models. This simulator is designed to be versatile so that future knowledge that is gained in the understanding of this weather phenomenon could be incorporated. 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 1.83 m (6 ft)-diameter fan that can generate a flow rate of 50 m^3/s in the tornado mode (updraft) and 47 m^3/s in the microburst mode (downdraft) was selected for the prototype laboratory simulator. A circular duct 5.5 m (18 feet) in diameter and 3.35 m (11 feet) high is suspended from a 2250-kg or 5 ton track crane so that it can move along a 10.4 m (34 ft) long by 6.1 m (20 ft) wide ground plane. Within this 0.30 m or 1 foot wide duct, a downdraft is simulated and some vorticity is imparted to this flow through the use of vanes at the top. This downdraft diverges upon hitting the ground, and a sizeable portion of the flow moves inward beneath a large fan 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 1.22 m (4 ft.), i.e. the distance between the maximum tangential velocities, with the maximum tangential velocity corresponding to the 1.22 m diameter core being 33 m/s (74 mph). Swirl ratio is the ratio of the vortex circulation compared to the accompanying flow rate into it. The maximum swirl ratio that was measured currently is 0.78 (based on a modified definition, i.e. based on the circulation, Γ, of the vortex calculated at the radius of the maximum tangential velocity; equivalent to greater than 1.0 as per conventional definition where circulation, Γ, is calculated at the maximum radius of the updraft), and the translation speed of the vortex can reach up to 0.61 m/s (2 ft/sec). The vortex height can vary from 1.22 to 2.44 m (4 to 8 ft) by adjusting the ground plane upward or downward. In the path of the vortex, models of structures scaled between 1/100 to 1/500, depending on the size of the prototype structure, are placed so that measurements of the surface pressures or overall loads can be made on them.

3.2.1 Experimental Setup

Velocity fields in the simulator were measured using a spherical 18-hole pressure probe (PS18 Omniprobe from Dantec). The pressures from the probe were measured with a Scanivalve zoc33/64 Px electronic pressure scanner. The 18-hole probe is conceptually organized to form a network of five-hole configurations (some ports/holes are shared by two groups). Because of this network, the probe can measure flow angularity up to 165 degrees with respect to the probe axis (Figure 3). The calibration software supplied with the probe uses a local least square fit with this network of 5-hole configurations to provide accuracy of 2% for velocity magnitude and 1.5 degrees for velocity angle.

Velocities were measured at three levels from the ground plane, z=12.7 cm (5 in.), 25.4 cm (10 in.) and 34.3 cm (13.5 in.). For all of these measurements, the ground plane was fixed at 45.7 cm (18 in.) below the exit of the outer duct and the fan speed was fixed at 20 Hz ($1/3^{rd}$ of the full speed, $Q_{1/3}$= 16.5 m^3). Measurements were done for vane angles of 35, 45 and 55 degrees. Data were sampled at the rate of 78 Hz for 26 seconds. The measurements were made with a stationary tornado, and the swirl ratio was estimated to be 0.78 (current definition) for the 55 degree vane angle setting.

3.2.2 Experimental Results

Figure 6 shows the tangential velocity plots. The radius of the core or radius of the maximum tangential velocity reduces while the magnitude of the maximum tangential velocity increases with reduced elevation like those observed in the Doppler radar data (Figure 5) although these changes are not as dramatic. There could be two primary reasons for the difference in results, namely, ground roughness and Swirl ratio that are different between laboratory and full scale. Figures 7 and 8 show the radial and vertical velocity plots at three elevations. It is observed that the inflow radial velocities first increase in magnitude and then decrease in magnitude with decreasing radial distance from the center of the core. The radial velocity becomes positive or outflow type and reaches a maximum at the radius of the core. Inside the core, the radial velocities are both inflow and outflow types. The flow is first a downdraft near the outer duct as expected, and becomes an updraft as it nears the center of the core reaching a maximum value at or near the radius of the core. The vertical velocity becomes zero at a radial distance of 2.29 m (90 in.) from the center of the core so this radius can be taken as the boundary of the laboratory flow field simulation for this ground plane and vane settings. Note that the flow is a downdraft near the center of the core, as observed or speculated for tornados with high swirl ratios like this one.

3.3 Numerical Simulation

Because radar observations are unreliable below 50 meters above 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 6.0 was used. In most of the prior studies conducting numerical simulation of tornados, the emphasis has been on processes influencing the general tornadic wind flow or on potential mechanisms for tornadogenesis or tornado dissipation. Such issues can be explored with grid spacing larger (roughly 50-100 m) than what is required to examine the fine-scale details of tornado wind structure near the ground. Because of the different focus of these earlier works, little information has been provided about wind variations near enough to the ground to impact most built structures. For instance, Lewellen (1993) states that the maximum velocities will occur below the top of the ground boundary layer (roughly 100 m above surface)—a result that has great significance for determining tornado-induced wind loads. Therefore, much more detail about the near-ground winds is needed.

Numerical simulations were primarily made using a domain that represented the controlled laboratory simulator (Figure 4). An initial shear inflow enters the bottom cylindrical domain with radial and tangential velocity components. As shown in Figure 2, the flow can be extracted from the big cylinder only through the small central cylinder at the top boundary. A fine grid for this geometry was set up using Gambit and then Fluent 6.0 was used to solve the flow with the initial condition. The inlet vertical velocity was assumed to be zero, while at the outlet boundary the radial and tangential components are assumed to be zero. All other boundaries were defined to be solid walls with the no-slip boundary condition. The inlet radial and tangential velocities were those of the laboratory simulator at r = 229 cm or 90 in. for a vane angle of 55 degrees and 1/3rd of the maximum fan speed. A length scale, λ_L = 1/200, and velocity scale, λ_V = 1/7.25, were determined by comparing the laboratory and Doppler radar data of maximum tangential velocity and its radius of occurrence at Z = 50 m. These scales will be somewhat different if temporal average of the Doppler radar data rather than the instantaneous data is taken and averaging time of the laboratory data is accounted for. The RNG k-ε model (2 equations) was used to solve the three dimensional steady-state model. The Standard Wall Functions were used to resolve the flow near the wall. The constants and parameters for the model were: $C_\mu = 0.0845$, $C_{1\varepsilon} = 1.42$, $C_{2\varepsilon} = 1.68$, Pressure: Standard, Pressure-velocity coupling: simple, Momentum: second order upwind, TKE: second, order upwind, Grid spacing: 20 m.The model was found to generally simulate the laboratory observations well, with the strongest winds in the lowest 50 m above the ground.

3.4 Comparison of Velocities

Scaled results from numerical and laboratory simulations are plotted in Figure 9 to compare with full-scale data. A length scale, λ_L =1/200, and a velocity scale, λ_V =1/7.25 (Scales 1), were used for scaling the numerical and laboratory data. Another set of scales was chosen on the basis of extrapolation of the tangential velocities, both inside the core that varies linearly with radius and those outside the core that varies non-linearly with radius, to define a unique maximum tangential velocity and radius of core. This was done since the radar data shows a broad region of maximum tangential speeds. On the basis of this unique point, a length scale, λ_L =1/164, and a velocity scale, λ_V =1/7.70 (Scales 2), were calculated and used to plot the laboratory data. As seen in Figure 9, these scales can make a difference in the comparison. However, the velocities in full scale are observed to be usually higher in magnitude than the laboratory values. Note that as per the time scale of 1/27.6 that was calculated using the first set of length and velocity scales, the averaging time of 26 seconds of laboratory data scales up to 12 minutes of full-scale data. Since the full-scale velocities are instantaneous values, it could mean that these values are at least 1.5 times the magnitude of the laboratory velocity measurements. Therefore, λ_V =1/4.83 instead of 1/7.25 which will change the time scale to 1/41.4. These are important issues that need to be considered in comparing the data between laboratory and full scale.

It is proposed that the outer region is divided into two parts for calculating the exponent 'n' in the velocity-radius equation, $VR^n = C$, since one curve does not capture the characteristic of this entire region. The 'n' values were calculated for both these regions for the laboratory data. They do not match with the full-scale data near ground (Z = 50 m). This mismatch of 'n' values close to the ground was expected since the ground plane of the laboratory simulator is much smoother compared to nature and the roughness is expected to influence the 'n' values close to the ground. On the basis of the comparison of velocity magnitudes and 'n' values, two modifications are proposed to improve the laboratory simulations, namely, increase the velocities at the outer duct for a given flow rate by reducing the area of the outer duct, and introduce roughness on the ground plane to replicate the roughness of the terrain where the tornado occurred.

The numerical results plotted in Figure 9 show the largest peak tangential speeds among all three data sets. This may be explained by the smooth boundary used in the numerical simulation. Greater surface roughness has been shown (in experimental and numerical simulations) to result in lower peak tangential speeds (Church et al., 2004; Lewellen et al., 2000). Future numerical work will investigate surface roughness effects. The numerical and laboratory data show consistency in terms of the radius of the core and the variation of tangential velocities with radial distance. Figure 10 shows consistent vertical flow structure from the numerical and laboratory work but again shows larger velocity magnitudes for the numerical simulation. Field data for vertical velocity is not available because the radar cannot acquire velocity components that are normal to its line of sight.

Radial inflow velocity plots for two different radial distances are shown in Figures 11 and 12. Numerical, laboratory and field results are shown. There are differences in velocity magnitudes at each elevation (z) in Figure 11. Again it is hypothesized that these differences are because of surface roughness in each case. The smoothest simulation (numerical) shows the largest velocities while the roughest simulation (the full scale) shows the smallest velocities. For the same reason, as observed in Figure 12, the numerical values are still negative or inflow type at the radius of the core while both the laboratory and full scale values with the exception of Z =20 m are outflow type. Also, the magnitudes of the outflow velocity in full scale are lower than those of the laboratory because of likely larger ground friction.

4.0 SUMMARY

This paper presents the preliminary velocity measurements from the ISU Tornado Simulator and compares the same with full-scale Doppler radar data of the F-4 rated tornado that occurred on May 30, 1998 near Spencer, South Dakota. Numerical simulations using Fluent was also performed to evaluate how well the laboratory velocity field can be replicated. The purpose of numerical simulation in this ongoing research is to do a parametric study of different variables that influence the tornado vortex and develop confidence in generating the velocity field in the near-ground region with input from full-scale Doppler radar data. Based on these comparisons, it is concluded that the laboratory simulator does a reasonably good job in simulating a real-tornado flow field. A few changes to improve the flow simulation in the laboratory simulator like increasing the downdraft flow speed compared to the current values for a given flow rate and modeling of the roughness were identified. The numerical modeling and its results were found to be satisfactory although it can be improved as well. Issues of scaling were identified to make a fair comparison between the laboratory and full scale values.

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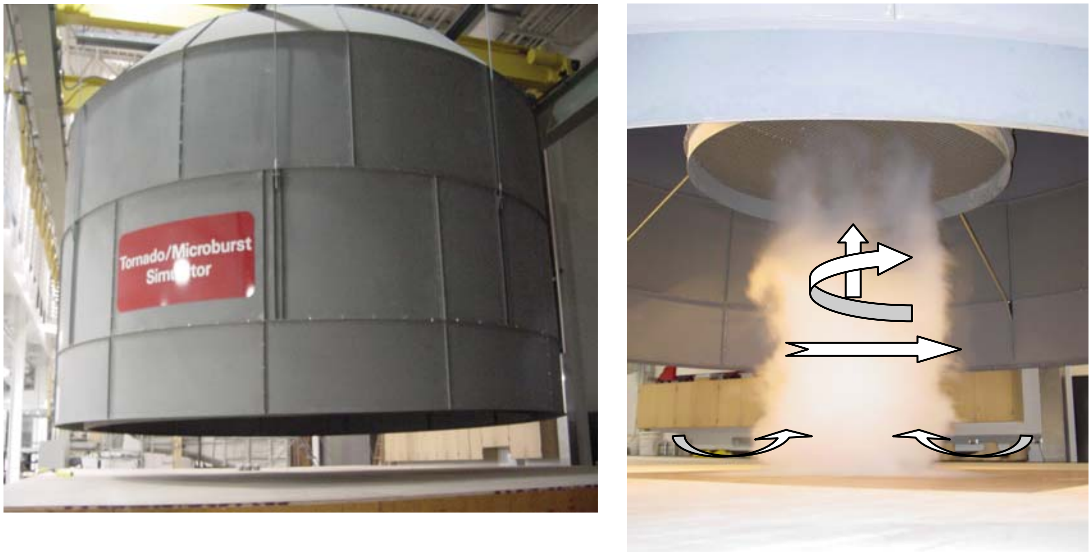

Figure 1: (a) ISU Tornado/Microburst Laboratory Simulator, (b) Flow visualization of the tornado in the Simulator showing the dynamic flow field.

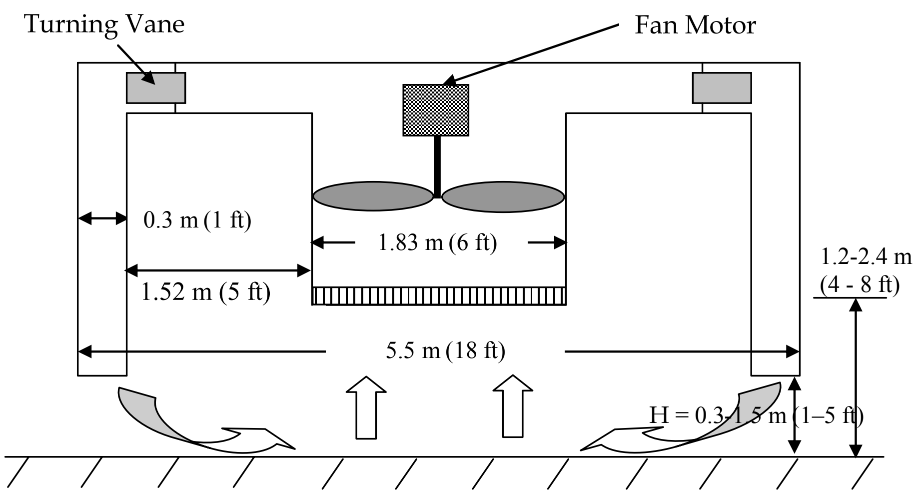

Figure 2: Schematic diagram illustrating the principle of operation of the tornado simulator.

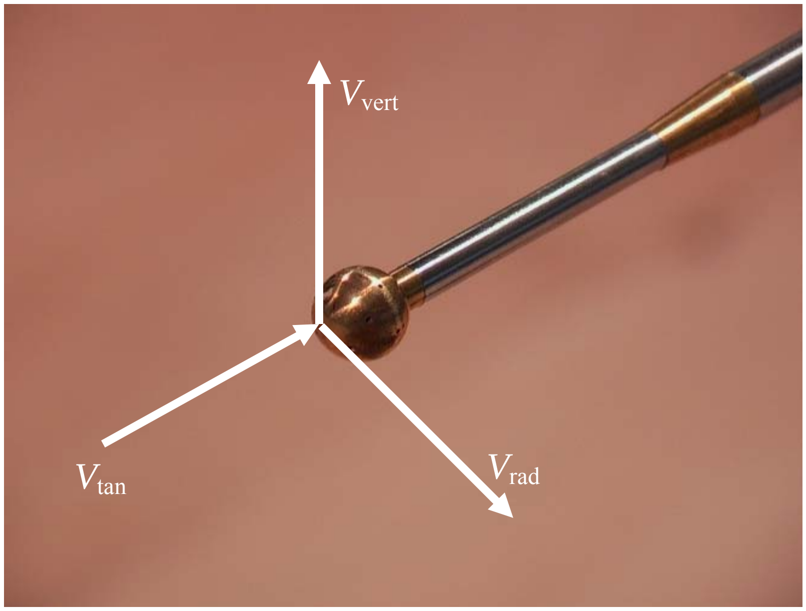

Figure 3: 18-hole Omniprobe used for tornado velocity field measurements.

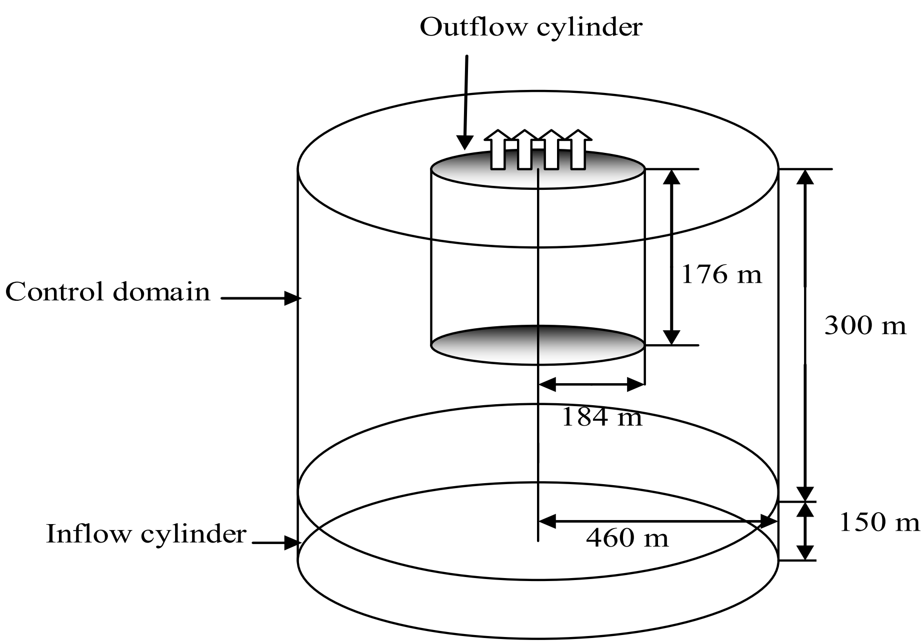

Figure 4: Computational domain for numerical simulation using FLUENT

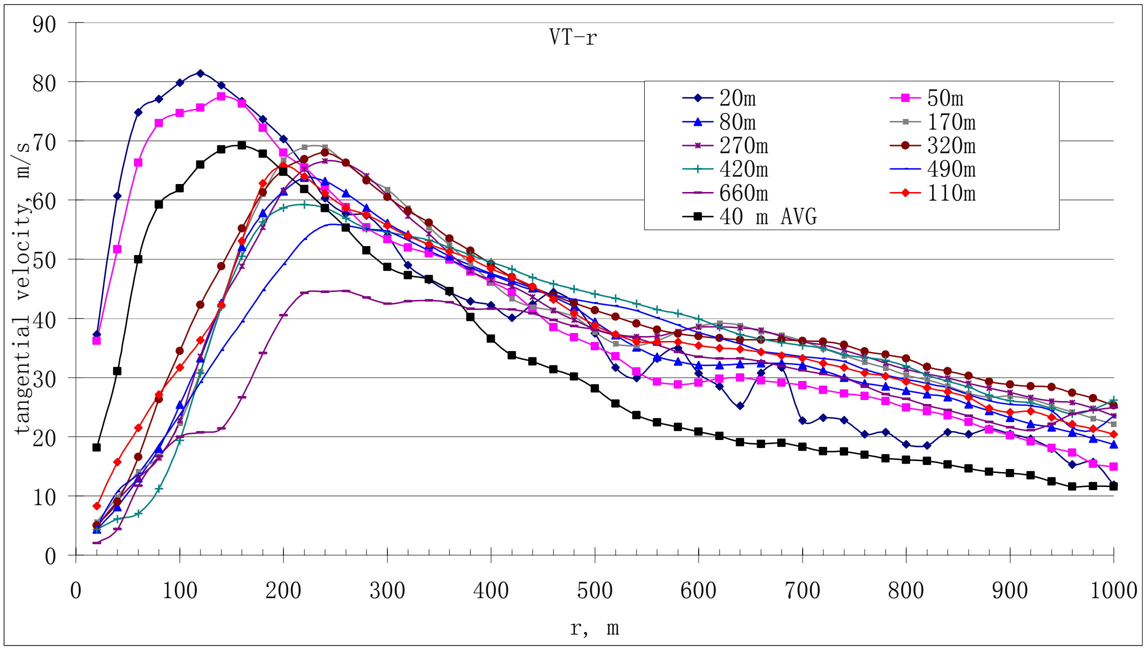

Figure 5: Radar-observed tangential velocity profiles in m/s (averaged azimuthally) as a function of radial distance (meters). Different colored curves show profiles at different elevations (m) above ground.

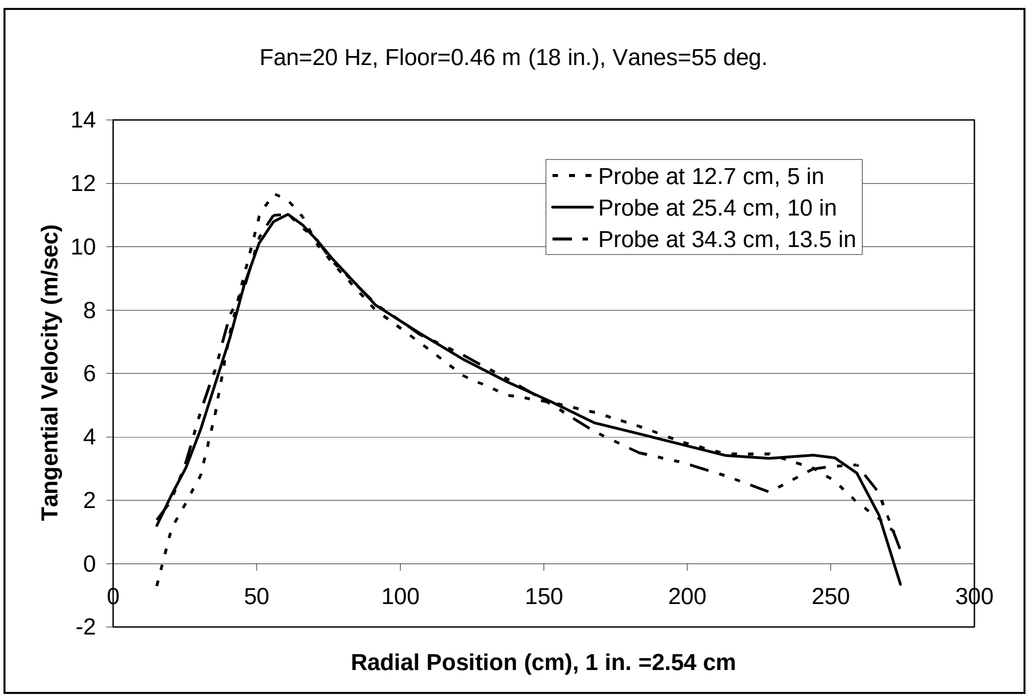

Figure 6: Tangential velocity plots for laboratory simulator at different levels from the ground plane; ground plane at 0.46 m from exit of the downdraft; vanes at 55 degrees; fan at 1/3rd of full speed ($Q = 16.5\ m^3/s$).

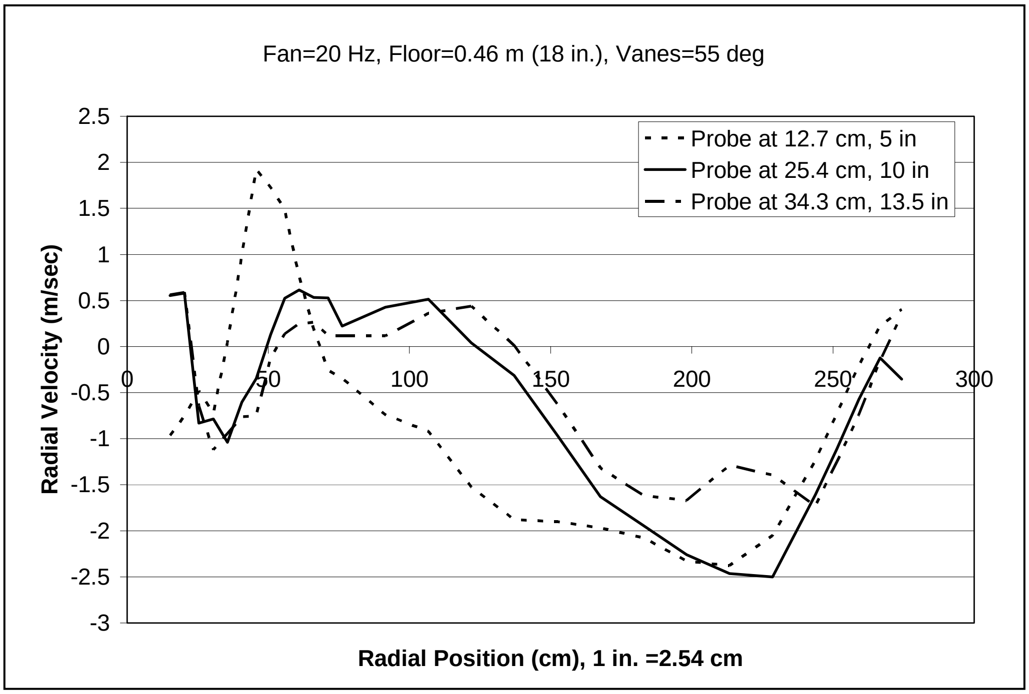

Figure 7: Radial velocity plots for laboratory simulator at different levels from the ground plane; same parameters as in Figure 6.

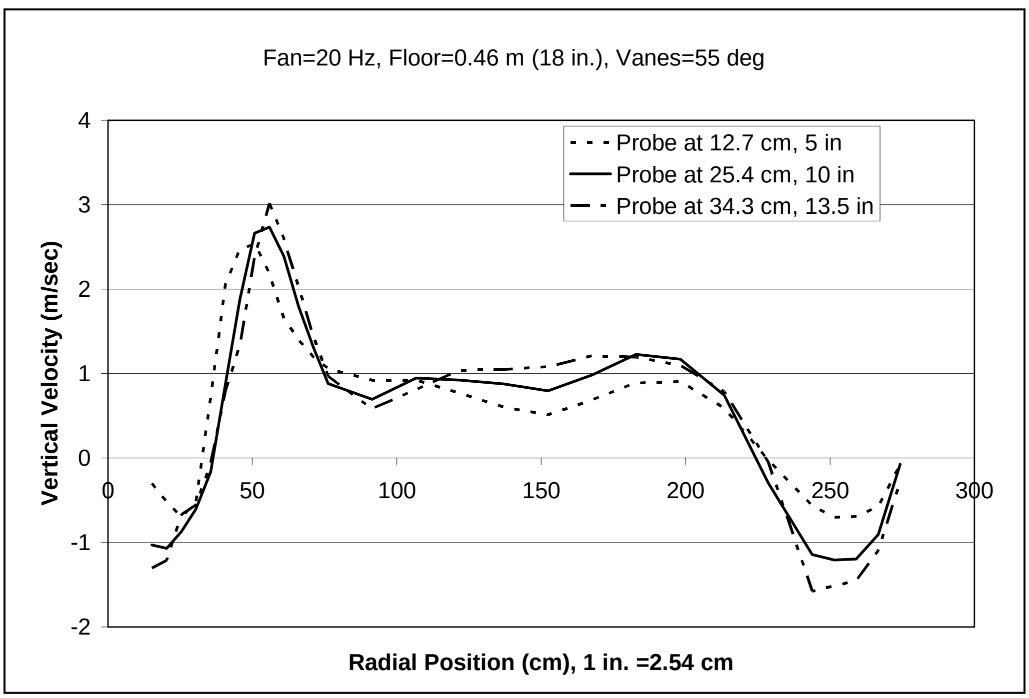

Figure 8: Vertical velocity plots for laboratory simulator at different levels from the ground plane; same parameters as in Figure 6.

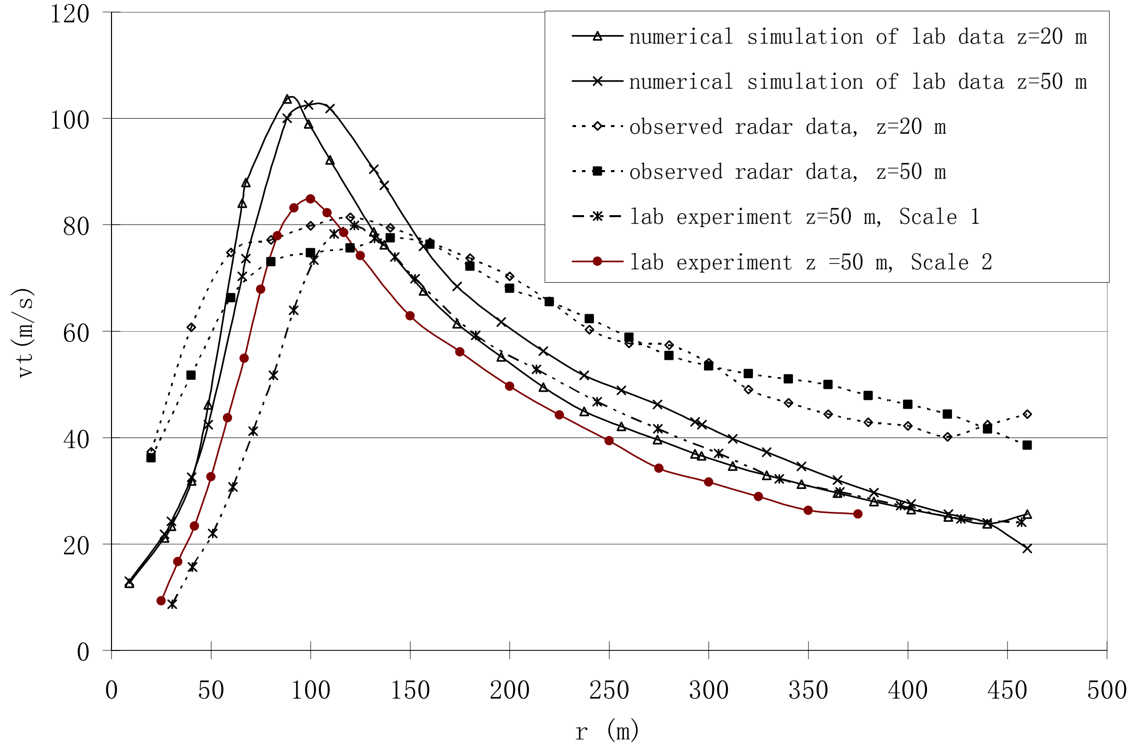

Figure 9: Comparison of tangential velocities at 50-m full-scale elevation between laboratory, Doppler radar data and numerical simulation of laboratory data; scales 1 -- $\lambda_L = 1/200$, $\lambda_V = 1/7.25$ and scales 2 -- $\lambda_L = 1/164$, $\lambda_V = 1/7.70$

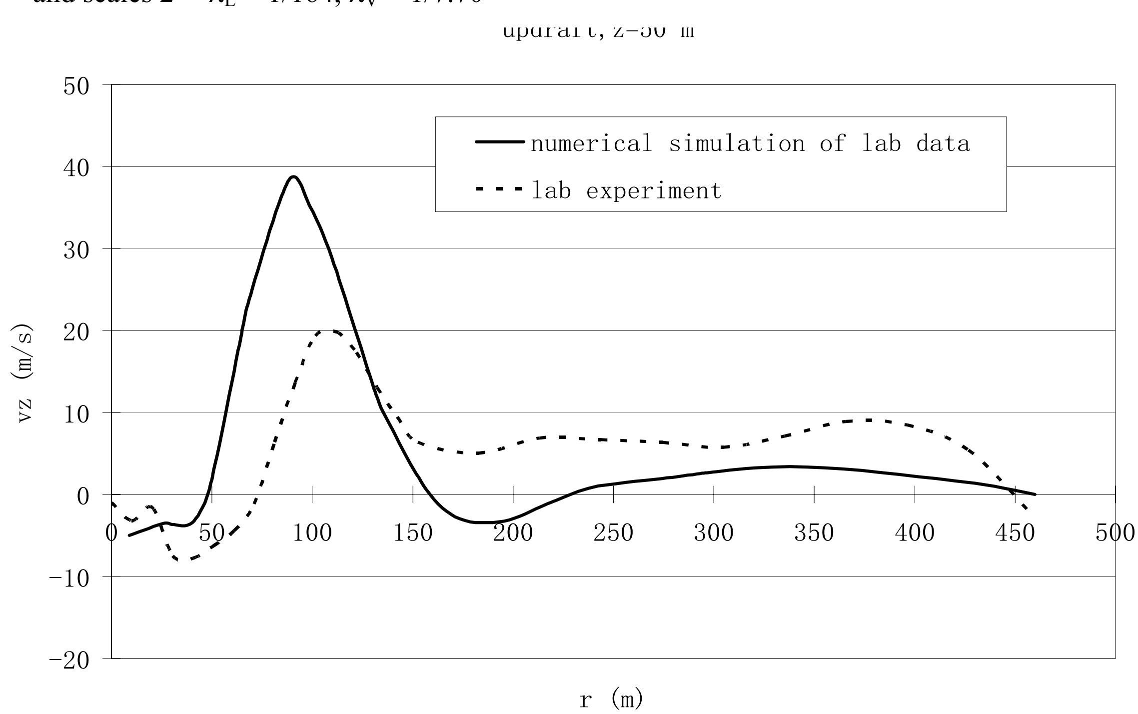

Figure 10: Comparison of vertical velocities at 50-m full-scale elevation between laboratory, and numerical simulation of laboratory data; scales -- $\lambda_L = 1/200$, $\lambda_V = 1/7.25$

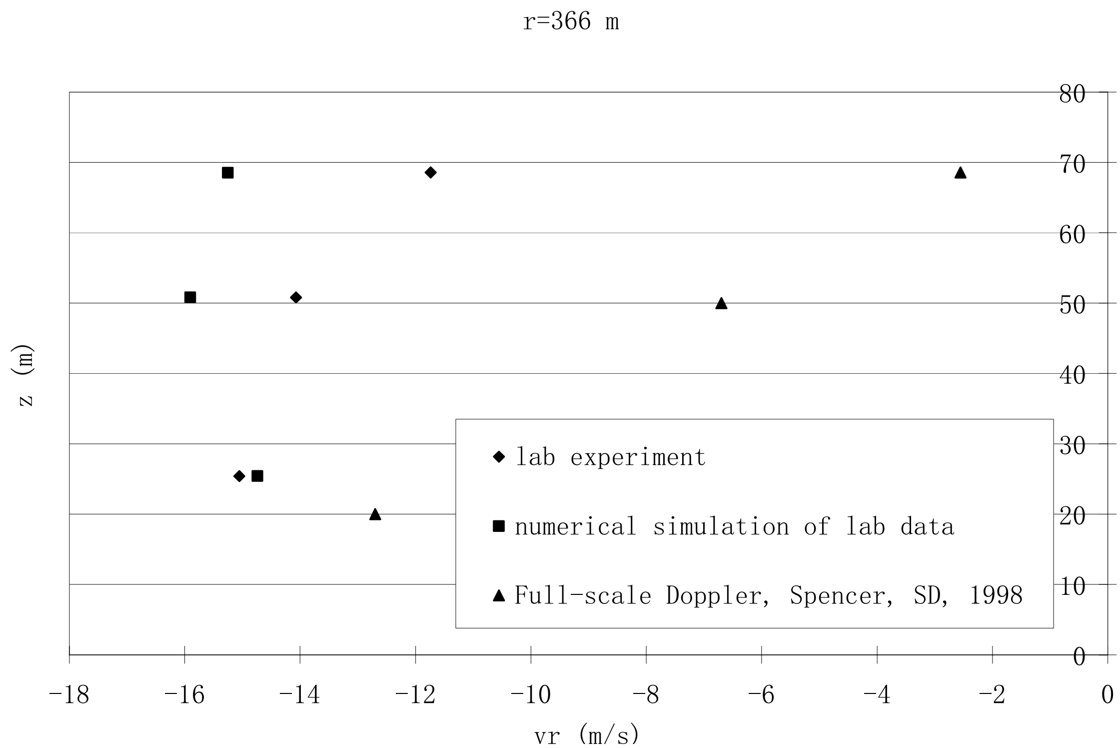

Figure 11: Comparison of radial velocities at 366-m full-scale radial distance from the center of core between laboratory, Doppler data and numerical simulation of laboratory data; scales -- $\lambda_L = 1/200$, $\lambda_V = 1/7.25$

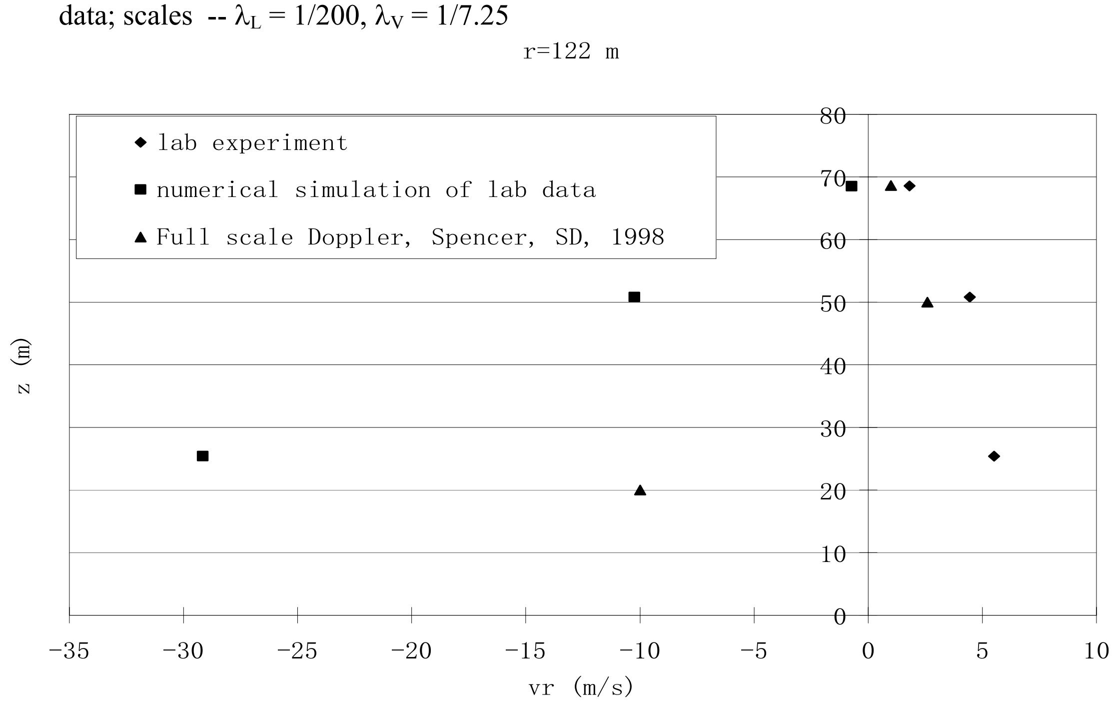

Figure 12: Comparison of radial velocities at 122-m full-scale radial distance from the center of core between laboratory, Doppler data and numerical simulation of laboratory data; scales -- $\lambda_L = 1/200$, $\lambda_V = 1/7.25$.