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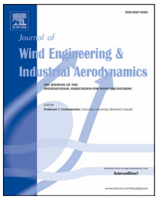

Near surface experimental exploration of tornado vortices

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ABSTRACT

Large scale and high-resolution surface pressure and Particle Image Velocimetry measurements were carried out in a new testing chamber, the WindEEE Dome, to investigate the structure of stationary tornado-like vortices and their surface layer over a broad range of swirl ratios and at the highest radial Reynolds numbers ever achieved in laboratory simulations of tornadoes. The large size of vortices simulated in this facility allows for the laboratory resolution needed for near surface exploration.

It is shown that at low swirls, tornado vortices are unstable and highly characterized by wandering. A qualitative investigation of the vortex wandering and a preliminary estimation of the effect of vortex wandering on time-averaged pressures are performed. Also, surface pressure data are used to examine the Reynolds number dependency of the flow. A clear demarcation of the surface layer behavior inside versus outside of the vortex core is observed. Normalizing axial profiles of core radii and tangential velocities in the region outside of the vortex core with the core radius and height of the maximum tangential velocity suggests self-similarity of the flow with future implications for empirical modeling. Axial profiles of the radial velocity are used to determine the vortex structure at various swirl ratios.

1. Introduction and background

Most of our existing knowledge on fluid dynamics of tornadoes come from laboratory and numerical simulations (Rotunno, 2013). Over the past few decades, laboratory simulations have proven to be successful in reproducing observed features of real tornadoes (Refan and Hangan, 2016; Tang et al., 2016; Haan et al., 2008; Mishra et al., 2008a) while numerical simulations have been a valuable tool, offering great flexibility with inflow and boundary conditions adjustments (Nolan et al., 2017; Liu and Ishihara, 2015, 2016; Natarajan and Hangan, 2012). Increasingly available full-scale tornado wind field data along with newly developed scaling methods have enabled researchers to properly replicate the velocity field of tornado vortices.

Despite all these achievements, experimental simulations of tornado vortices have always faced few major limitations including limited size and therefore resolution, e.g. (Mishra et al., 2008a; Church et al., 1977; Hashemi Tari et al., 2010), or limited capability to investigate effects of the swirl ratio (S) and the radial Reynolds number (Re_r) (e.g. Refan and Hangan, 2016; Haan et al., 2008), which are the two main kinematic and dynamic parameters associated with tornado-like vortices (Ward, 1972; Church et al., 1979; Snow, 1982). The simulators' size restricts the near surface resolution and therefore its investigation and at the same time is one of the main contributors to the limited number of available tornado wind load studies. On the other hand, the largest Re_r that has been reached in laboratories is of the order of 10^5 which is many orders of magnitude smaller than the likely atmospheric range of 10^9-10^{11} (Rotunno, 2013; Church et al., 1979; Fiedler and Garfield, 2010). Zhang and Sarkar (2012) examined the near-ground flow structure of simulated tornado vortices using a Particle Image Velocimetry (PIV) system. However, this study was limited to $S \leq 0.3$ and the effect of the small Re_r of the flow (10^3 to 10^4) on the flow structure is not inspected. Mishra et al. (2008b) measured surface static pressures experienced by a cubical building model (30 mm long edges) located in the path of a single-celled tornado-like vortex. Haan et al. (2010), using the Iowa State University (ISU) tornado simulators, recorded transient wind loads on a one-story model building (91 mm × 91 mm × 66 mm) with a gable roof. Geetha Rajasekharan et al. (2013) examined how the net local roof wind force is influenced by the relative location of a simulated vortex to a model building of 30 mm × 30 mm × 30 mm. While extremely useful, all previous studies were performed on very small building models (less than 10 cm in dimension) which do not allow for a meaningful wind-induced load measurement with an adequate resolution. Recently, Case et al. (2014) investigated the effect of geometry on pressures experienced by modeled low-rise buildings as wide as 23 cm. However, as previously

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discussed by Refan et al. (2013), the relation between the vortex simulated at the ISU and real tornadoes has not yet been clarified and therefore, the 1:100 scaling ratio used in these set of experiments is debatable.

The effect of *S* has been investigated in relatively small scale Tornado Vortex Chambers (TVC) mainly through qualitative flow visualizations or point velocity measurements (Lund et al., 1993). More recently, Hashemi Tari et al. (2010) have used PIV measurements to define the flow field dependency on swirl but their experiments were again at small scales and limited to $S < 0.7$. Numerical simulations using both RANS and LES models have been employed to study swirl ratio effects on the overall flow characteristics (Nolan et al., 2017; Bryan et al., 2017; Liu and Ishihara, 2016; Natarajan and Hangan, 2012; Hangan and Kim, 2008).

The dependency of tornado vortex characteristics on Reynolds number has been investigated in few studies. Ward (1972), Davies-Jones (1973, 1976) and Church et al. (1979) showed that for a given geometry, if Re_r is large enough, vortex characteristics, e.g. the core radius, are independent of the Re_r and are mostly controlled by *S*. These results are supported by recent numerical modeling of Fiedler and Garfield (2010) and experimental simulations of Refan and Hangan (2016). However, in all previously discussed studies, Re_r dependency of the flow is investigated over a narrow range of Reynolds numbers with less than one order of magnitude difference.

The recently designed and built wind facility at the University of Western Ontario, namely the WindEEE Dome, can produce 4.5 m wide and 4 m tall tornado vortices of high Re_r and over an extended range of *S*. This simulator, for the first time, provides the spatial resolution needed for the investigation of the surface layer of tornado-like vortices as well as for tornado wind-induced load studies of various structures and buildings.

In the current study, exceptionally detailed surface pressure measurements for stationary (non-translating) tornadoes are used to investigate the effects of *S* and Re_r on the vortex structure and to investigate Re_r independency. A large field of view (LFOV) Particle Image Velocimetry setup is further used to study the flow field dependency on *S*, complementing the vortex core and surface layer results from the pressure measurements. The PIV measurements are also used to compare the laboratory velocity field with full scale tornado wind field data. The scaling ratios (i.e. geometric and velocity scales) of simulated vortices are identified. This unique set of measurements creates a one-of-a-kind data base impacting the validation of numerical simulations and allowing for development of advanced empirical and analytical models for tornado-like vortices. Also, outcomes of this research aim to bring important insights into the effects of *S* and Re_r on the structure of tornado vortices.

2. Simulator description

The WindEEE Dome is a hexagonal wind testing chamber capable of simulating straight atmospheric boundary layer flows, tornado vortices, gust fronts and downbursts. Herein, the facility is described from tornado simulations point of view. The design concept of the WindEEE Dome as well as its capability to produce a large range of tornado-like vortices are discussed in great detail by Hangan (2014) and Refan and Hangan (2016). Tornado vortices are produced using 6 fans at the top chamber to provide updraft and periphery vanes at a given angle at the lower chamber to generate rotation (see Fig. 1). A bell-mouth connects the lower chamber to the upper one. The coupling between the suction and the swirl at the surface level produces tornadoes of various sizes and structures. A guillotine system is employed to translate the bell-mouth and consequently the vortex at up to 2 m/s over a 5 m distance. The test chamber is 25 m in diameter and approx. 4 m high.

There are three main controlling parameters in a tornado flow: aspect ratio ($a = h/r_0$), swirl ratio ($S = r_0\Gamma_{max}/2Qh$) and radial Reynolds number ($Re_r = Q/2\pi\nu$). Where, *h* is the inflow depth, r_0 is the updraft radius, Γ_{max} is the maximum circulation in the flow, *Q* is the volumetric flow rate per unit axial length and ν is the kinematic viscosity of the fluid. The swirl ratio in WindEEE Dome can be adjusted by changing the angle of vanes at the periphery while *Q* (and consequently the Re_r) can be set by varying the top fans speed. The inflow depth is fixed at 0.8 m. However, the updraft radius is variable between 0.8 m and 2.25 m. Therefore, the aspect ratio is varied between 0.35 and 1 by changing the updraft opening.

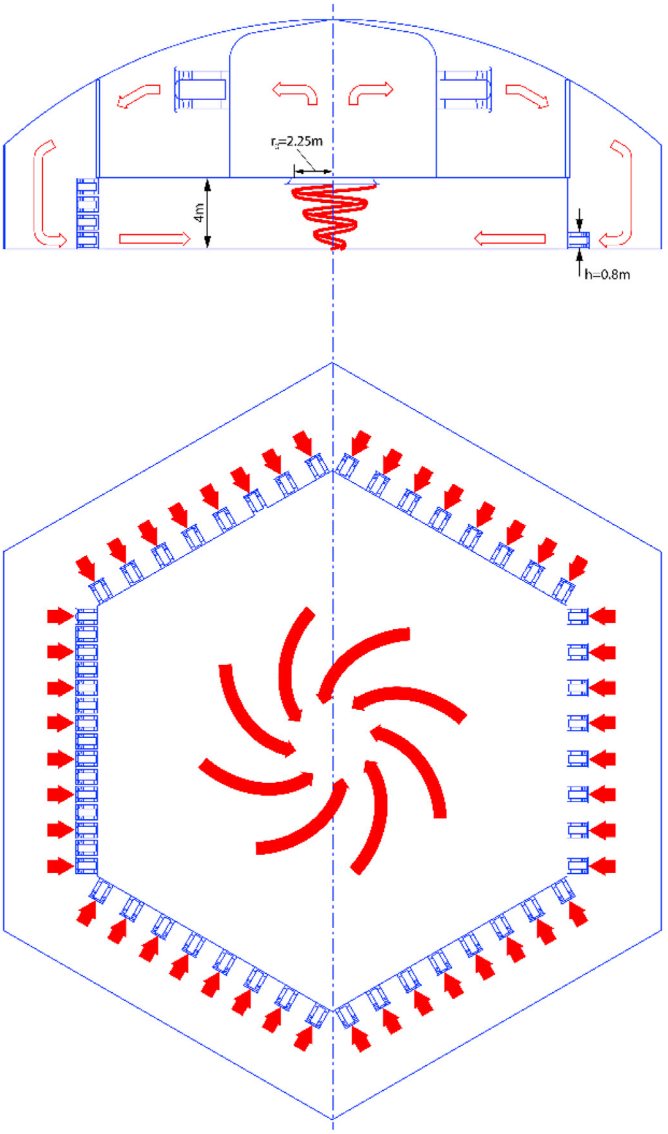

Fig. 1. Design concept of tornado vortex generation in WindEEE Dome.

3. Experimental set-up and data analysis

To investigate simulated tornado vortices characteristics, a series of experiments was planned and performed in the WindEEE Dome at the University of Western Ontario. These tests are as follows: (i) flow rate measurements at the updraft region, (ii) static pressure measurements on the floor of the chamber and (iii) horizontal velocity field measurements at different heights along the axis of the vortex. The smallest aspect ratio, i.e $a = 0.35$, was selected for these experiments as recent field measurements (Kosiba and Wurman, 2013) have shown an inflow depth of 10–14 m for tornadoes, much shallower that previously reported values.

The configurations, i.e. combination of *S*, Re_r and heights above ground (*z*), investigated in this study for every test are summarized in Table 1. Note that given the extent of the effort required to perform PIV measurements and the estimated geometric scale of the vortex (~1:150),