









and data of Manchester tornado. The reason may be that the real tornado has the translation velocity, while the tornado vortex in present research is static.

In short, it can be concluded that the vortex generated in the TVS can be considered as a reasonable representation of actual tornadoes, and it can be applied to simulate the tornadoes with different scales and swirl ratios.

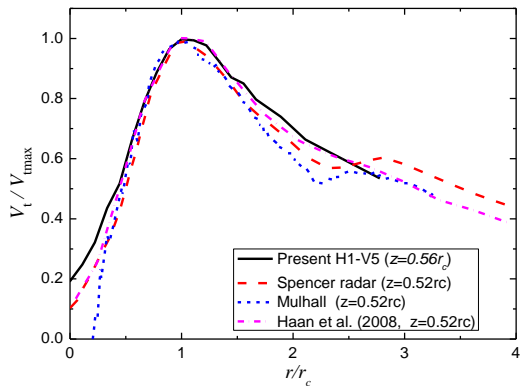


Fig. 3 Comparison of normalized mean tangential velocity profiles

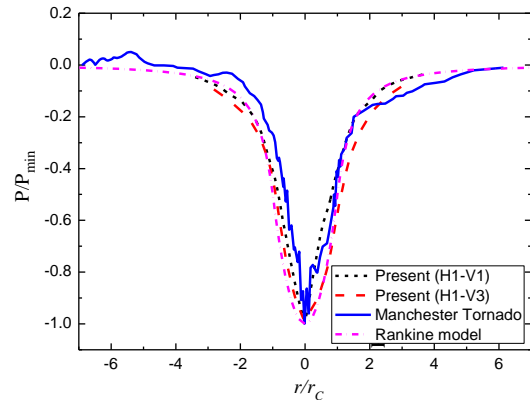
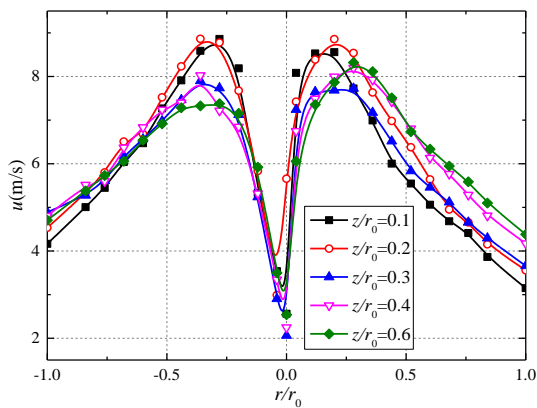


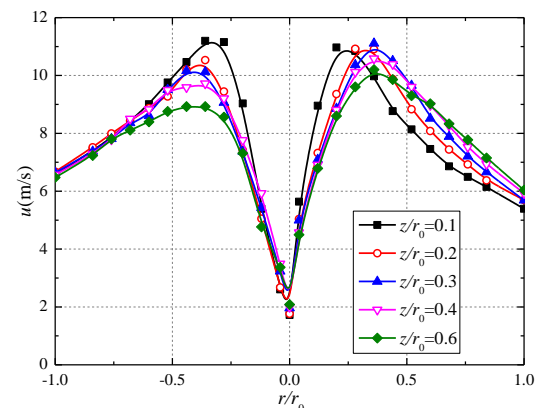
Fig. 4 Comparison of normalized mean surface pressure profiles

### 3.2 Mean tangential velocity

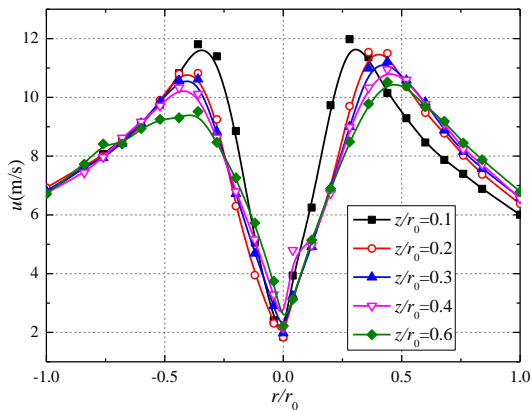
Fig. 5 presents the mean tangential velocities at different height for four cases. It can be obvious found that the velocity profiles of different cases show substantially "M" type, where the mean tangential velocity increase and decrease with the increase of core radius inside and outside of the core cell, respectively.



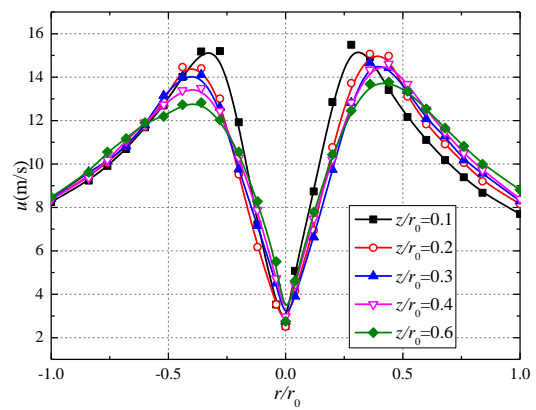
(a) H1-V1 ( $S=0.114$ )



(b) H2-V3 ( $S=0.300$ )



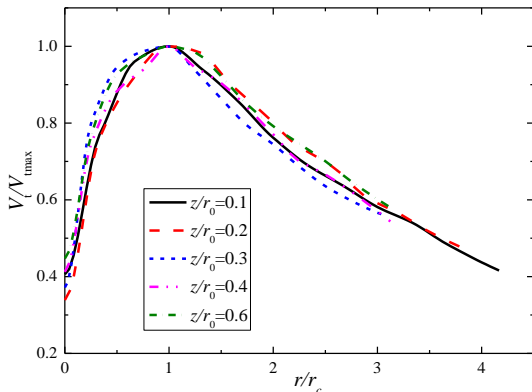
(c) H3-V5 ( $S=0.722$ )



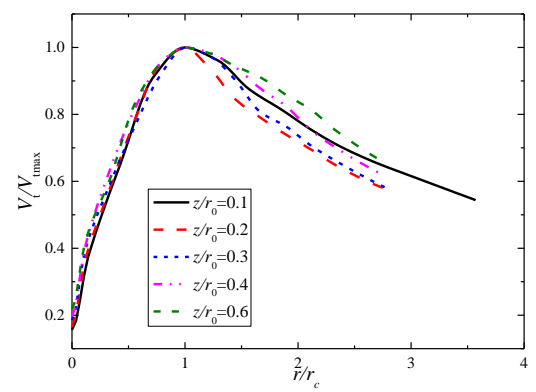
(d) S-H1-V5 ( $S=0.541$ )

Fig. 5 The mean tangential velocity for different cases

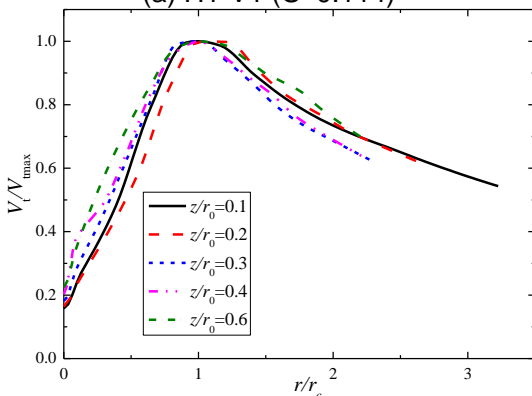
In order to study the effects of swirl ratio on mean tangential velocities, all the results are obtained using the velocity measurements from the horizontal plane measurements and normalized by the maximum tangential velocities corresponding to each height at each given swirl ratio. As shown in Fig. 6, Both inside and outside of the core radius, the variation of mean tangential velocity shows gentler with increase in vane angle, which means that the collapse of data improves with increase in swirl ratio. However, the trend of profile is consistent for different swirl ratio, which is similar with the Rankine vortex model.



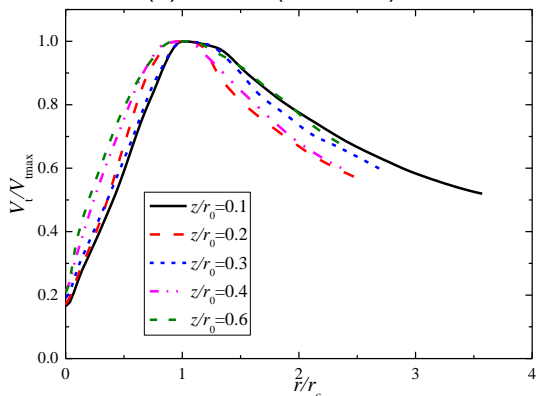
(a) H1-V1 ( $S=0.114$ )



(b) H2-V3 ( $S=0.300$ )



(c) H3-V5 ( $S=0.722$ )



(d) S-H1-V5 ( $S=0.541$ )

Fig. 6 The normalized mean tangential velocity profiles for different cases

As mentioned above, the core radius is defined as the radius of maximum mean tangential velocity. Fig. 7 shows the variation of core radius for different case at each height, where the radial positions are scaled by the radius of updraft hole  $r_0$ . It can be obviously found that the core radius increases with an increase in swirl ratio, which was also found by Tari et al. (2010).

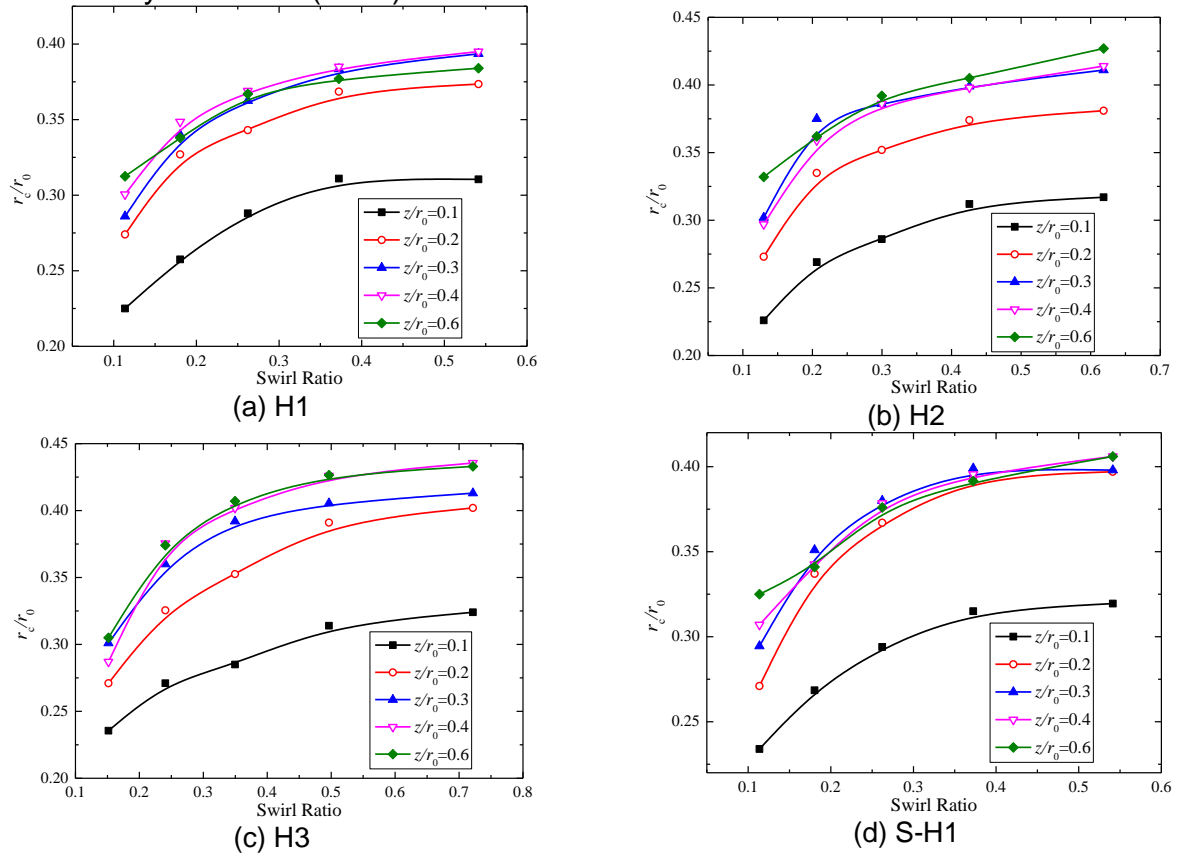


Fig. 7 Core radius versus height for different swirl ratios

Fig. 8 presents the variation of ore radius versus height for different cases. As for all the cases, the core radius increases rapidly with the increase of height near the ground ( $z/r_0 < 0.3$ ). It implies that the tornado vortex simulated by our TVS has a funnel-shaped structure near ground, which is common shape of the real tornado. However, as for the areas far from near ground, the core radius still increases rapidly, nearly constantly and constantly with the increase of height, when the swirl ratio is low, intermediate and high, respectively. For example, at  $S=0.114$  (Case of H1-V1), where a low swirl jet occurs, the core radius are about 56mm, 68mm, 71mm and 78mm at height of  $z/r_0=0.1, 0.2, 0.3$  and  $0.6$ , respectively. At intermediate swirl  $S=0.372$  (Case of H1-V4), the core radius are about 78mm, 92mm, 94mm and 95mm at height of  $z/r_0=0.1, 0.2, 0.3$  and  $0.6$ , respectively. It means the vortex core radius is almost constant with height corresponding to a columnar type vortex. With increase of swirl ratio, the core radius presents a local maximum and becomes asymptotically constant as for Case of H1-V5 ( $S=0.541$ ). The reason may due to the tornado flow directly determined by swirl ratio, which include the structure and scale.

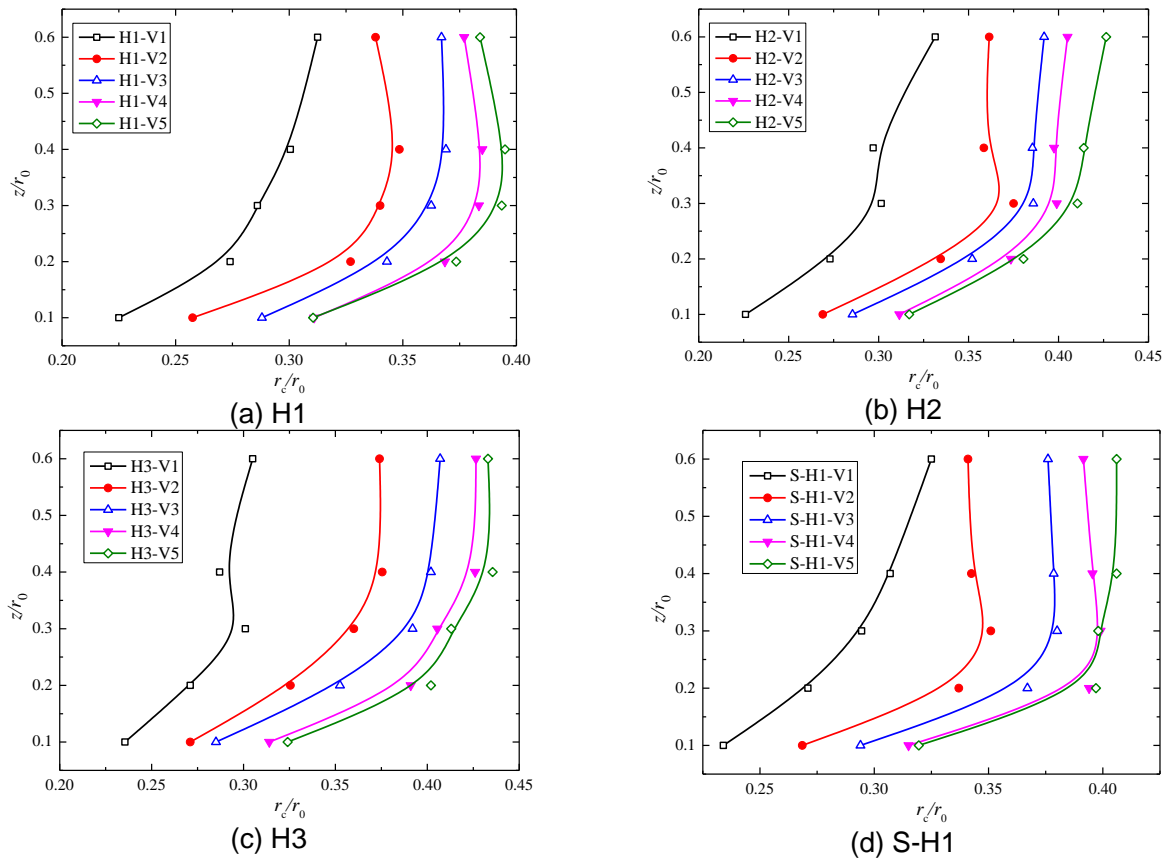
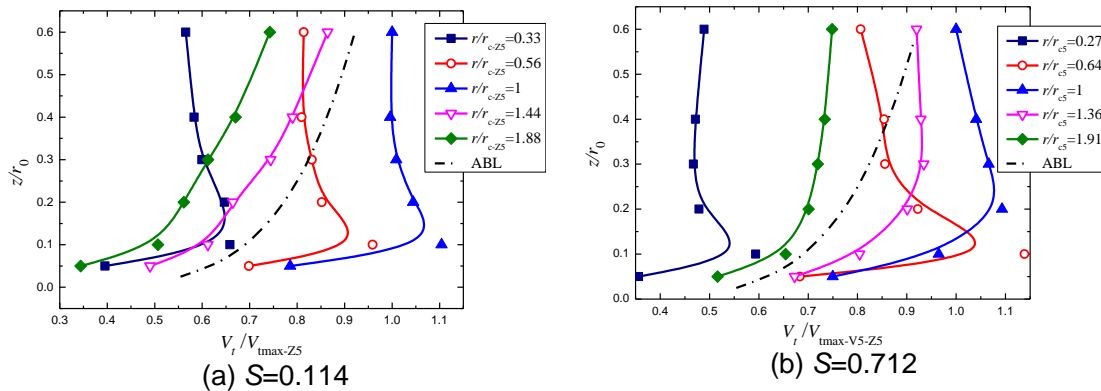


Fig. 8 Core radius versus height for different cases

In addition, Fig. 9 shows the distribution of mean tangential velocity with respect to height for the two swirl ratios, where the mean tangential velocity was normalized by the maximum tangential velocity at height of  $z/r_0=0.6$ . Comparing the profile of conventional atmospheric boundary layer, that of tornado-like flow shows strong velocity shear, which is more obvious with increase of swirl ratio.



(a)  $S=0.114$

(b)  $S=0.712$

Fig. 9 Tangential velocity profiles for different swirl ratios

### 3.3 Mean radial velocity and axis velocity

Fig. 10 and Fig. 11 present the mean radial and axis velocity profiles at each height, where the radial positions are scaled by the radius of updraft hole  $r_0$  and the mean velocity is normalized by the maximum tangential velocity. From Fig. 10, it can be found that the maximum radial velocity decreases with increase in swirl ratio, which has similar trend with the results of Haan et al. (2008). Meanwhile, near to the core region the radial



velocity decreases and shifts to axis velocity. As shown in Fig. 11, the axis velocity near central region (inside of the core) is negative for H1-V1 case. It means that the two-cell tornado exists when swirl ratio is large enough, which will be also demonstrated by the surface pressure profile as mentioned below.

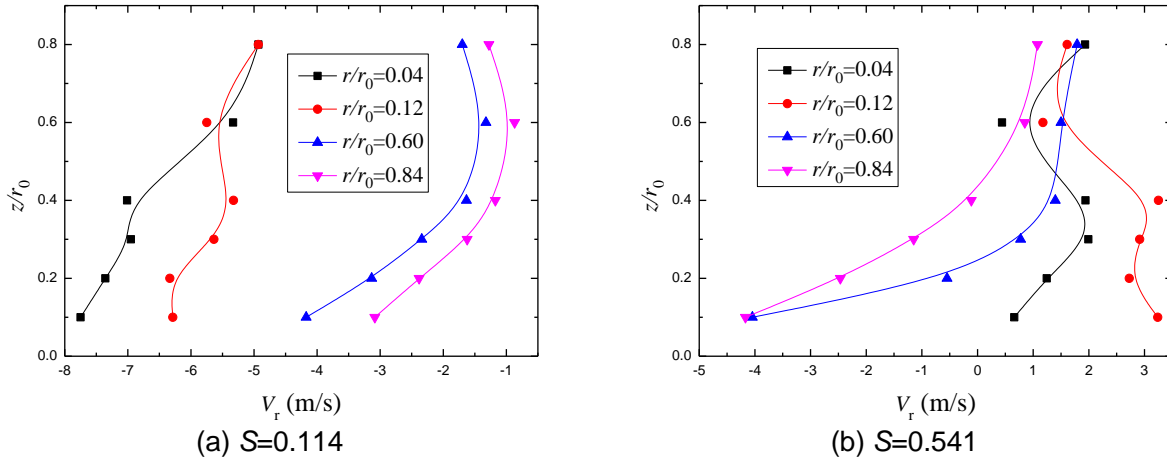


Fig. 10 The radial velocity profiles

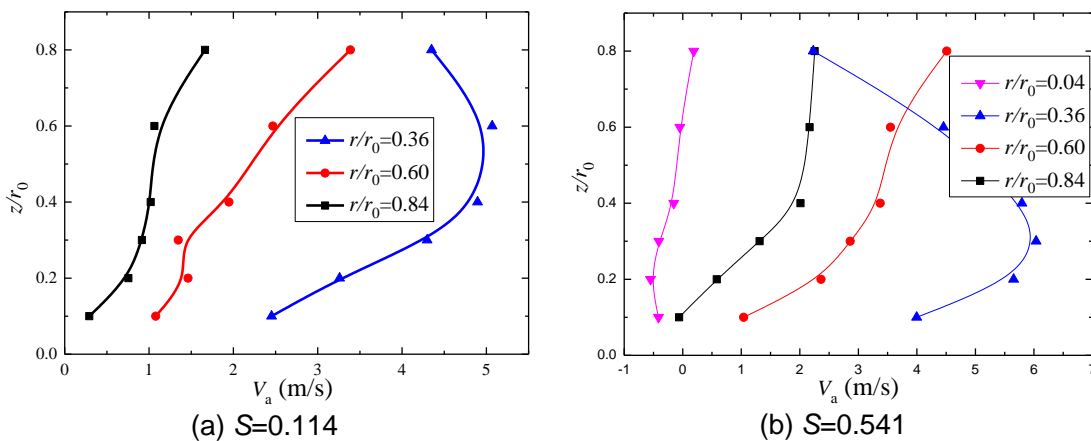


Fig. 11 The axial velocity profiles

### 3.4 Turbulence characteristics

In order to investigate the turbulence characteristics, the root mean square (RMS) of velocity are analyzed. As shown in Fig. 12, the fluctuation of tangential velocity  $V_{trms}$  increase by increasing of swirl ratio at different heights. The fluctuation of radial and axis velocity also have a similar trend, which means that the turbulence characteristics are determined by the swirl ratio. The results also show that the locations of maximum rms-value for all the cases do not appear in the position of  $r/r_c=1$ . Meanwhile, the turbulence shows stronger near to the ground by comparing the results at different heights.

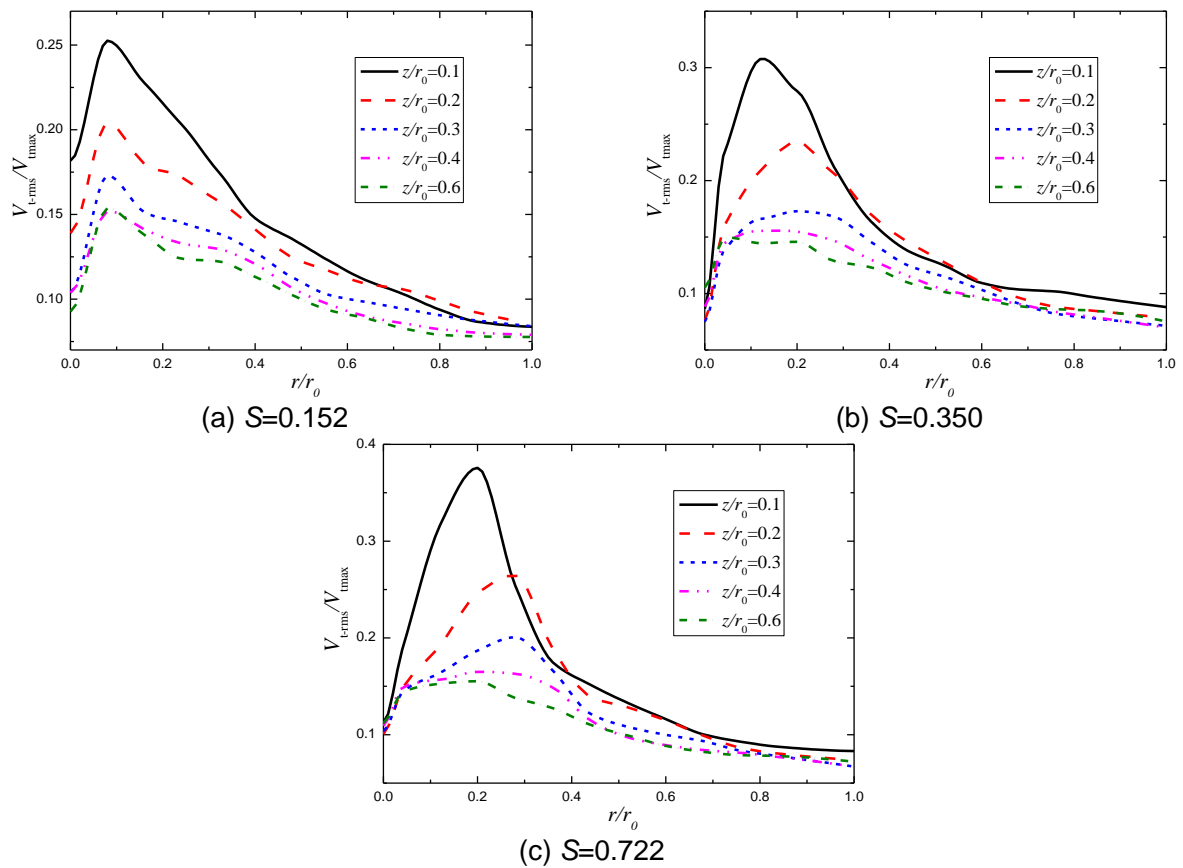


Fig. 12 Profiles of RMS-velocity for different swirl ratios

#### 4 CONCLUDING REMARK

The flow structures of tornado-like vortex dynamics were investigated in a prototype tornado vortex simulator (TVS) at Tongji University.

The results shows that the mean tangential velocity profiles agree well with the data from Spencer and Mulhall tornados. In addition, the normalized surface pressure profile in our TVS fits well the data from Manchester tornado. Thus the tornado vortices generated by our TVS can be considered as actual tornadoes and can be used to carry out further researches of tornado effects on structures.

The mean tangential velocity, as well as core radius increase with the increase of swirl ratio, while the maximum radial velocity decreases with increase in swirl ratio. As the core radius increases with the height, the near-ground tornado vortex shows a funnel-shaped structure. The flow becomes more turbulent with increase in swirl ratio. The negative axis velocity and flattened surface pressure profile inside the core radius shows that the two-cell tornado vortex exists for the large swirl ratio.

#### 5 ACKNOWLEDGEMENT

This research was funded in part by the Natural Science Foundation of China (NSFC) Grant No. No. 51278435, 51378442 and 51478402.

## 6 REFERENCES

1. Bienkiewicz, B., Dudhia, P., 1993. Physical modeling of tornado-like flow and tornado effects on building loading. In: Proceedings of the Seventh US National Conference on Wind Engineering, vol. 1, pp. 95–104.
2. Church, C.R., Snow, J.T., Baker, G.L., Agee, E.M., 1979. Characteristics of tornado-like vortices as a function of swirl ratio: a laboratory investigation. *J. Atmos. Sci.* 36, 1755–1766.
3. Chang, C.C., 1971. Tornado wind effects on buildings and structures with laboratory simulation. In: Committee, J.O. (Ed.), Proceedings of the Third International Conference on Wind Effects on Buildings and Structures, pp. 231–240.
4. Cleland, J.D., 2001. Laboratory measurements of velocity profiles in simulated tornado-like vortices. *J. Undergrad. Res. Phys.* 18, 51-57.
5. Davies-Jones, R.P., 1973. The dependence of core radius on swirl ratio in a tornado simulator. *J. Atmos. Sci.* 30, 1427–1430.
6. Golden J.H., Snow J.T., 1991. Mitigation against extreme windstorms, *Rev. Geophys.* 29 (4), 477-504.
7. Haan, F.L., Sarkar, P.P., Gallus, W.A., 2007. Design, construction and performance of a large tornado simulator for wind engineering applications. *Eng. Struct. J. Earthquake Wind Ocean Eng.* 30, 1146–1159.
8. Hashemi-Tari P, Gurka R, Hangan H (2010) Experimental investigation of tornado-like vortex dynamics with swirl ratio: the mean and turbulent flow fields. *J. Wind Eng. Ind. Aerodyn.* 98, 936–94.
9. Ishihara T, Oh S, Tokuyama Y (2011) Numerical study on flow fields of tornado-like vortices using the LES turbulence model. *J Wind Eng. Ind. Aerodyn.* 99:239–248.
10. Lewellen, D.C., Lewellen, W.S., Xia, J., 2000. The influence of a local swirl ratio on tornado intensification near the surface. *J. Atmos. Sci.* 57, 527–544.
11. Lund, D.E., Snow, J.T., 1993. Laser Doppler velocimetry measurements in tornado like vortices. In: Church, C., Burgess, D., Doswell, C., Davies-Jones, R. (Eds.), *The Tornado: Its Structure, Dynamics, Prediction, and Hazards. Geophysical Monograph Series*, vol. 79. American Geophysical Union Press, pp. 297–306.
12. Lee, J., Samaras, T., 2004. Pressure measurements at the ground in an F-4 tornado. In: Proceedings of the 22nd Conference on Severe Local Storms, Hyannis, MA.
13. Mishar, A.R., James, D.J., Letchford, C.W., 2008. Physical simulation of a single-celled tornado-like vortex, Part A. Flow field characterization. *J. Wind Eng. Ind. Aerodyn.* 96, 1243–1257.
14. Matsui, M., Tamura, Y., 2009. Influence of incident flow conditions on generation of tornado-like flow. In: Proceedings of the 11th American Conference on Wind Engineering, Puerto Rico, USA.
15. Rotunno, R., 1979. A study in tornado-like vortex dynamics. *J. Atmos. Sci.* 36, 140–155.
16. Sabareesh, G. R., Matsui, M., Tamura, Y., 2012. Dependence of surface pressures on a cubic building in tornado like flow on building location and ground roughness. *J. Wind Eng. Ind. Aerodyn.* 103, 50-59.
17. Ward, N.B., 1972. The exploration of certain features of tornado dynamics using a laboratory model. *J. Atmos. Sci.* 29, 1194–1204.
18. Wei, W., Zhao, Y., 1995. The characteristics of tornados in China. *Meteorological Monthly (in Chinese)*. 21(5): 36-40.