Differences in flow structures of tornado vortex and efficiency of different tornado chambers

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ABSTRACT:
Identifying similarities in flow pattern such as the way in which flow enters, progresses and exits tornado chamber (TC), different TCs are classified into five major categories. Experimental and CFD TCs falling in each of five categories are listed and the differences in flow structure of tornado vortex in those TCs are analysed by comparing touchdown swirl ratio (S_T). However, while comparing S_T of different TCs, it was found that different definitions of swirl ratio (S) are used in different works of literature. So, in this work, different definitions of S are converted into a consistent form for comparison. Besides, efficiency of different TCs is also analysed by comparing S_T. The higher the S_T, the higher the energy a TC needs as well as higher is the CFD computations. From analysis, the TCs with side openings and fully open outlet at top are found to be more efficient than others.

Keywords: swirl ratio, touchdown, efficiency

1. INTRODUCTION

With increasing swirl ratio (S), a single-celled vortex first touches down and then transforms into a double-celled vortex. The swirl ratio at which vortex touches the base of tornado chamber (TC) is termed as touchdown swirl ratio (S_T). The effect of geometrical differences and/or the flow generation mechanism of different tornado chambers may have their own contribution to disparity of S_T values observed in different chambers but different ways of defining swirl ratios by choosing different radial locations of flow domain is also a major factor for the disparity and a wide range of S_T values in different TCs. In Fig. 1, a sketch of a typical tornado chamber is shown and some associated notations used to describe chamber geometry and tornado flow is labeled.

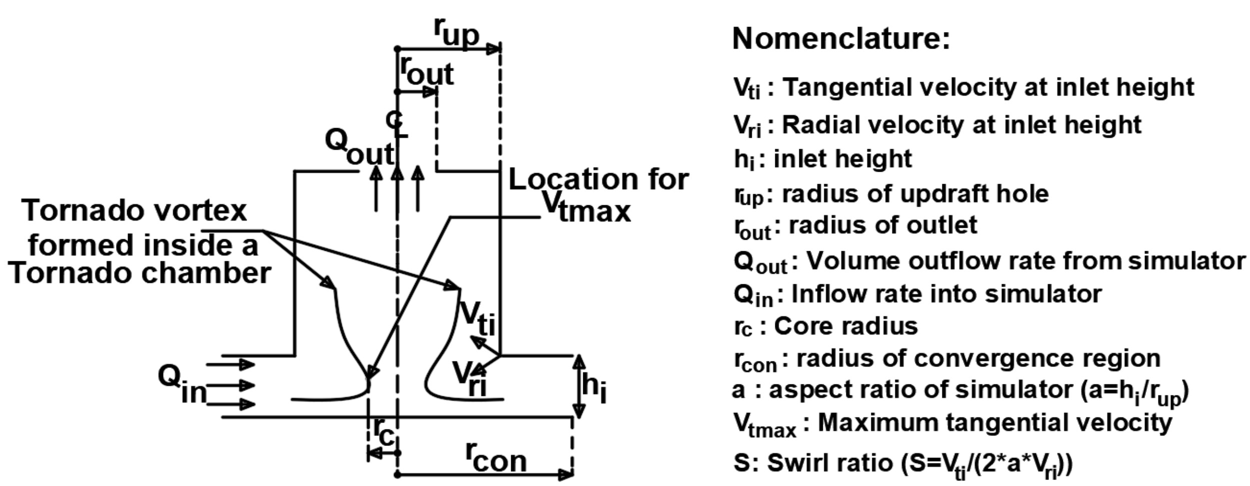

Figure 1. Graphical representation of notations used to describe geometry and tornado flow in a tornado chamber

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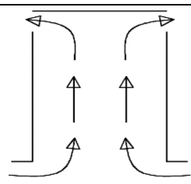
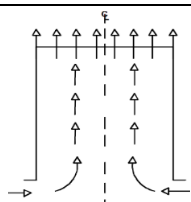
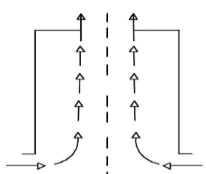
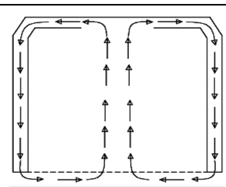
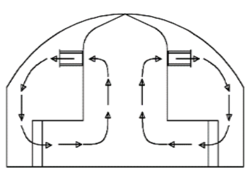
2. RESULTS

Tornado chambers around the world have differences in geometry and tornado flow generation mechanism. However, identifying the macroscale flow similarities such as the manner in which flow enters, progresses and exits via outlet, tornado chambers can be broadly categorized into 5 major types, viz. (a) Side Opening System (SOS) (b) Top Full Opening System (TFOS) (c) Top Partial Opening System (TPOS) (d) ISU and (e) WindEEE. In Table 1, the value of S_T of different TCs is documented along with ratio of outlet to updraft section whereas in Table 2, the total computation time required for tornado chambers with different S_T is documented.

Table 1. Documentation of touchdown swirl ratio in different tornado chambers using consistent definition of 'S'

S.N.	Tornado Chamber	References	r_{out}/r_{up}	Outlet Condition	S_T
1		a) Tang et al. (2018) - EXP b) Verma and Selvam (2020) - CFD c) Harlow and Stein (1974) – CFD	a) 0.18 b) 0.18 c) 0.22	SOS	a) 0.22-0.36 b) 0.22-0.36 c) 0.29
2		a) Verma and Selvam (C) - CFD b) Rotunno (1977) - CFD c) Verma and Selvam (2021) - CFD d) Ward (1972) - EXP e) Kashefizadeh et al. (2019) –CFD	a) 1 b) 1 c) 1 d) 1 e) 1	TFOS	a) 0.30 b) ≈0.40 c) 0.45 d) 0.48 e) 0.50
3		a) Church et al. (1977) – EXP b) Verma and Selvam (C)-CFD c) Gillmeier (2019) - EXP d) Verma and Selvam (C) - CFD e) Liu and Ishihara (2015) – CFD	a) 0.89 b) 0.75 c) ≈ 0.32 d) 0.50 e) 0.67	TPOS	a) 0.34 b) 0.45 c) 0.50-0.69 d) 0.60 e) 4.42
4		a) Yuan et al. (2019) - CFD b) Haan et al. (2008) – EXP	a) 0.376 b) 0.375	ISU	a) 1.46 b) 2.23
5		a) Karami et al. (2019)- EXP ; Refan and Hangan (2018) – EXP	a) 0.064- 0.18	WindEEE	a) 1.96

*Note:- In 3rd column, 'C' indicates CFD simulation from current work; EXP: Experimental; CFD : CFD simulation

Table 2. Comparison of total computation (CPU) time of Tornado Chambers with different S_T

S.N.	Tornado chamber	S_T	Total Grid points & simulation type	Total computation time (minutes)
1	SOS (a = 1.0)	0.22	75 x 75 x 70 (Transient)	460
2	TFOS (r_{out}/r_{up} = 1.00)	0.40	75 x 75 x 70 (Transient)	2136
3	TPOS (r_{out}/r_{up} = 0.75)	0.45	75 x 75 x 70 (Transient)	3655
4	TPOS (r_{out}/r_{up} = 0.50)	0.60	75 x 75 x 70 (Transient)	6778

In Table 2, the aspect ratio of SOS type chamber is used rather than r_{out}/r_{up} (= 0.18 from Table 1) ratio because the reported value of $S_T = 0.22$ corresponds to configuration of tornado chamber at aspect ratio of unity. For the same tornado chamber but with aspect ratio of 0.5, touchdown was observed at 0.36. As aspect ratio of tornado chamber can influence the value of S_T, the aspect ratio of the reported case is explicitly stated for SOS in Table 2. Besides, the total number of grid points used to discretize the computational domain is stated in 4th column of Table 2 and all the simulation work in Table 2 are transient calculations.

3. CONCLUSIONS

Using a single consistent definition of swirl ratio, the touchdown swirl ratio of different TCs are compared. Different flow structures of tornado vortices exist in different tornado chambers at similar swirl ratio as each tornado chamber has different value of S_T (Refer Table 1). Due to differences in flow structure of tornado vortices from different tornado chambers, tornado forces and pressures on buildings are also likely to differ from one tornado chamber to another. This is due to the fact that different flow structures of tornado vortices have different wind profiles and pressure distribution and thus their interaction with buildings is likely to produce different impacts resulting in different force and pressure coefficients. Similarly, it can be observed from Table 2 that the TCs that have higher S_T takes longer computation time for completion of simulation, so, the TC with comparatively low values of S_T are more efficient than those with higher S_T. From Table 2, it is concluded that the tornado chambers with side openings (SOS type TCs) are more efficient in producing a stationary touched-down tornado vortex than others.

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