Numerical Study on the Effects of Surface Roughness on Tornado-like Flows

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ABSTRACT

The effect of surface roughness on tornado-like vortices is studied using Fluent6.2 software. The investigations are carried out for swirl ratios between 0.1-2.0, covering a broader range of values than hitherto. The effects on velocity vectors, pressure deficit and core radius are observed. Only mild roughness case is considered at this stage. While there is broad agreement between the current results and earlier reported ones, certain differences have also been noted with respect to roughness effects on tangential velocity.

INTRODUCTION

Previous studies have shown that surface roughness affects tornadic flow; in particular it affects the velocity distribution, pressure distribution and the core radius of the flow. For tornado-like flows Lewellen[1] and Davies-Jones[2] have shown that the main governing non-dimensional parameters are the aspect ratio $A = H_0/R_0$ (R_0 is the radius of updraft and H_0 is the depth of inflow), the Swirl ratio $S = V_0/2AU_0$, (U_0 and V_0 are radial and tangential velocity at R_0), Reynolds number and Froude number. Of these, the swirl ratio is seen to be the dominant governing parameter (Ward[3] and Church et al.[4]) and so the study of effect of surface roughness across a range of swirl ratios is important.

Dessens[5] and Leslie[6] have studied the effects of surface roughness on tornadic flows in laboratory simulations. Their studies have shown that the increase in surface roughness causes the radial and axial velocities to increase and tangential velocities to decrease. Church and Snow[7] argued that in these earlier experimental studies, roughness elements used in the simulations were extreme when compared to atmospheric roughness. Consequently, the effect of roughness may have been over stated in some of the results. Rostek et al.[8] used properly scaled surface roughness elements in a laboratory simulation, but only studied the roughness effect on radial surface pressure deficit for different swirl ratios.

Lewellen and Sheng[9] have analyzed the effect of surface roughness numerically and arrived at conclusions similar to that of laboratory simulations. However, their study only addressed two swirl ratios. Recently Kuai et al.[10] have numerically studied the effect of surface roughness for swirl ratios less than 0.21.

The present work attempts to address the effect of surface roughness on tornado-like flows for a large range of swirl ratios (0.1-2.0). Numerical analysis is carried out using second order RANS models in Fluent6.2. The effects on radial, axial and tangential velocity profiles are examined. Also the effects on the surface pressure distribution and core radius are investigated. The length scale between laboratory scale simulation and atmospheric vortex given in Hangan and Kim[11] is used to scale the domain. The roughness is introduced in the simulation as an equivalent sand grain roughness as discussed in Blocken et al.[12] In the following section the numerical analysis is briefly discussed with modeling roughness and numerical setup. The paper concludes with the results and discussion and preliminary conclusions

NUMERICAL SIMULATION

MODELING ROUGHNESS

Roughness effects are introduced in CFD codes by modifying the wall function which is otherwise based on the universal near-wall velocity distribution (log law). In Fluent6.2, the modified wall function is given by

$$\frac{U_P u^*}{\tau_w/\rho} = \frac{1}{\kappa}\ln\left(E\frac{u^* y_P}{\nu}\right) - \Delta B \tag{1}$$

Where U_P and y_P are the velocity and height at the centre point *P* of the wall adjacent cell. E is the empirical constant for the smooth wall with a value 9.793, τ_w is the wall shear stress, ρ is the fluid density and u^* the wall friction velocity defined as

$$u^* = C_\mu^{1/4} k_P^{1/2} \tag{2}$$

In the above equation, k_P denotes the turbulent kinetic energy in the wall adjacent cell centre point *P* and C_μ is a constant with default value 0.09.

The basis for the modification of the wall function (Equation 1) comes from the experiments of Nikuradse[13] on roughness effects on flow in pipes roughened with sand grains. He showed that the mean velocity distribution near a rough wall is parallel to the log law distribution, i.e. with the same slope (*1/κ*) but different intercept (*ΔB*). In Fluent 6.2, the roughness function (*ΔB*) *is* defined as a function of dimensionless sand grain roughness height K_S^+.

$$K_S^+ = u^* K_s / \nu \tag{3}$$

Where K_S is the equivalent sand grain roughness height. Depending on the value of K_S^+, the roughness is classified in to three regimes: aerodynamically smooth ($K_S^+ < 2.25$), transitional ($2.25 \le K_S^+ < 90$) and fully rough ($K_S^+ > 90$). The formula for *ΔB* depends on the roughness regime and is given by Cebeci and Bradshaw[14]. The tornadic flow over rough terrain falls in the fully rough regime, and the formula corresponding to this regime is the following.

$$\Delta B = \frac{1}{\kappa}\ln\left(1 + C_S K_S^+\right) \tag{4}$$

C_S is the roughness constant with a range of 0-1. In Fluent6.2 the roughness is introduced by specifying the values for the sand grain roughness height K_S and the roughness constant C_S in the wall boundary condition.

As Fluent introduces roughness as sand-grain roughness height, a relationship between the aerodynamic roughness lengths y_0 and the equivalent sand-grain roughness heights K_S is needed to numerically simulate the effect of surface roughness in tornadic flow. Based on the first order continuity fitting of the atmospheric boundary layer (ABL) log law and the modified wall-function log law (Equation 1) at height y_P, Cebeci and Bradshaw[14] arrived at the relationship as

$$K_S = \frac{9.793}{C_S} y_0 \tag{5}$$

For a default value of $C_S = 0.5$, the Equation 5 simplifies to $K_S \approx 20 y_0$. This equivalent sand-grain roughness is used in this paper. However while implementing roughness as equivalent sand-grain roughness, there is a limitation in Fluent code that needs to be considered. The height of the centre point *P* of the wall-adjacent cell to the ground surface y_P needs to be larger than the physical roughness height K_S (i.e. $y_P > K_S$). For modeling roughness in a city-centre where the y_0 value is around 2 m, the K_S is around 40 m and the first cell height has to be greater than twice the K_S at 80 m. In tornadic flow where the velocity profile for a height of 100 m is studied, this is not acceptable, so this method can only be applied to study low roughness terrains with smaller y_0, corresponding to open country, forested and thinly populated suburban terrains.

NUMERICAL SETUP

Hangan and Kim[11] matched a Doppler radar data for real scale tornado with a CFD simulation of a laboratory scale tornado with a cylindrical domain of radius 0.6m and height 0.6 m. By comparing the highest wind speed (and the height at which the highest wind speed occurs) in the CFD model and full scale data they approximated a length scale of 3756 and velocity scale of 12.8 between the CFD model and the real scale tornado.

A full scale tornado simulation (CFD model scaled up with the length and velocity scale) is computationally very expensive as the number of grid points required to maintain the non-dimensional wall unit y^+ between 30 and 500 is very high. On the other hand in a laboratory scale tornado, when the aerodynamic roughness lengths y_0 is scaled down using the above length scale and introduced as equivalent sand grain roughness height, the wall roughness falls in the aerodynamically smooth regime. In the current simulations an optimal domain of 1/20th the scale of full scale tornado was chosen so that the wall roughness falls in the fully rough regime and the non-dimensional wall unit y^+ is maintained between 30 and 500 less expensively. The cylindrical domain used in the current simulations is as shown in Figure 1 with radius R_0 equal to 112.68 m and height H_0 equal to 112.68 m.

Fluent6.2 software is used for the finite volume analysis and Reynolds Averaged Navier-Stokes (RANS) equations are solved on structured grids. The second order standard KE turbulence model with SIMPLEC pressure-velocity coupling is used.

The boundary conditions are as shown in Figure 1. The velocity inlet boundary condition is specified on the cylindrical surface, using the radial and axial velocity profiles shown in equations 7 and 8, along with the turbulent kinetic energy k and dissipation rate ε profiles for ABL modeled by Richards and Hoxey[15].

$$U(z) = U_h * (z/z_h)^{1/7} \tag{7}$$

$$V(z) = 2 * S * U(z) \tag{8}$$

$$k(z) = \frac{u_{ABL}^{*\,2}}{\sqrt{C_\mu}} \tag{9}$$

$$\varepsilon(z) = \frac{u_{ABL}^{*\,3}}{\kappa z} \tag{10}$$

Where U and V are radial and tangential velocities, U_h and z_h are the reference velocity and height (0.192 m/s, 4.695m), S is the swirl ratio, u_{ABL}^{*} is the ABL friction velocity and κ is the von Karman constant (~ 0.41). The bottom surface is defined as wall and standard wall function is used. For the zero roughness case (Y0), $K_S = 0$ is used, and for the mild roughness case (Y1) with $y_0 = 0.1$m, scaled down with length-scale of 1/20 and converted to equivalent sand-grain roughness, $K_S = 0.1$m and $C_S = 0.5$ is used. The top of the cylinder is defined as outflow boundary condition.

Initial structured grid was developed using the commercial software Gambit and subsequent grid adaptation was done using the 'Region-adaptation' feature in Fluent. The flow in the central near surface region is only of interest, so finer grids were adapted in the central near surface region as shown in Figure 2. Following grid convergence, grids comprising upwards of 300000 were used for simulations. Keeping in mind the limitation stated in the previous section, the wall adjacent cell centre point height is maintained at 0.125m and y^+ is around 300.

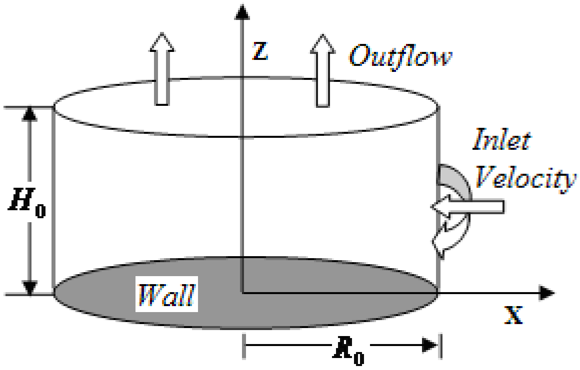

Figure 1: Computational domain with boundary conditions

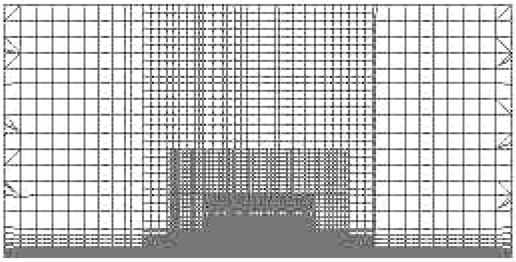

Figure 2: Cross-section view of the grid

RESULTS AND DISCUSSIONS

The numerical simulations were performed for swirl ratios ranging from 0.1 to 2.0. For all the swirl ratios, the velocity vectors along the Z-axis (height) were compared for the smooth and rough-wall cases at different radial locations. For a given swirl ratio, the radial location where maximum tangential velocity (V_{max}) was observed in smooth-wall flow is termed R_{max} and region between the centre and R_{max} called the core. For the smallest swirl ratio S = 0.1 (Figures 3 and 4), introducing roughness resulted in a mild increase in the radial and axial velocity velocities at radial locations inside the core ($R/R_0 < R_{max}/R_0 \sim 0.05$), closer to the centre. As the swirl ratio increased, the increasing trend in the radial and axial velocities was more pronounced, as shown in Figures 6 and 7 for the highest swirl ratio S = 2.0. Moreover there is increase in radial velocity at radial locations even away from the core ($R/R_0 > R_{max}/R_0 \sim 0.23$). Also, there is very high increase in axial velocity inside the core. Lewellen and Sheng[9], Dessens[5] and Leslie[6] have reported increase in radial and axial velocities and decrease in maximum tangential velocity. In the current simulations, the variation in tangential velocity does not completely match their results. While the introduction of roughness causes a decrease in tangential velocity at radial locations outside the core, there is an increase at locations inside the core. A possible explanation for this could be vortex stretching due to the increase in axial velocity inside the core. Two cases are illustrated in Figures 5 and 8 in support of this explanation.

For swirl ratio 0.1 (Figures 3 and 5); the increase in axial velocity inside the core is less and a correspondingly small increase in tangential velocity is observed. On the other hand for swirl ratio 2.0 (Figures 6 and 8); there is a substantial increase in the axial velocity inside the core and therefore greater increase in tangential velocity. However, certain limitations related to numerical damping and the averaging nature of RANS model adopted should be recognized. One possible outcome of these limitations is the inability to simulate multiple vortices at high swirl ratios (S > 1.5).

The central pressure deficit for the range of swirl ratios (0.1-2.0) is shown in Figure 9. For swirl ratios 0.1, 0.28 and 05 there is decrease in the central pressure deficit but an increase in the central pressure deficit is observed for higher swirl ratios.

The core radius at different normalized heights for the range of swirl ratios is shown in Figure 10. A decrease in core radius is observed for increased surface roughness. Mongi and Wang[16] reported an increase in core radius with the increase in roughness based on experimental study, but the radius is based on the measured width of the smoke filled core.

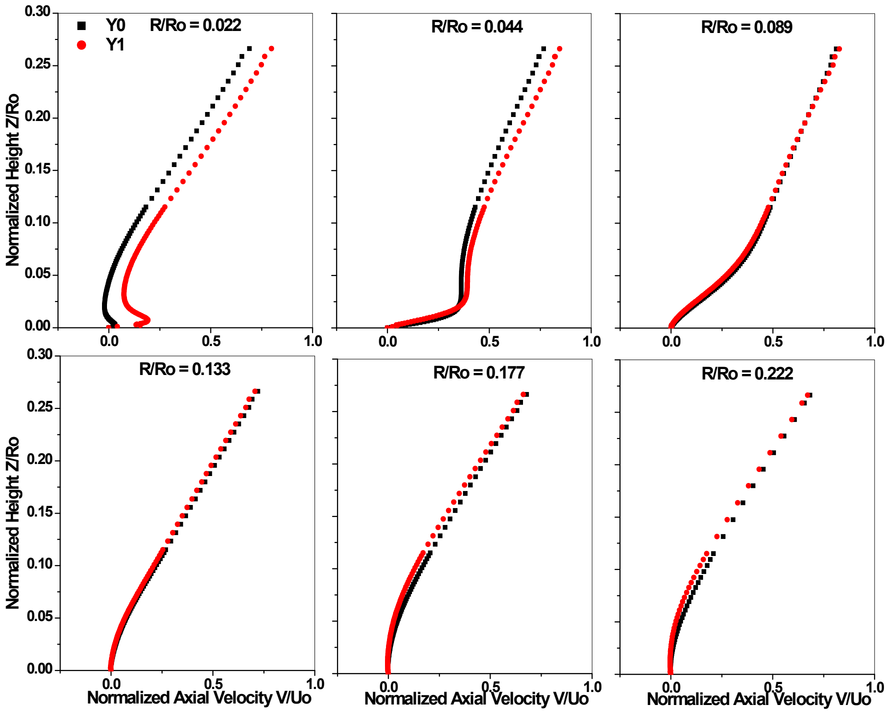

Figure 3: Normalized axial velocity along the normalized height for different radial location for swirl ratio 0.1

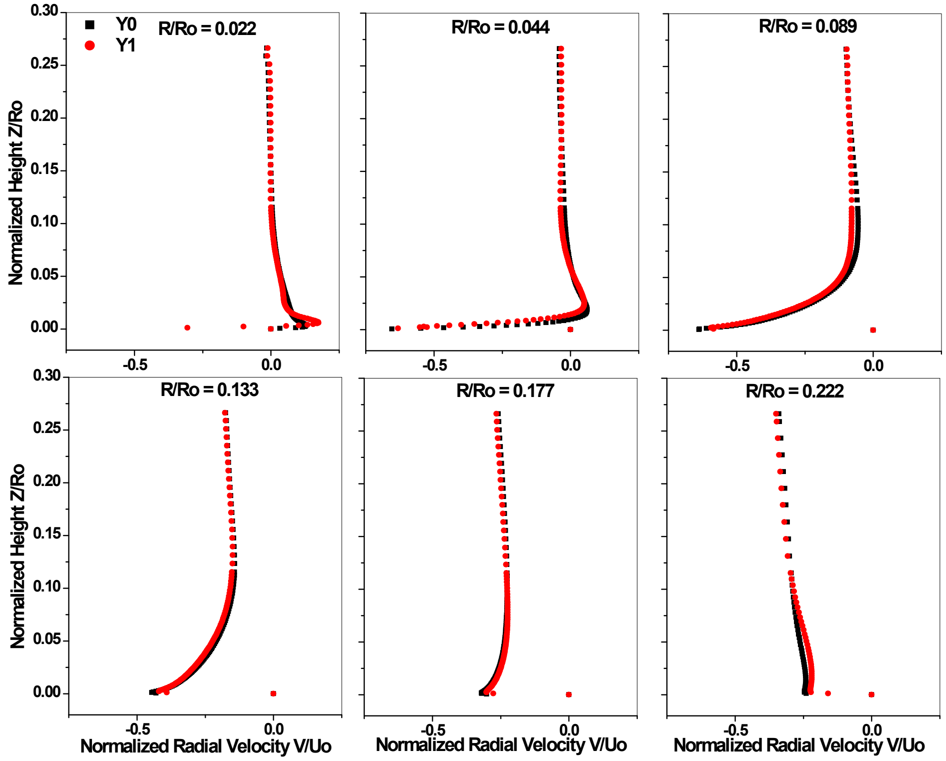

Figure 4: Normalized radial velocity along the normalized height for different radial location for swirl ratio 0.1

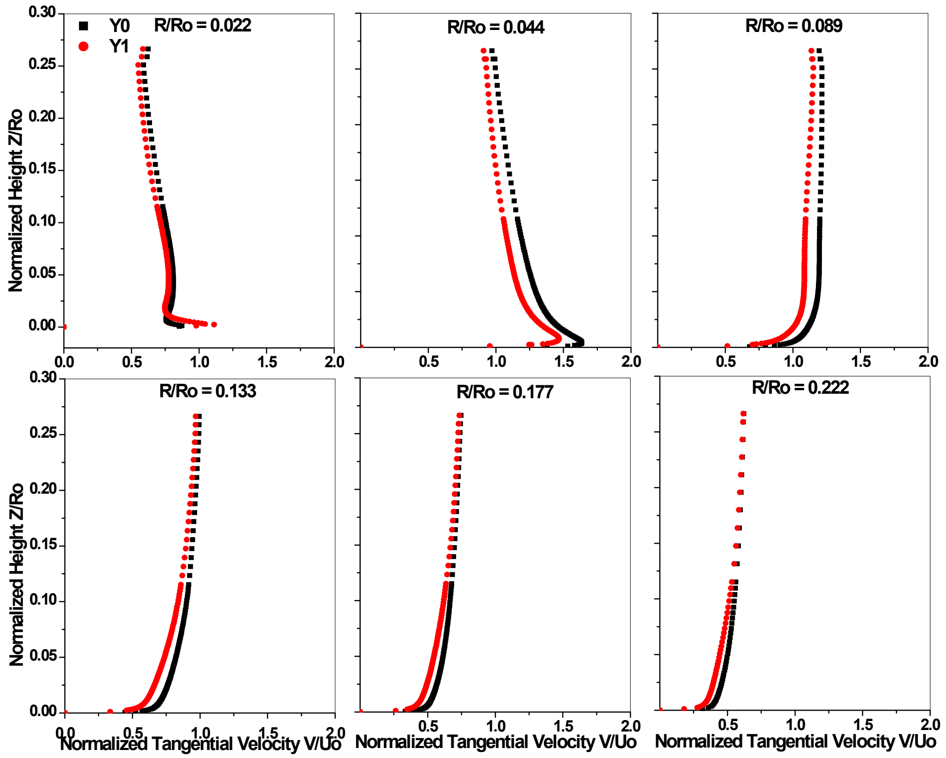

Figure 5: Normalized tangential velocity along the normalized height for different radial location for swirl ratio 0.1

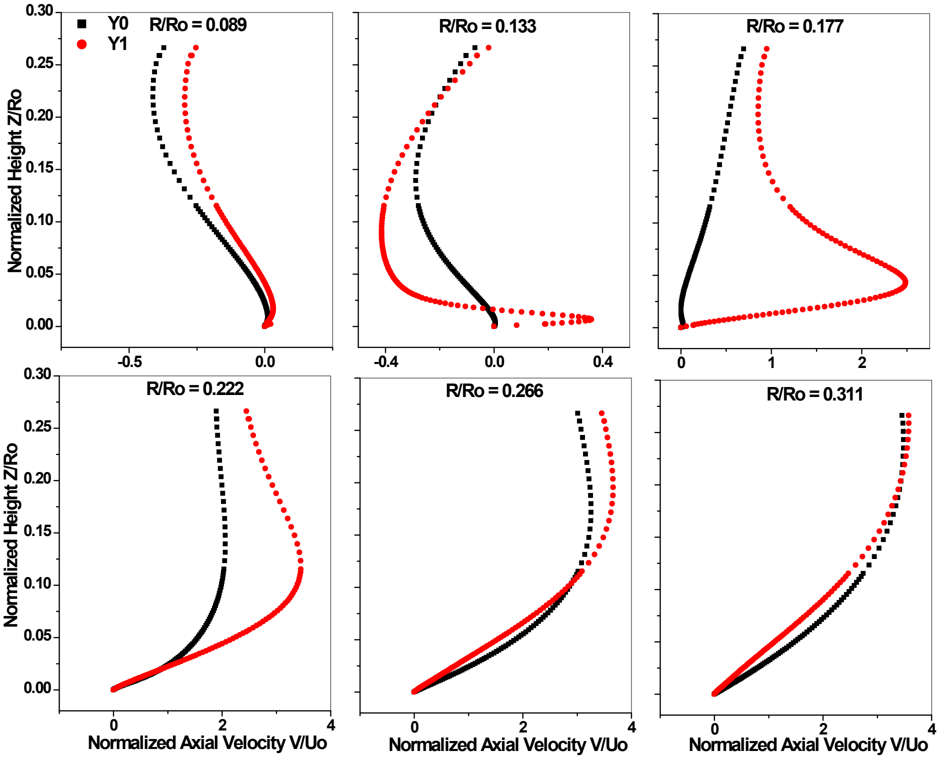

Figure 6: Normalized axial velocity along the normalized height for different radial location for swirl ratio 2.0

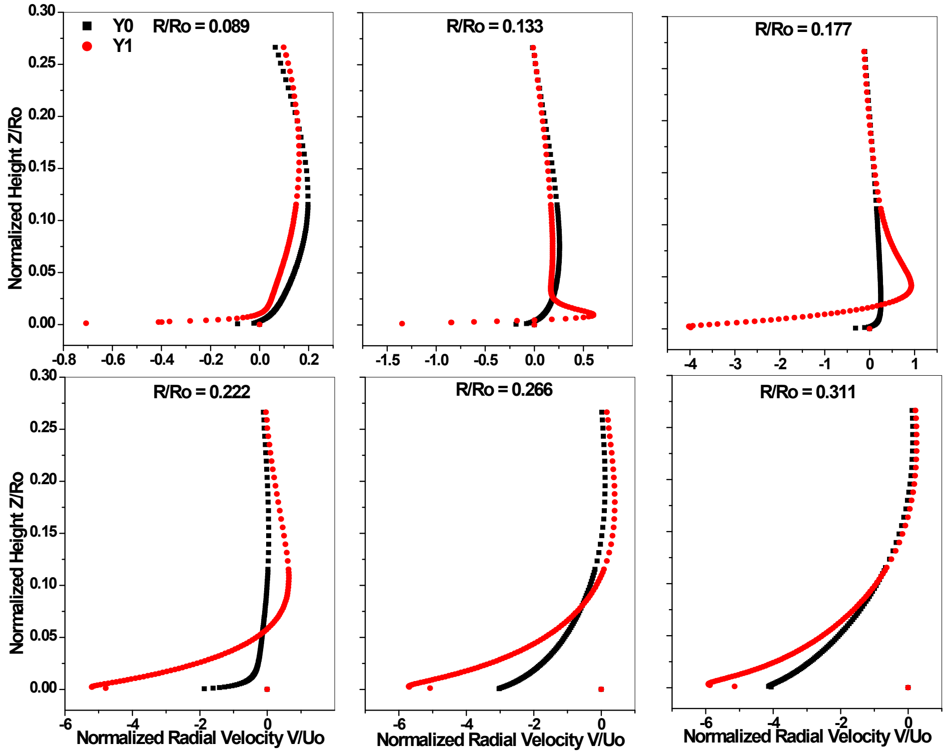

Figure 7: Normalized radial velocity along the normalized height for different radial location for swirl ratio 2.0

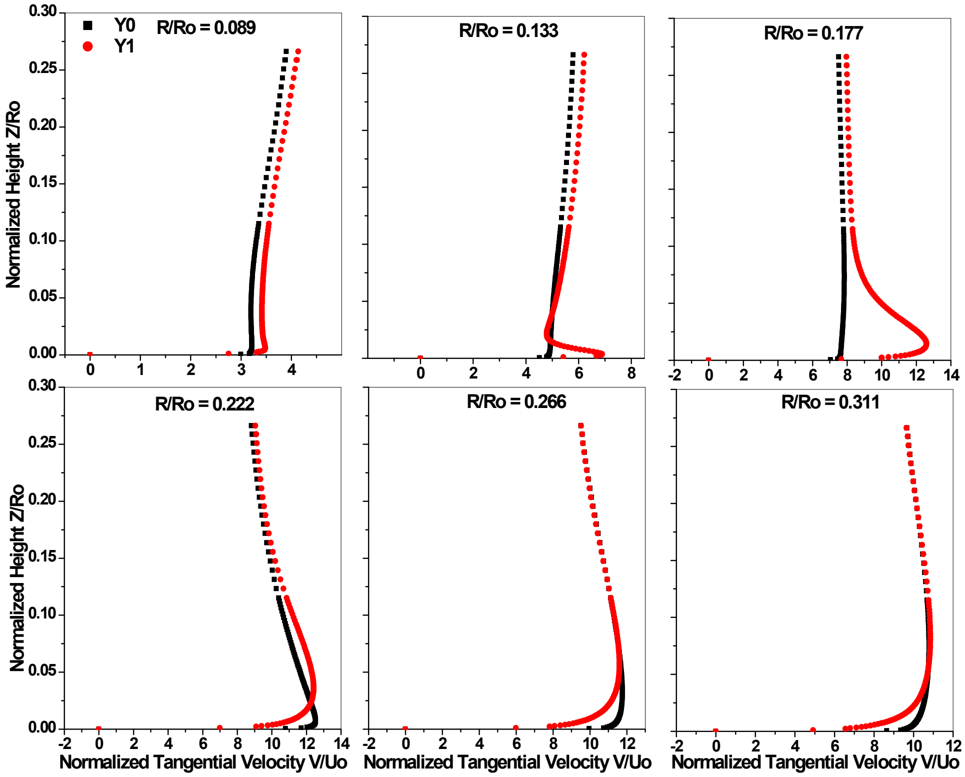

Figure 8: Normalized tangential velocity along the normalized height for different radial location for swirl ratio 2.0

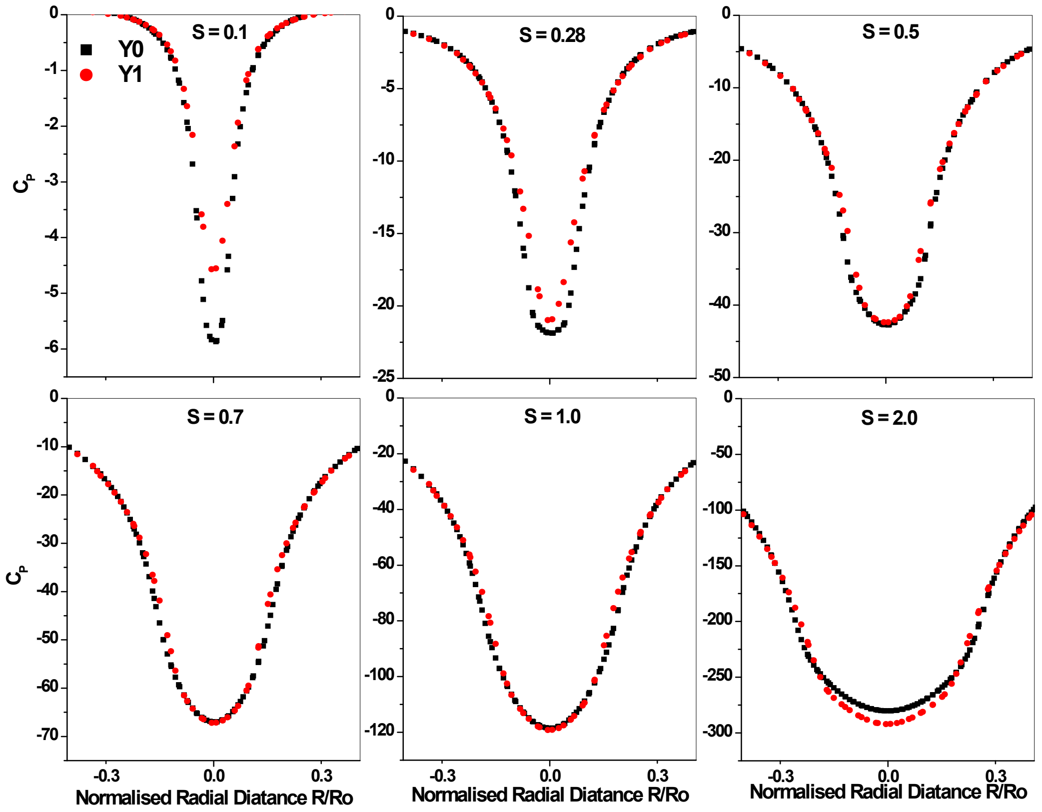

Figure 9: C_p along the normalized radial location for different swirl ratio

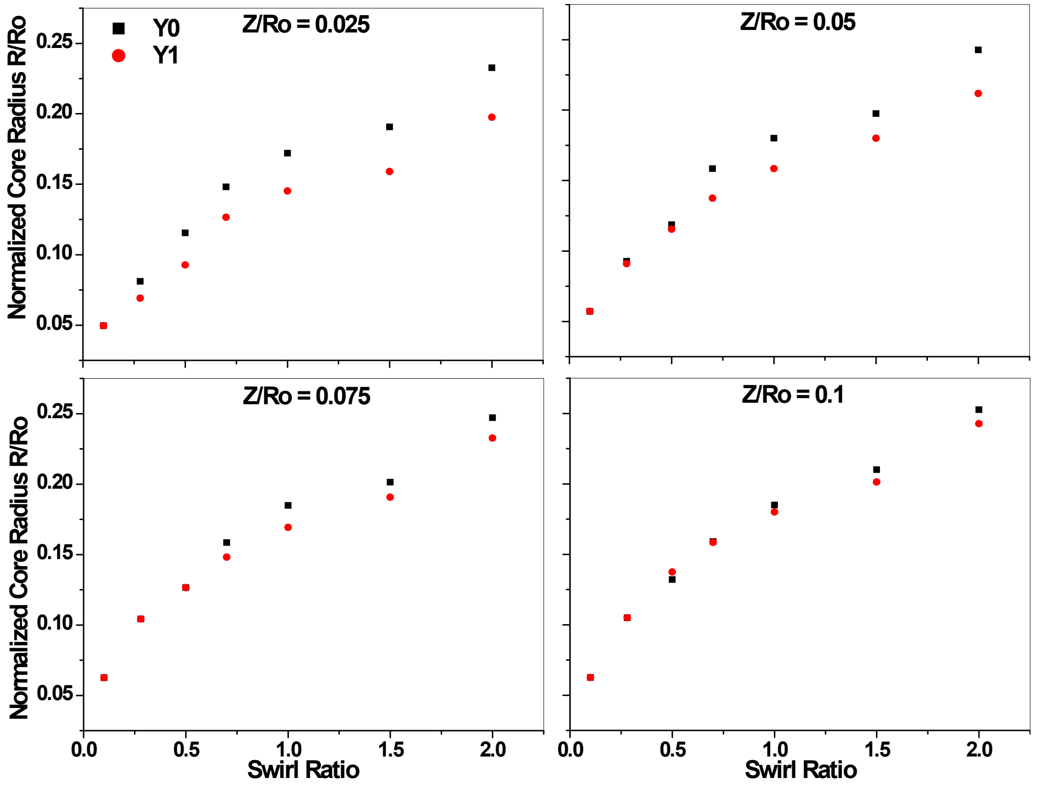

Figure 10: Normalized core radius along swirl ratio for different normalized height

CONCLUSION AND FUTURE WORK

A preliminary study on the effects of surface roughness on tornado-like flow was performed for mild roughness case. A proper scaling for the atmospheric roughness length was used. Introducing roughness increases the radial, axial and tangential velocities inside the core region. Outside the core region introducing roughness decreases the tangential velocity for all swirl ratios. For swirl ratios 0.28 and above, roughness increases the radial velocity outside the core. A fractional decrease in axial velocity is seen outside the core for all swirl ratios. Further detailed studies are required before final conclusions can be made on the effects of surface roughness across the range of swirl ratios.

The limitations in fluent software, limits this study to only low roughness case. A more robust method is required to study the effect of high roughness cases (for e.g. suburban and city-centre roughness). Possibilities include numerical studies based on physical modeling of roughness elements (blocks) and such simulations are underway.

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