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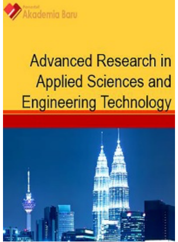

Novel Boundary Conditions for Investigation of Environmental Wind Profile Induced due to Raised Terrains and Their Influence on Pedestrian Winds

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ABSTRACT

In comparison to the terrains on planes, where wind follows a conventional profile. On interaction with a raised terrain like a hill or a mountain, the wind gets an added component of velocity in the vertical direction. This added vertical component gives air parcel a couple like moment, that causes the wind to twist. This twisted wind, alters the flow conditions, especially at the pedestrian level, and demands investigation. The authors in this research have developed a set of conditions, to recreate the complete 3D flow field of a twisted wind profile, on interaction with an isolated building using commercial CFD code FLUENT, to make it suitable for faster adoption by industry. The conditions are derived to ensure horizontal homogeneity in the domain. Lateral wind speed along altitude is applied in the computational domain to sustain the twist throughout the empty domain and subsequently with the structure within the domain. The results are validated with the wind tunel experiments of Tse *et al*. [5] for validation and comparison. The results suggest twisted wind alters pedestrian wind profile in comparison to conventional wind profile by shifting the high-pressure zones along the vertical twist angle, indicating lower intensity eddies in the wake on the structure, with possible negative effect on thermal comfort.

Keywords:
Buildings, CFD, Pedestrian winds, Numerical modelling, Twisted wind, Wind tunnel

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1. Introduction

Rising urbanisation has led to minor settlements (villages with average height of building below 50m) convert to urban settlements, with taller buildings (greater than 75m) increasing in density. The interaction of wind with these tall structures is known to alter the microclimate of the region, by accelerating wind in low pressure zones while stagnating pollutants at high pressure zones at pedestrian level. This leads to thermal discomfort of pedestrians as regulation of body temperature becomes difficult, added to settling pollutants leads to several diseases [1-4]. This was seen in 2020-2021 COVID19 outbreak in hill station of Mussoorie, the lack of ventilation due to

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altered pedestrian wind profile saw one section of the hill station reporting more cases, which matched with the satellite images of pollutant/viral load coagulation in that zone.

Study done by Tse *et al*. [5] indicated that upstream-downstream terrain, atmospheric stability and emissions tend to alter the pedestrian wind profile. The movement of air parcel over a raised terrain, adds an extra vertical component of velocity along with the horizontal and results in wind approaching with a twist rather than conventionally (constant wind direction along the height), as shown in Fig 1. Wind twist is similar to the Ekman Spiral but with comparable turbulence diffusivity, momentum transfer and turbulence intensity. The twist is more near the surface of the terrain and reduces with altitude [6,7], which creates varying intensity levels along the flow direction and makes it difficult to sustain in a computing domain. The degree to which the wind direction varies along height is expressed as in equation (1).

$$\theta = \arctan\left(\frac{v}{u}\right) \tag{1}$$

where *v* and *u* are wind velocities in the across(lateral) and longitudinal direction respectively.

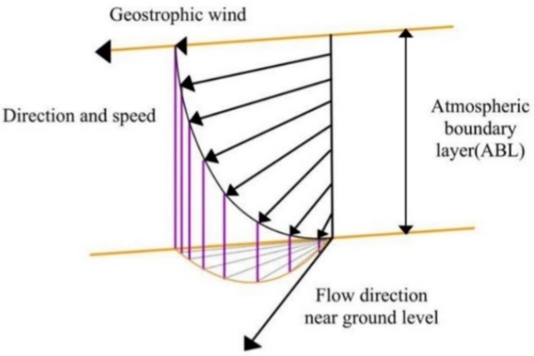


Fig. 1. Schematic of wind twist

Tse *et al*. [5] using a boundary layer wind tunnel was able to recreate variations in mean velocity (u), turbulence diffusivity (k) and dissipation (ε), for the twisted wind profile of 13 degrees and 22 degrees. The recreation was done using wooden vanes. Tse *et al*. [5] observed due to the wind twist the corner streams became asymmetric, the building's wake shifted clockwise from the centreline and a separate low wind speed zone along the wall of the structure was produced. While tending to explain the flow pattern the details of the flow field are obscured. The possible reason for this shortcoming is 3D flow data from the field were not completely recreated in wind tunnel, Tse *et al*. [5] made logical assumptions on the wind physics to explain the behaviour of twisted wind. But the explanation is short of evidence, particularly that of simultaneous and real time calculations of wind speed and wind profile in PLW(pedestrian level wind) environment. The main objective of the paper is thus to solve the above gap by using numerical modelling and CFD.

CFD studies have proven effective for PLW investigation due to isolated buildings [8-10], around arrays of buildings [11,13] and idealised city models [14-16]. The critical factor in numerical modelling of wind being accurate inflow conditions to sustain the equilibrium boundary layer till the wind leaves the computing domain. Several boundary conditions for RANS *k- ε* have been examined [17-19] for conventional flow, with used shear stress model plotting u as logarithmic function of height. The top boundary condition to sustain equilibrium in the domain, was studied by Sullivan [21]. While majority work has been done in RANS k- ε, no work has been done for k- omega SST, which is a more effective model for modelling fluids. This research focused to develop novel conditions across the walls of the domain to recreate an equilibrium atmospheric boundary layer, and generate wind twist by balancing the forces.

In the study, numerical modelling of twisted wind on an isolated building is conducted to determine the changes induced due to modified wind field, the results are validated from the wind tunnel experiments of Tse *et al*. [5] and compared with the PLW conditions due to conventional wind profile (CWP). The 3D flow field in CFD aids in better explaining the changes in PLW wind field, in comparisons to the wind tunnel tests.

The paper proceeds with generation of new boundary conditions and numerical settings to run the model, testing it's sustainability in empty domain, validation with experimental results and discussing the simulated wind field in comparison to wind tunnel data and details of PLW due to twisted wind flow, ending with the concluding remarks.

2. Novel Boundary Conditions

2.1 Generation of Inflow Conditions

The modelling has been done via the k-omega SST model and RANS equations. In order to ensure horizontal homogeneity (∂/∂x = 0;∂/∂y = 0) and w=0 [17,18] . The use of *k*-omega SST ensures effective near-wall treatment and provides the versatility of k-epsilon. Based on above the *k*-omega equations transform as (2)-(4):

$$\frac{\partial}{\partial z}\left(K\,\frac{\partial u}{\partial z}\right)=0 \tag{2}$$

$$\frac{\partial}{\partial z}\left(K\frac{\partial v}{\partial z}\right)=0 \tag{3}$$

$$\frac{\partial}{\partial z}\left(\frac{K}{\sigma_k}\,\frac{\partial k}{\partial z}\right)=0 \tag{4}$$

$$\omega = C_\mu^{\frac{3}{4}}\frac{k^{\frac{1}{2}}}{l} \tag{5}$$

Generation of turbulence which is a function of shear flow is taken to be equal to the specific turbulent dissipation rate (ω).

$$K = C_\mu \frac{k^2}{\varepsilon} \tag{6}$$

where *v* is the wind velocity across the domain and u is longitudinal speed, *k* the turbulent kinetic energy, K is vertical turbulent diffusivity and z is along height in vertical direction and C_μ is a model constant. To equation (4) will be added the dissipation and generation of turbulent kinetic energy.
The derivation of as per the logarithmic law based on the shear stress model is shown by [17,18] and hence is not included. Equation (3) depicts the vertical variation in wind direction, thereby ensuring a twisted profile. Hence from above, equations (3)-(5) for the k-omega SST model form the inlet conditions at various wall boundaries of the domain, having σ_k=1.

$$v(z) = C_{v1}u\,(z) + C_{v2} \tag{7}$$

$$k(z) = C_{k1}u\,(z) + C_{k2} \tag{8}$$

$$\omega(z) = \sqrt{C_\mu k\,(z)}\sqrt{\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2} \tag{9}$$

while equation (7) develops profile of v as function of u. Equations (8) with (9) computes the profiles of k and omega along vertical direction. Surface roughness factor (z_0), is part of calculations for both u and v. Major resistance to wind comes from the terrain and that due vertical variation in wind profile is neglected. The residual levels of ω is determined by the solutions of C_{k1} and C_{k2}, as the turbulence intensity of simulated wind field is lower than 50%.

2.2 Application of Boundary Conditions on Empty Domain

As the study is application based for the wind industry, user-friendly commercial product FLUENT was used for application of the derived inflow conditions. An empty domain, with dimensions 4.05m length, 2.7 m width and 1.35m height as shown in Fig 2. Is constructed. Growing meshes of 200 cells in longitudinal, 40 cells in lateral and 100 cells in vertical direction. The cells grow from centre to longitudinal and lateral directions, leading to total 0.8 million total cells.

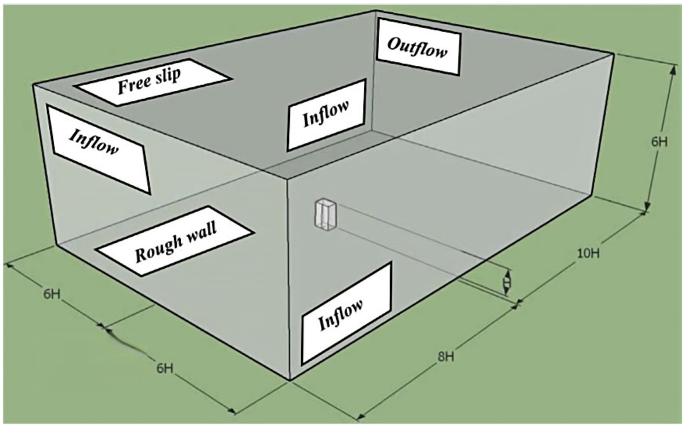


Fig. 2. Dimensions and characteristics of computational domain

The conditions being applied at different walls is briefly put in table 1. And must be read in comparison to Fig 2.

Table 1
Wall conditions for CFD simulation

Zone	Typology	User-defined functions
Inlet Wall	Velocity Inlet	$u(z) = \frac{u_*}{\kappa}\left(\frac{z+z_0}{z_0}\right), v(z) = C_{v1}\,u(z) + C_{v2}$, SST $k-\omega;\ k(z) = C_{k1}(z) + C_{k2}$ $\omega(z) = \sqrt{C_\mu}\,k(z)\sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2}$
Outlet	Outflow	$\frac{\partial}{\partial x}$ and $\frac{\partial}{\partial x}(u, v, w, k, \varepsilon) = 0$
Right Wall	Velocity Inlet	$u(z) = \frac{u_*}{\kappa}\left(\frac{z+z_0}{z_0}\right), v(z) = C_{v1}\,u(z) + C_{v2}$, SST $k-\omega;\ k(z) = C_{k1}(z) + C_{k2}$ $\omega(z) = \sqrt{C_\mu}\,k(z)\sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2}$

Left Wall	Velocity Inlet	$u(z) = \frac{u_*}{\kappa}\left(\frac{z + z_0}{z_0}\right), v(z) = C_{v1}\, u(z) + C_{v2}$, SST $k - \omega;\ k(z) = C_{k1}(z) + C_{k2}$ $\omega(z) = \sqrt{C_\mu}\, k(z) \sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2}$
Top Wall	Free Slip condition	$w = 0 \frac{\partial}{\partial z}(u, v, k, \varepsilon) = 0$
Ground	Normal Wall	Roughness amplitude of K_s = 0.00032 m and C_s = 0.5 is the roughness constant.

These conditions satisfy the equations (7)-(9). The profiles of wind velocity adopted reproduce that of Tse *et al*. [5] and two yaw angles of TWP13 degrees and TWP22 degrees are reproduced. Fig 3. Compares the simulated wind profile with that of wind tunnel data of Tse *et al*. [5]. Target velocity of u*=0.2738 m/s and z_0 =0.000012m is matched and as evident the model defined by equation (7)-(9) matches values from Tse *et al*. [5] with little deviations of v and k.

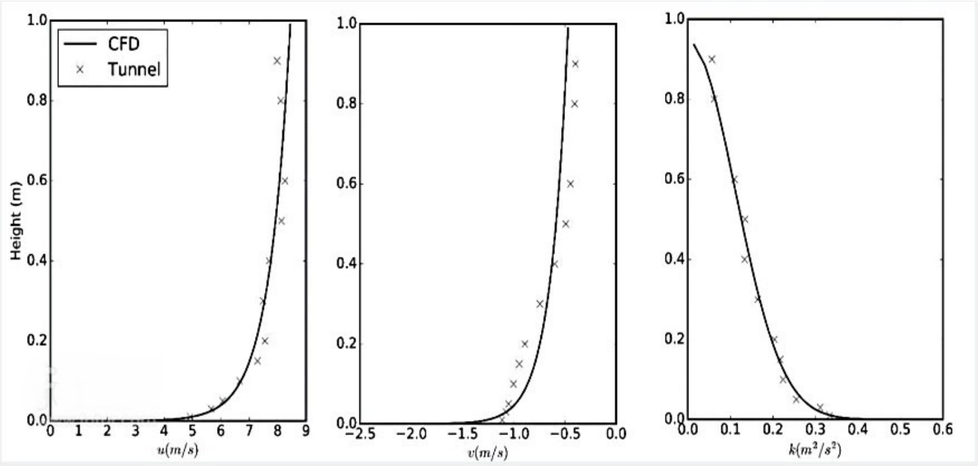


Fig. 3. Input values of u,v,k of wind tunnel and CFD model for TWP13

While u and v profiles are contrasted at centre of domain and outlet (as shown in Fig. 4), it is evident that the twisted profile is sustained all across the domain.

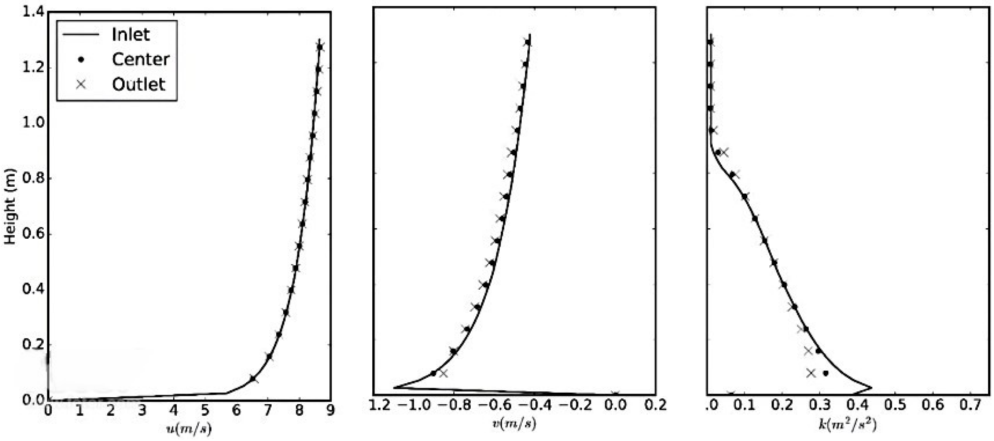


Fig. 4. Plot of *u*,*v*,*k* at inlet, outlet and centre

The little deviation of *k* is due to the near wall treatment in FLUENT. Hence the derived boundary conditions can be adopted and reproduced for analysis of wind twist profile on PLW due to a single building.

3. Application with Isolated Building

The Boundary conditions are later applied in a domain with the isolated building to study the PLW environment. The height of the building is 600mm width is 150mm and depth of 100mm, with an aspect ratio of 4:1. For comparison a CWP is also simulated along with TWP13 and TWP22. Grid independence test is conducted with 1.7 million cells, 0.8 million cells and 0.9 million cells. For discretizing the momentum term, QUICK scheme is adopted along with SIMPLE algorithm to solve the turbulence model and governing equations. The total iterations were 15000. The lateral measurements of wind velocities at pedestrian levels were recorded and plotted along X= 225m to X= -225m and shown in Figure 5.

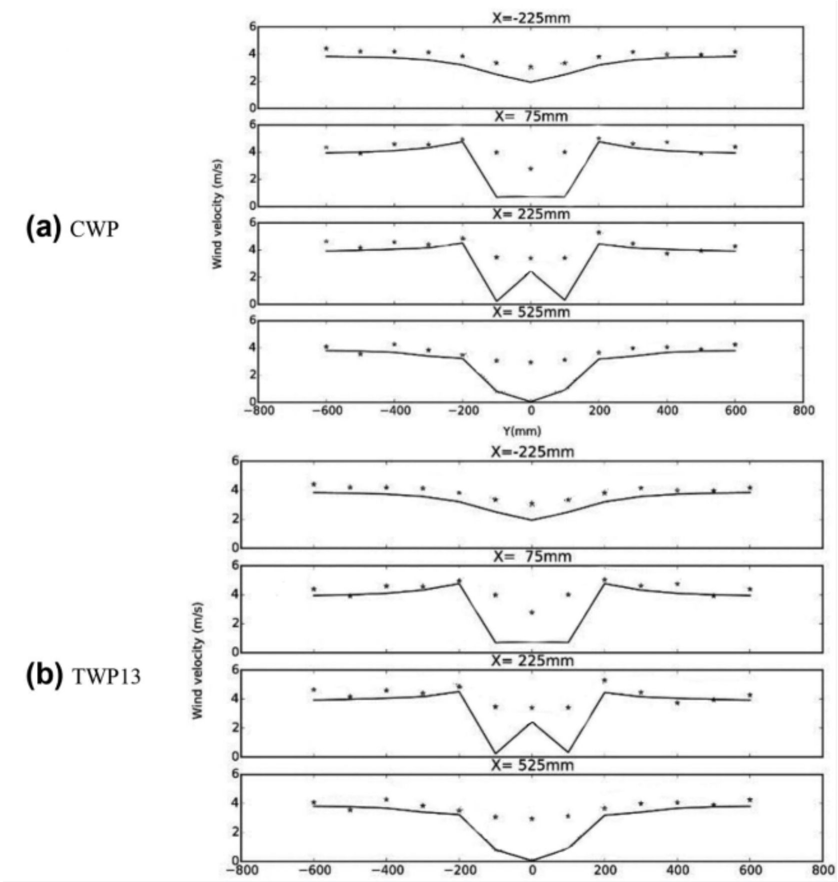
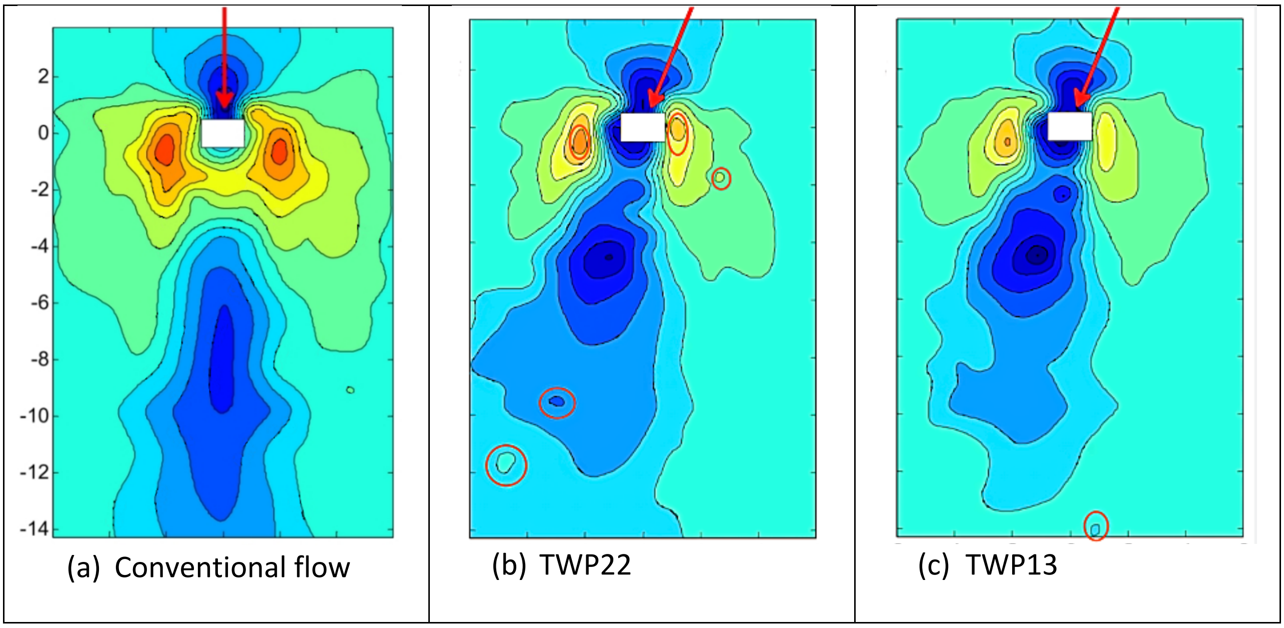


Fig. 5. Mean PLW wind speeds from wind tunnel (stars) and FLUENT(solid line) for (a) CWP (b) TWP1

The difference between numerical simulation and data from tunnel can be attributed to limited capacity of Irwin probes [2] and inability of wind tunnel to reproduce the complete 3D wind field in comparison to numerical simulation. While Tse *et al*. [5] assumed asymmetric profile was due to oblique attack angle. The simulation offered a better explanation, due to the position of Downstream Far Field Low Wind Speed (DLFWS) zone. The area with wind speed lower than 80% of inlet attack wind speed. For TWP13 and TWP22 the DLFWS shifts clockwise, the angle of deviation (α). TWP22 angle is greater than TWP13 (Fig. 6), highlighting importance of twist angle. There is absence of vertical eddies in the wake of twisted wind flow, indicating lower momentum exchange, while these eddies in CWP are important for removal of pollutants.



(a) Conventional flow
(b) TWP22
(c) TWP13

Fig. 6. Wind speed distribution at pedestrian level (a) CWP (b) TWP13 (b) TWP22

5. Result and Discussion

From fig 6. It is evident that the flow due to TWP has asymmetrical distribution of wind speeds in comparison to that of CWP. Previous studies done by Tse *et al.* [5] hypothesized the asymmetrical nature of flow due to oblique wind attack angle. However, the 3-dimensional flow pattern developed due to numerical modelling, reveals the important role of DFLWS zone in generating asymmetric velocity distribution. It is the zone with 80% velocity less than free stream velocity. The DFLWS zone is dependent on the angle of twist. The zone shifts along clockwise direction. It is important to quantitatively analyse the flow, for which the authors have used the deviation angle α. It is the angle between the centre of the building and the centre of the DFLWS zone, at pedestrian level height.

In the case of CWP, the stream lines are parallel to the building and hence the DFLWS behind the structure is also symmetric. The extra vertical force component makes the streams attack the building at an oblique angle. The displacement of the DFLWS zone is expressed by α, which in turn depends on the yaw of the wind profile at pedestrian height. The interference due to the structure, affects the yaw angle of the wind, hence the angle α lies within the range of the yaw of attack and shift due to the structure. This comparison reveals the importance of variation of twist along vertical direction.

Also, it is important to highlight that, as the angle of twist increases the vertical transport of momentum gets reduced. Which is not so in case of CWP. The weak vertical transport, indicates accumulation of pollutants at pedestrian level, which creates pedestrian discomfort.

Above discussion reveals that, the wind velocity along the altitude in TWP cases is not as large as compared to CWP winds.

6. Conclusions

The developed conditions prove satisfactory consistency and accuracy across both field and wind tunnel data. The results were adopted to investigate alterations in PLW environment over a raised terrain. And it was inferred that the changes occurring are due to the relative location of DLFWS zone and vertical eddies. The vertical circulation is stronger in CWP. The conditions can be directly adopted to analyse PLW for urban planning over a raised terrain.

Therefore, based on the 3D wind field data extracted from the numerical model, the following points can be inferred:

1. Numerical model accurately expresses the wind flow due to the twisted wind flow over a raised terrain. The small differences between wind tunnel data can be attributed to the limitations of wind tunnel in revealing the complete flow pattern.
2. The difference in wind velocity distribution at pedestrian height is due to the shifting of DFLWS zone, which is dependent on the vertical flow of wind over the structure and lateral flow around the structure.
3. The vertical transport due to TWP was found to be weaker in comparison to that of CWP. And this depends on the yaw angle near the surface.
4. Wind velocity along the height is smaller in TWP as compared to the CWP. This negatively affects the dispersion of pollutants at pedestrian level. Hence, affecting pedestrian comfort.

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