Kinematic Similarity for Urban Aerodynamic Wind Tunnel Tests Using Retrofit Atmospheric Boundary Layer Screen Filter

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1 INTRODUCTION

Wind tunnel experiments provide a controlled environment for investigating urban airflow patterns and their impact on pollutant dispersion at reduced scales, making urban environment research cost-effective. To conduct realistic urban wind tunnel experiments, it is crucial to achieve geometric, dynamic, and kinematic similarities with the actual model. For urban aerodynamics studies, boundary layer (BL) wind tunnels are commonly used as they are designed to replicate the natural wind structure by covering a considerable length of the wind tunnel's floor with a material of suitable roughness. However, this method requires a long test chamber to form the BL and often results in an uneven boundary profile along the horizontal space, making it less feasible for realistic urban studies [1].

Atmospheric Boundary Layer (ABL) characteristics inside a wind tunnel can be produced either actively, using controllable devices like oscillating spires and multiple fans, or passively, by introducing flow conditioners such as spires, roughness elements, and screens. Recent studies have focused on improving techniques for replicating natural wind characteristics and forming the atmospheric boundary layer (ABL) in wind tunnels with short test sections [1,2,3]. These studies primarily employed passive approaches, extending the test section length and incorporating spires and roughness elements to create an ABL flow field. Pires [3] found that spires and thin screens were the most efficient passive devices for forming the boundary layer with minimal area required.

Based on previous results from ABLs characterization in wind tunnels, the need for generating velocity profiles that adhere to natural wind flow in short test sections was identified. Therefore, the main goal of this study is to replicate ABL characteristics within the wind tunnel using a flow filter screen and to improve the quality of passively regulated airflow methods, facilitating realistic urban wind dispersion analysis.

2 THEORY CALCULATIONS

Atmospheric boundary layer is composed of a mean wind speed and an overlaid fluctuation due to the turbulence that varies based on topography of terrain. The wind speed within the urban inertial sublayer is uniform in the horizontal direction and it is almost windless in the vertical direction, and the wind speed in the horizontal direction varies only with the height. For describing the lower part of the boundary layer, known as the Prandtl layer, the logarithmic law of the wall suggested by Thuillier and Lappe [1] is generally used.

The variation of the mean horizontal velocity, $\overline{u(z)}$ with height, z can be represented by Eq. 1,

$$\frac{\overline{u(z)}}{u^*} = \frac{1}{\kappa}\ln\left(\frac{z+z_0}{z_0}\right) \tag{1}$$

Where, $u^*$is Frictional velocity, κ is von Karman constant and z_0 is aerodynamic roughness height.

In urban aerodynamic studies, *Re* of airflows in the wind tunnel is much lower than that of actual atmospheric flows. Thereby, *Re* of full-scale and model-scale cannot be equal. Therefore, the wind tunnel experiments must be conducted at the critical *Re* where the Reynolds independence theory is valid. Plate [4] introduced the *Re*-independence criteria for flow over an urban model in terms of Roughness Reynolds (Re_Z) Eq. 2,

$$Re_Z = \frac{u^* Z_{0,Model}}{\nu} > 5 \tag{2}$$

The value of $z_0$depends on the atmospheric stability and surface roughness of topographic features. Proper scaling of ABL wind properties ensures that the flow characteristics in the wind tunnel are representative

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of those in the full-scale urban environment. Therefore, it is necessary to replicate these conditions in wind tunnels to study urban aerodynamics under realistic scenarios.

3 METHODS

This work has been carried out in the open subsonic wind tunnel located in the EngCore department at South East Technological University (SETU). The cross section of this wind tunnel is 304x304 mm with the length of 650 mm testing chamber. The wind tunnel has two pitot tube measuring devices to record the dynamic pressures positioned at 200 mm and 550 mm from honeycomb screen respectively.

In order to achieve the boundary profile similar to ABL, a new screen filter has been designed to passively regulate the free stream airflow within the wind tunnel test chamber. This screen functions as a flow manipulator, transforming the upstream flow exiting the honeycomb into a logarithmic flow profile. The ABL screen comprises a grid of slots with widths increasing logarithmically, as shown in Fig. 1. Initially, the velocity profile of the free-flow wind in the test section is recorded at different fan speeds to serve as a baseline for comparison with the velocity profiles after the ABL screen is introduced.

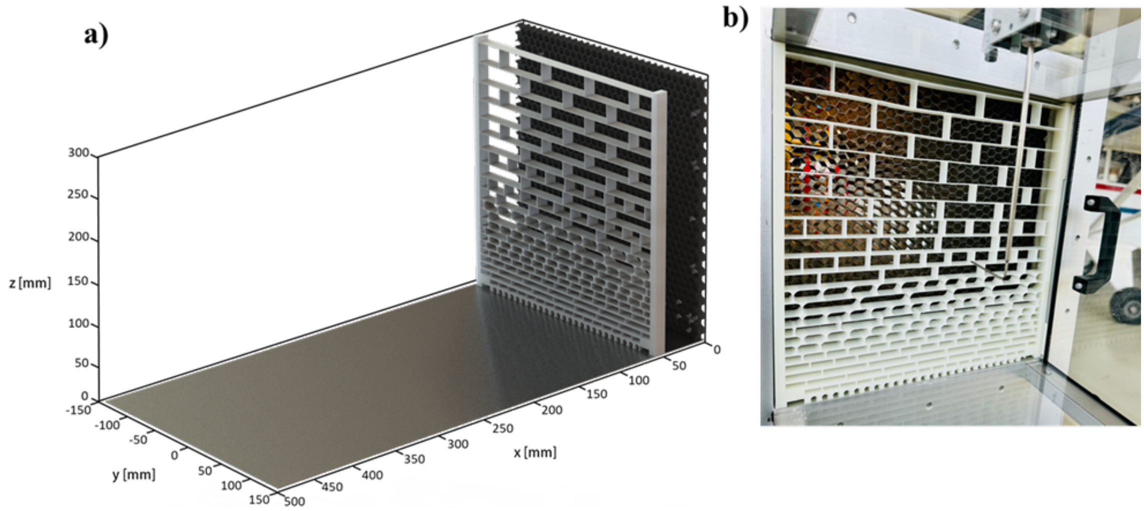

Figure 1, a) Position of the ABL screen in the test chamber; b) 3D-printed model for experiments

The ABL screen measures 300x300 mm and comprises 21 vertical rows with variable slot configurations. The height of each pair of adjacent vertical rows is determined by Eq. 3, while the width of the horizontal slots in each row are designed to produce a uniform velocity at each layer. The primary objective of this ABL screen design is to restrict flow near the ground and gradually reduce blockage to enhance vertical fluid flow, thereby replicating the natural wind profile. Slot widths in each row are adjusted according to the velocity profile observed near the test section. Additionally, 5 mm diameter holes at the bottom accommodate skin friction effects near the wind tunnel's bottom wall.

$$D(n) = 5 + \sum_{k=1}^{n} \ln(k) \tag{3}$$

Where, $D(n)$ is the width of rows; and row number$n \in (2,4,6,8,10)$.

The dynamic pressure of the airflow in wind tunnel was measured with a standard pitot tube manometer, and the respective velocities were calculated based on the dynamic pressure readings. The procedure resulted in calibration errors below 2%, which are typical of pitot tube applications. The experimental uncertainty in the measurement of ambient conditions is 0.5%. This result is an uncertainty of < 5% in the estimation of the Reynolds number, with the confidence interval of 95%.

4 RESULTS AND DISCUSSION

The CFD simulations are performed on the wind tunnel model to analyze the flow structure after introducing the designed mesh screen. A uniform velocity distribution is observed in the test chamber as shown in the Fig. 2. The ABL was fully developed at x=150 mm, showing an even velocity horizontally at each layer in the wind tunnel, due to different slots at each row on the screen.

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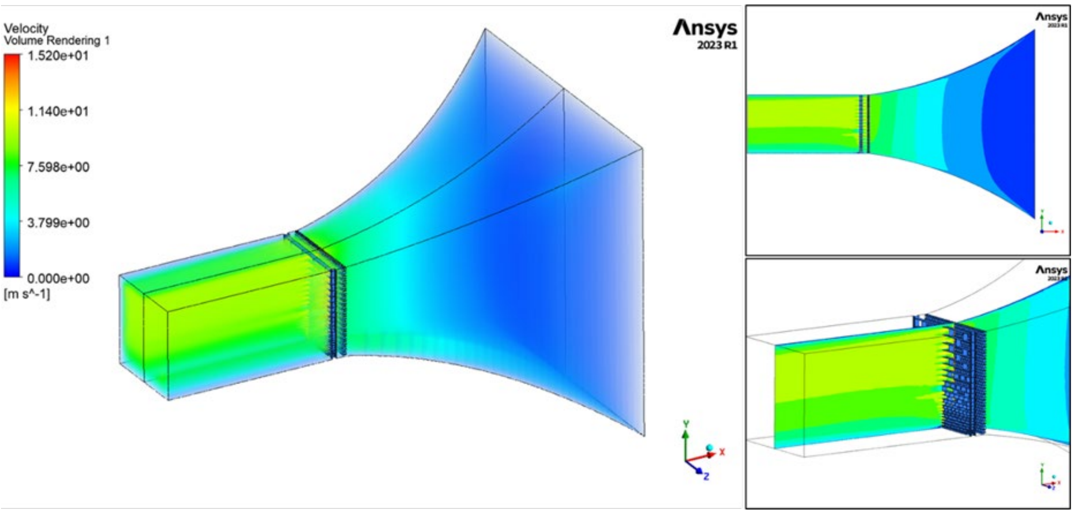

Figure2, Velocity distribution in the wind tunnel at free stream velocity of 8.5 m/sec

Three different fan speeds were selected for the experiments: 8.5 m/s, 17.7 m/s, and 35 m/s. The frictional velocity and effective roughness height of the developed flow structure were obtained by fitting wind profiles on a semi-logarithmic scale. The analysis yields the model aerodynamic surface roughness length $Z_{0,m}$=0.0005m and the friction velocity u^*= 0.152 m/s at the mean freestream velocity $\bar{u}$ = 8.5 m/s; $Z_{0,m}$= 0.00055m and u^*= 0.164 m/s at $\bar{u}$ = 17.7m/sec; $Z_{0,m}$=0.0008m and u^*= 0.195m/s at $\bar{u}$ = 35m/sec. Table 1 summarizes the experimental values of aerodynamic roughness height (Z_o) and roughness Reynolds numbers (Re_z) at different free stream velocities after retrofitting the developed ABL screen. The effective roughness heights showed nonsignificant differences at low and medium fan speeds. However, the frictional velocities and roughness heights after introducing the ABL screen fell within the recommended theoretical ranges for dense urban region aerodynamic studies at all fan speeds [5,6]. The critical Reynolds number condition defined by Plate [4] ($Re_z>5$) is satisfied for the medium and high-speed conditions, which indicates that the flow replicated the natural wind conditions in the test section. Additions of roughness elements are required at low fan speed to improve the flow characteristics near the ground level as Re_z is very close to critical value.

Table 1, Airflow parameters and Re inside wind tunnel test section at different fan speeds

Wind Speed (m/sec)	**Dynamic Pressure (mm H_2O)**	**Roughness height ($z_{o,m}$)**	**Frictional velocity(U^*) m/s**	**Roughness Reynolds**
8.5	5	0.0005	0.152	5.14
17.7	20	0.00055	0.164	6.09
35	75	0.0008	0.195	10.54

Variations in mean and turbulent flow profiles along the spanwise direction were used to ensure the development of the ABL. To evaluate the results in relation to real ABLs, the mean flow profile was compared to theoretical log-law profiles. Fig. 3 presents the developed velocity profiles after introducing the ABL screen, compared with free flow wind profiles and the theoretical log-law profile at different speeds. Introducing the ABL screen resulted in significant changes in velocity profiles across all cases. A good agreement was observed between the experimental mean flow characteristics and the theoretical log-law profiles representing the urban boundary layer, particularly near the ground surface levels at all three fan speeds. Therefore, the present study suggests that the mean flow characteristics of the ABL can be effectively simulated in a short wind tunnel using the ABL screen device. Nevertheless, the turbulence characteristics within the test section can be controlled by adjusting the slot dimensions on the ABL screen according to the terrain conditions of the targeted urban study region.

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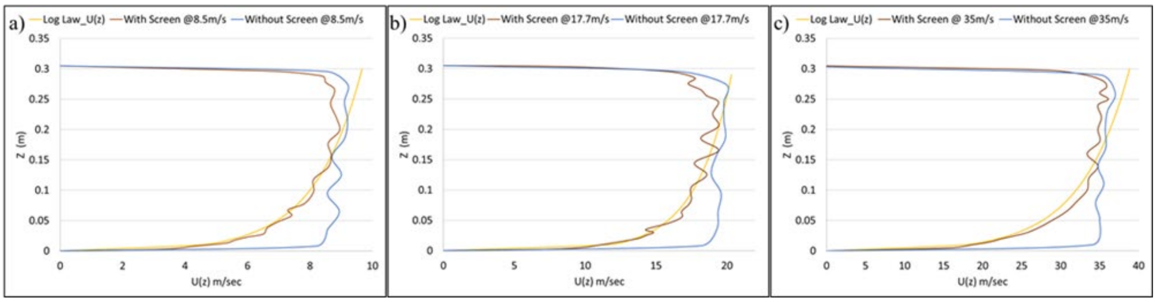

Figure3, Velocity profile inside wind tunnel compared with theoretical log profile and free flow wind profile at: a)8.5m/sec; b)17.7m/sec; c)35m/sec

5 CONCLUSION

In this study, atmospheric boundary layers (ABL) over a generic urban terrain were simulated in a subsonic wind tunnel using the ABL screen flow modifier technique. Initially, the velocity profile properties in the test section of the empty wind tunnel were evaluated at different wind speeds. The goal was to replicate ABL characteristics within the shortest possible wind tunnel extension and with minimal pressure loss, achieving a velocity profile similar to natural wind for realistic urban wind dispersion analysis. This was accomplished by passively regulating airflow using an ABL screen positioned near the inlet. To generate ABL flow characteristics, a screen filter with vertically varying height rows and a grid of slots was proposed. The screen's effectiveness was validated through wind tunnel tests with a 3D-printed screen.

The effective roughness height and frictional velocity in the test section after introducing the ABL screen show good agreement with theoretical values typically used to represent the ABL over urban terrain. Additionally, a uniform wind velocity distribution throughout the test section, adhering to the logarithmic law near the ground, is achieved with the developed screen. The main characteristics of wind in an ABL are well reproduced in these experiments, demonstrating the potential of using the ABL screen flow modifier technique to generate the atmospheric boundary layer in wind tunnels with short test sections. To meet the requirements of wind engineering applications in short wind tunnels, further experimental studies are needed, particularly to address the inadequacy of the generated turbulence intensity in the upper part of the boundary layer. Nonetheless, the ABL screen used here is suitable for reproducing ABLs over nearly flat terrains with low-height dense urban areas.

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