An investigation of urban boundary layer towards achieving similarity criteria in a short wind tunnel

A W M Yazid¹, N A Che Sidik¹, S Mansor², A B Abdul Rahman³, I S Ishak², and N Dahalan²
¹Department of Thermo-Fluids, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia
²Department of Aeronautics, Automotive & Ocean Engineering, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia
³Aeronautics Laboratory, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia

E-mail: azwadi@fkm.utm.my

Abstract. An experimental investigation was conducted in an effort to artificially thicken the boundary layer which has the characteristics of an urban boundary layer in a short wind tunnel. Turbulence grid was developed and then systematically tested to quantitatively investigate the formation of a thick and uniform boundary layer over location of interest. Investigated parameters were the mean velocity and turbulence intensity to assess the similarity of the simulated boundary layer. The measurement analysis shows that the current design provides the desired boundary layer profile under fully rough conditions at just 1.5 m downstream of the test section inlet, which allows for the building models to be placed over turntable. However, the roughness length value is high which reflects the determination of the model scale while the turbulence intensities levels is low which is not desirable characteristics of an urban boundary layer. The results presented here may facilitate future improvements in the design of the turbulence grid and measurement techniques.

1. Introduction
Vertical profile of atmospheric boundary layer is relatively different over specific location such as complex terrain (i.e., hill, mountain), offshore (i.e., coastal regions, sea) and built-up area (i.e. suburbs, city center) [1]. In particular, the urban boundary layer is essentially different from the boundary layer created over complex terrain or offshore due to the thickening of boundary layer as a result of vertical exchanges of momentum, heat and moisture amongst roughness elements. Figure 1 shows the schematic drawings of vertical structure of urban boundary layer, which indicates some of the layers and the terminology used throughout this paper. The layer extended from the ground (z = 0) up to the mean height of the roughness elements, zH is called urban canopy layer (UCL) [2]. In this layer, the wind flow is horizontally inhomogeneous as the processes of airflow and energy exchange are controlled by microscale, site-specific characteristics and processes [3, 4]. The effects of individual roughness elements on wind flow are discernible in the roughness sublayer (RSL) which extends from the ground up to height between 2zH in densely built areas (closely spaced), to about 5zH in low density areas [3-5]. Above the roughness sublayer is the inertial sublayer (IS) also known as constant
flux layer, where the wind flow is horizontally homogeneous due to the constant turbulent fluxes with height [4]. Both RSL and IS are jointly addresses as the surface layer (SL), which extends up to an elevation approximately 10% of the total depth of the urban boundary layer [6]. The top layer in urban boundary layer is the outer layer (OL) also known as mixed layer or Ekman layer, in which the combined effects from pressure gradient force and Coriolis force resulting from convection process and surface friction due to the Earth’s rotation respectively, becomes important [1]. For a detail descriptions about urban boundary layer, a comprehensive review can be found in [7].

![Schematic of the vertical structure of the urban boundary layer.](image)

**Figure 1.** Schematic of the vertical structure of the urban boundary layer.

In general, there are two physical methods of studying the wind characteristic over Earth’s surface (i.e. man-made structures, hills, forests, sea) namely the field measurement and reduced-scale measurement. Field measurement provides the most realistic results of parameter under investigations whereby it encompasses the original size of the structures or locations area with real atmospheric conditions. However, field measurements is not controllable due to the variable meteorological conditions and the data is limited due to the limitations of sensor and instrumentation capacities [8]. Besides, the experiment period is usually long and is costly to perform [9, 10]. Reduced-scale experiment via wind tunnel is an alternative to the physical experiment, which requires a special wind tunnel to simulate atmospheric boundary layer. The boundary conditions in wind tunnel measurements can be accurately controlled and the repeatability of the measurement is high [11]. One of the major drawback associated with wind tunnel measurement is the requirements of fulfilling the similarity criteria with that of full scale conditions [12], which can limit the extent and the range of problems that can be studied [8]. The boundary layer wind tunnel must have capabilities for creating flows that simulate the basic characteristics of natural wind at a site in order to obtain wind-effect data representative of full scale conditions [13]. The test section in boundary layer wind tunnel is generally long enough (at least 6 m [14, 15] to more than 20 m [16, 17], to allow the development of a thick turbulent layer along the tunnel floor. The method of generating a thick boundary layer simulation in a wind tunnel is hugely depends on the length size of the test section and the target to achieve specific vertical wind profile and turbulence levels [18]. For a short wind tunnel, the method includes the combination of a few vortex generators align perpendicular to the freestream along the start of the test section, a barrier, and a fetch of roughness elements afterwards which will increase turbulence levels near the floor [13]. As the boundary layer thickness increases along the tunnel over roughness elements and model, the cross sectional area for the free stream becoming smaller, resulting in higher free stream velocity and lower static pressure as the flow propagate downstream. An adjustable ceiling height is needed to compensate for the loss of cross section area and thus ensure that there is no streamwise pressure difference. Turntable on the test section floor provide additional feature which allows for variety of incoming wind direction towards area of interest.
The Universiti Teknologi Malaysia, low speed tunnel (UTM-LST) is a research facility mainly used for aerodynamics testing of ground vehicles [19], aeronautics [20, 21] and marines transportation [22]. Industrial cooperation for the aerodynamics testing of an offshore drilling and production platform model immersed in marine boundary layer has been attempted before [23]. Past research on the application of UTM-LST on building aerodynamics research over urban area is limited, whereby uniform inlet wind profile was assumed [24]. On the other hand, the vertical profile of flow over Earth’s surface is non-uniform and the profile is greatly influence by roughness parameters and atmospheric conditions as explained at the beginning of the section. Conventional methods in simulating the urban boundary layer such as combination of vortex generators and roughness elements in UTM-LST may not be practical as the ceiling of the test section is non-adjustable and the turntable is located 1.5 m from the inlet as figure 2(a). Thus, the motivation of this study was to check the feasibility of an initial design of turbulence grid developed by Aeronautics Laboratory group, UTM to simulate urban boundary layer flow within a short distance. The investigation will look at the variation of vertical wind profile and the similarity of the simulated mean wind velocity and turbulent intensity in the wind tunnel with that of full scale. The present simulation of the urban boundary layer is limited to be under neutral atmospheric conditions only, in which the conditions does not affected by thermal conditions.

2. Methodology

2.1. Similarity Considerations

A guideline on the similarity criteria for wind tunnel experimentation in the area of buildings aerodynamics covered by ASCE 1999 [13] is referred. There are two types of equations that represent the vertical profile of atmospheric boundary layer namely the power law and the logarithmic law. The power law is valid for any value of height, \( z \) within the atmospheric boundary layer [25]. Besides, the power law is often used instead of logarithmic law when other factors are not available such as surface roughness or atmospheric stability [26]. Meanwhile, the logarithmic law is only valid in the IS, which extends from a height of 2 to 5 times the mean building height to approximately 10% of the boundary layer depth [27]. The power law is given as in equation (1). Consequently, the vertical mean velocity profile generated must be similar to the one observed in full scale where the relationship is given in equation (2) [13].

\[
\frac{U(z)}{U_{ref}} = \left( \frac{z}{z_{ref}} \right)^{\alpha}
\]

(1)

\[
\alpha_M = \alpha_N
\]

(2)

where \( U_{ref} \) is reference velocity at reference height, \( z_{ref} \), \( \alpha \) is the exponent constant of the profile and subscript M and N represents the model and nature respectively. The mean velocity profile within IS is expressed by a logarithmic law as given in equation (3):

\[
\frac{U(z)}{U_*} = \frac{1}{k} \ln \left( \frac{z}{z_0} \right)
\]

(3)

The logarithmic equations provides unknown values which are friction velocity, \( U_* \) and roughness length, \( z_0 \). By fitting the data of simulated boundary layer with equation (3), the value of both friction velocity and roughness length can simultaneously be determined. Table 1 shows the range of exponential and roughness length value over two typical terrain types of urban area.
Table 1. Characteristics of urban boundary layer over selected terrains.

| Terrain type    | Power law exponent, $\alpha$ | Roughness length, $z_0$ (m) |
|-----------------|-------------------------------|-----------------------------|
| Suburbs         | 0.20-0.24                     | 0.4-0.7                     |
| City centers    | 0.28-0.4                      | 0.7-1.5                     |

*a*from Plate, 1995 [26]  
*b*from Wieringa, 1993 [28]

One of the important criterion that define an atmospheric boundary layer over a fully rough surface in wind tunnel is the roughness Reynolds number, $Re^*$ and is given as

$$Re^*_0 = \frac{U_* \times z_0}{\nu}$$  \hspace{1cm} (4)

where $\nu$ is the kinematic viscosity of working fluid. The roughness Reynolds number will determine whether the flow near the floor is affected by viscous effects. Uehara et al., 2003 [29] suggested a critical roughness Reynolds number of 5, regardless of model height. In addition to that, the ratio between the simulated roughness length in the wind tunnel and the nature will represent the model scale, $M$ where the relationship is given in equation (5) [30].

$$\frac{z_{0,M}}{z_{0,N}} = M$$  \hspace{1cm} (5)

ASCE, 1999 [31] expressed a relationship of stream wise turbulence intensity profile with roughness length as given in equation (6). Besides the mean velocity profile and the roughness length, the turbulence intensity profile of the model must likewise be similar to the one observed in nature as given in equation (7) [31].

$$I_u(z) = \frac{1}{\ln\left(z/z_0\right)}$$  \hspace{1cm} (6)

$$I_{uM} = I_{uN}$$  \hspace{1cm} (7)

It is worth mentioned that a plane surface may have vertical displacement height value between zero and average height of roughness elements for flows over very rough surface (i.e. forests, buildings) and is highly dependent on the areal density of roughness elements. Due to that reason, the calculation of equation (1), (3) and (6) will have to be modified, where the displacement height must be deduct from the height elevation written as $z+d$ instead of only $z$. However, for wind flow profile over smooth surface or flow past through isolated structure, $d=0$ can be assumed [32, 33].

2.2. Experimental Set-up

The experiments in this study is carried out in a closed-loop and low speed wind tunnel (UTM-LST) at the Aeronautics Laboratory, Universiti Teknologi Malaysia. This wind tunnel was able to deliver a maximum air speed of 80 m/s inside the test section. The size of test section was 2.0 meters wide, 1.5 meters height, and 5.5 meters long. In order to develop the urban boundary layer, a turbulence grid made of a bar and rods are located at the entrance of the test section with horizontal alignment (figure 2(a) and (b). The size of the rods ranges from 1 cm to 2.8 cm in diameter with mostly is 2 cm in diameter and was displaced to each other according to the target vertical velocity profile as figure 3(a) which will be explain later in the next section. To reduce vibration on the turbulence grid, caused by
high freestream wind speed, 2 rods separated 40 from each other were located at the center of the turbulence grid with vertical alignment. The location of in situ calibration and the subsequent measurements are located 1.5 m from the inlet. The measurement of urban boundary layer were made along vertical direction at three spanwise locations figure 3(b). Due to the size of the probe support and probe support holder, the measurement can only be made at the lowest elevation of 4 cm from the ground.

![Figure 2](image1.png)

**Figure 2.** The installation of the turbulence grid and the measurement equipment in UTM-LST (a) overview of the experimental layout and (b) dimensions schematic of the experimental layout.

![Figure 3](image2.png)

**Figure 3.** Schematic drawing of (a) turbulence grid from side view and (b) location of the measurement points looking upstream in UTM-LST.

### 2.3 Measurement Technique

The mean velocity and turbulence was measured using a constant temperature, 1-D hot wire anemometer (HWA) of Dantec 55P11 in conjunction with a 90C10 constant temperature anemometer, where both are connected into StreamLine 90N10 frame. First, the HWA is calibrated in situ facing the tunnel free stream in the middle of the wind tunnel test section against a pitot-static tube as a
reference reading with 11 number of calibration points ranging from 2 to 32 m/s. Data was collected with a sample rate of 1 kHz for 10 seconds and a calibration curve for the HWA was obtained with polynomial curve fitting as in equation (8) where \( E_{\text{corr}} \) is the corrected output voltage constant while \( C_0, C_1, C_2, C_3 \) and \( C_4 \) are calibration constants.

\[
U = C_0 + C_1E_{\text{corr}} + C_2E_{\text{corr}}^2 + C_3E_{\text{corr}}^3 + C_4E_{\text{corr}}^4
\]  

(8)

Two main flow characteristics were simulated simultaneously, namely the mean streamwise velocity and the streamwise turbulence intensity. By simulating these 2 main characteristics, the similarity laws of wind tunnel studies, which are described in previous section, are expected to be fulfilled.

3. Result and discussion
Throughout this study, a reference height of \( z = 0.1 \) m from the floor tunnel with approximate velocity speed of 10 m/s was taken as a reference in order to ensure that the speed measured between 0.04 m up to 0.1 m or more are essentially higher than the lower limit of calibrated wind speed (2 m/s). Subsequently, the gaps between the rods are adjusted in the attempt to match with that of a typical velocity profile over city center (\( \alpha = 0.3 \)). The streamwise velocity profiles at each locations are approximated using power law to check the similarity of power law exponent value of 0.3. The profiles and power law trend lines are plotted in figure 4 and shows that the values obtained are close to 0.3, represented by the power over x-axis (\( z/z_{\text{ref}} \)).

![Figure 4. Vertical mean streamwise velocity profile at 3 locations.](image)

Alongside the mean streamwise velocity profile and streamwise turbulence intensity were also measured along the vertical at three locations as figure 2(b), 1.5 m from the turbulence grid. Both the mean streamwise velocity and the turbulence intensity are plotted in logarithmic trends as shown in figure 5(a) and 5(b) respectively. The mean velocity profiles show linear log profile for a height between 158.4 mm up to 400 mm. The results of streamwise turbulence intensity also coincide with the mean velocity where the values are scattered for height below \( z = 158.4 \) mm and then reduced up to \( z = 400 \) mm before increased again for a height of more than 400 mm. The scattered values below 158.4 mm may indicate a region of roughness sublayer (RS), in which previous wind tunnel studies have shown that the streamwise turbulence intensities and Reynolds stress value are scattered below
the roughness elements (made of sharp edge blocks, placed in staggered or in line configuration) up to twice the mean height of the roughness elements [34, 35]. Thus, the turbulence grid used in present study was able to produce the roughness sublayer without a fetch of roughness elements. A region of inertial layer was observed for height more than 158.4 mm where the flow is horizontally homogeneous. In other words, the profiles are linearly increased or decreased with height. At height of more than 400 mm, the profiles shows irregularity especially for the mean streamwise velocity and is at increasing trends for longitudinal turbulent intensity due to a few huge gaps between specific rods of the turbulence grid (The first gap is between 445 mm up to 572 mm, the second gap is between 657 mm up to 784 mm and the third gap is 784 to 900 mm). These large gaps may have caused the effects of an individual rod to take place rather than small gaps. Nevertheless, the region at height more than 400 mm is not really concerned with the characteristics of the simulated boundary layer in the present study as our intention is to look at the profile near the ground (in particular, up to a height which consists partial region of IS) which reflects the similarity characteristics of the simulated boundary layer with that of actual boundary layer.

![Figure 5](image)

Figures 5. Vertical profiles at three locations of (a) mean streamwise velocity and (b) longitudinal turbulent intensity.

By further examining the mean streamwise velocity within the simulated IS, the roughness length and consequently the friction velocity of each profile were obtained through logarithmic law relationship. Such relationship is plotted in figure 6(a) and the roughness length was deduced from the line fitted to the mean velocity profile in logarithmic form which intercept at zero velocity value which are: Middle: \( z_0 = 6.07 \) mm; Left: \( z_0 = 19.83 \) mm; Right: \( z_0 = 11.49 \) mm. The friction velocity of each profiles is determine by substituting the predetermined roughness length values into the logarithmic law equation which then yields the following friction velocity: Middle: \( U^* = 1.44 \) m/s; Left: \( U^* = 2.03 \) m/s; Right: \( U^* = 1.72 \) m/s. By taking the average of these three profiles of roughness length and friction velocity, the average roughness length is 12.463 mm while the average friction velocity is 1.73 m/s.
Based on the results of the simulated flow described above with the following experimental conditions at 27 °C and pressure at 105 kPa, the average roughness Reynolds number can be calculated as

\[
\text{Re}_{\!*} = \frac{u_{*\!*} \times z_{0\!*}}{\nu} = \frac{1.73 \text{m/s} \times 0.0125 \text{m}}{1.576 \times 10^{-5} \text{m}^2/\text{s}} = 1372 \text{m/s}
\]

Hence, the simulated boundary layer was fully under rough condition. By taking the roughness length in nature of 1 m representing the mid-range of city center [29], the ratio between the \(z_{0,M}\) and \(z_{0,N}\) produce the average model scale of the present study as

\[
\frac{z_{0,M}}{z_{0,N}} = \frac{0.0125 \text{m}}{1 \text{m}} \approx \frac{1}{80}
\]

With such model scale and the expected model height to be at maximum of only half the height of RS (≈ 80 mm) [3, 5], the simulated boundary layer could only be possibly immersed over an actual building height of 6.4 m. The 6.4 m building height is a typical building height found in suburban residential area and is not a building height found in city center where it was typically found to be more than 10 m high [35]. It is worth noting that the roughness length at the center and lateral side of the wind tunnel are varied, where the least roughness length is located at the center while higher roughness length are at lateral sides. Such variations has direct implication in the determination of model scale, M. If the roughness length could be maintained at values which is same with that at the middle of the test section, the model scale will be 1:160. At 1:160 model scale, a model height of 80 mm is equivalent to an actual building of 13 m high, which is well representative of an average buildings height in city center. Uehara et al., 2003 [29] obtained consistent roughness length value regardless of freestream tunnel speed. Hence, the variations of roughness length values in the present

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**Figure 6.** Vertical profiles at three locations a) mean streamwise velocity and b) longitudinal turbulent intensity.
study suggest that there is lack of vertical rods align at lateral side of turbulence grid and may have contributed to the inconsistency.

The streamwise turbulence intensity of the present study and the theoretical streamwise turbulence intensity profile at the scale of 1:80 with typical minimum roughness length of city center (0.7 m [30] ) is plotted in figure 6(b). Another theoretical streamwise turbulence intensity profile but at the scale of 1:160 was also included. From figure 6(b), the profiles of the whole streamwise turbulence intensity profile of the simulated boundary layer has failed to reproduce within the minimal value of streamwise turbulence intensity representing a full scale profile over central city. In particular, the simulated turbulence intensity at height less than 100 mm is about 70% to 80% lower than what it should be like in nature at 1:80 scale. Even if the model scale is at 1:160, there are still deficiencies of about 50% to 68%. The comparisons were made with the lower limit of city center category and the deficiency will be even more at higher roughness length. The lack of turbulence profile may be caused by the high free stream velocity of wind tunnel where previous wind tunnel study by Uehara et al., 2003 [29] shows the same trend. The reason of using higher freestream velocity in current study is to allow the measurement to be made within the calibrated speed of the HWA but at the cost of turbulence intensity deficit. However, the deficit of turbulence intensity reported by Uehara et al. 2003 [29] was not significantly reduced at higher speed which suggest that a fetch of roughness elements on the floor must have properly maintained the levels of turbulence intensity even at higher freestream speed. Recent studies have shown the important of having a combination of various passive devices such as screen, spires, and roughness elements to produce an acceptable boundary layer profiles within a short wind tunnel [36, 37]. Therefore, using only turbulence grid may not be enough to produce high turbulence intensities near the ground and an artificial element to augment the turbulence intensity levels near the tunnel floor must be considered.

4. Conclusions
A turbulence grid has been developed and tested to control the simulation of urban boundary layer development under neutral atmospheric condition in UTM-LST within a short distance. Results show that a good vertical mean velocity profile representing an urban boundary layer flow over city center with fully rough condition can be produced in UTM-LST. However, the following statements related to the deficiency in the present study can be deduced as follows:

i. The roughness length simulated in this study is rather high, which affects the determination of the model scale. The reason is due to the influence from the lack of vertical rods at lateral sides of turbulence grid.

ii. There is much deficiencies of streamwise turbulence intensity in the whole simulated urban boundary layer. The reasons may be due to the high freestream velocity of the wind tunnel and the lack of physical interactions near the tunnel floor to enhance the turbulence production.

The following actions can be taken to improve measurement techniques and enhance flow quality:

i. Inclusion of more vertical rods to reduce and maintain the roughness length values along spanwise of the test section inlet.

ii. Calibrate the HWA at lower wind tunnel speed to check whether the turbulence could be enhance at lower tunnel freestream speed. X-probe HWA can also be used to determine the similarity of lateral and vertical turbulence intensity and also to complement the turbulent intensity obtained with Reynolds stress.

iii. A fetch roughness elements may help to enhance turbulence levels near the floor. However, careful consideration must be taken especially in determining its size, due to the wind tunnel constriction of non-adjustable ceilings.

Based on the deficiencies observed in the present study, future works should focus on the enhancement of current design and measurement technique for quality assurance of future study of flow through building models or transport phenomena experiments immersed in urban boundary layer.
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