Generation of atmospheric boundary layer in the IIUM low speed wind tunnel

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Abstract. The purpose of this paper is to describe an attempt made to simulate the atmospheric boundary layer (ABL) in the Low Speed Wind Tunnel (LSWT) at IIUM. This was performed through modifications of the inlet and surface conditions of the test section. Devices such as spires, fences and surface roughness were used. The ASCE 7-10 standard was used as a reference to validate the results between the wind tunnel data and the full-scale ABL flow characteristics. The velocity profile and turbulence intensity were measured using a one-dimensional hotwire (CTA) probe. The data obtained show good agreement with ASCE 7-10 velocity profiles for exposures B and C while using a scale of 1:488 to match the wind tunnel data. The turbulence intensity profiles do not show a good agreement.

1. Introduction

The atmospheric boundary layer is the air close to the earth’s surface. The atmospheric wind has had a robust impact on human beings and their surroundings. The interest to study the effect of wind include economic loss and loss of life cause by wind devastation, problems that constantly grow due to the increase in world population and urbanization. For engineering and design purposes, it is important to understand the wind flow of atmospheric boundary layer and the characteristics of turbulent flow associated with it.

Most of the wind tunnels are usually designed for aeronautical and/or automotive testing purposes. Typically, the flow in the test section is nearly laminar or of low turbulence intensity. The boundary layer in such wind tunnels is as thin as possible on the walls in the test section. On the other hand the Atmospheric Boundary Layer (ABL) has much higher turbulence intensity and the boundary layer in the tests section is very thick. The test section of IIUM low speed wind tunnel is too short (6 m long) when compared to an environmental wind tunnel test section. Thus, the creation of the ABL in this wind tunnel requires certain devices to make the boundary layer thicker and have much higher turbulent intensity in a relatively short distance.

For this study, the generated ABL in the IIUM wind tunnel will be compared with recommended standard values in international wind loading standards and codes.

The surface of the earth can be categorized into three distinct terrain types; urban and suburban, rural, and smooth surface. The ASCE 7-10 [1]standard categorizes each type of terrain according to the type of ‘exposure’ as follows:
• Exposure B
“Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions having the size of single family dwellings or larger. This exposure is representative of terrain in the upwind direction for a distance of at least 460 m (1,500 ft.) or 10 times the height of the building or other structure, whichever is greater”.

• Exposure C
“Open terrain (rural terrain) with scattered obstacle having heights generally less than 9.1 m (30 ft.). This category includes flat open country, grasslands and shorelines in hurricane prone regions”.

• Exposure D
“Flat, no obstacle areas exposed to wind flowing over open water for a distance of at least 1.61 km (1 mile). Shorelines in this exposure include inland waterways, the Great Lakes and coastal areas such as California. Exposure D extends inland from the shoreline a distance of 460 m (1500 ft.) or 10 times the height of the building or structure, whichever is greater”.

Numerous researchers have obtained the ABL in a wind tunnel (for example, [2, 3]). They and others have contributed in many ways to construct the atmospheric boundary layer in the wind tunnel. This simulation of the atmospheric boundary layer in a long test section wind tunnel is performed by simulating a long stretch of terrain upstream of the model so that vertical shear and turbulence will develop naturally. [4] remarks that, there must be target characteristics which should be met. [5] have defined that “the characteristics are; the variation of the mean wind speed and turbulence intensities with height”.

2. Experimental Techniques
To generate ABL, a combination of spires, fence and surface roughness are needed. To alter the external flow, spires are used that extend the bottom wall into the oncoming flow. Design formulae have been developed by [6] for spires. These are used to determine the height and width of the spires used in this work. The surface roughness elements were also designed by using the design formulae of [6]

![Figure 1: Irwin (1981) Spire dimensions](image_url)
[4] evaluated three types of roughness surfaces. The first type consisted of wooden strip panels attached to removable thick floor boards. The strip panels lay cross stream to the flow and characterized a "rough terrain".

A later modification added blocks to the floor boards in order to increase the effective roughness of the strip panels. The square blocks were applied in a diamond-shape pattern on the floor board next to the wooden strip panels. Carpet was utilized as the third type of roughness fetch to characterize a smoother type terrain. The carpet extended from the downstream fence barrier to the boundary layer test section area.

In order to avoid wake effects on the model, [7] felt that the last row of the roughness elements should not be closer to the model than ten times their dimension. Also without any further floor roughness between the last row of large roughness elements and model location, an inner boundary layer with a typical smooth-surface velocity profile will develop. In order to retard the development of such a smooth surface profile, seven rows of smaller cubic roughness elements are placed at regular intervals just upstream from the model location.

2.1. Thickening devices/Barriers
The role of the barrier is to give an initial momentum deficit and depth to the layer which is mixed into the developing layer by turbulence generated by the mixing-device. The flow is tricked by the barrier into believing the fetch of roughness to be longer, and by the mixing-device that the barrier is not there at all. In the ideal case, the flow in the test area near the downstream end of the surface roughness should have the characteristics of a boundary layer grown naturally over a much longer fetch of the same surface roughness, without any additional characteristics imposed by the barrier. The intended role of the barrier is therefore to establish the boundary-layer height h. There is often interaction between the barrier and the mixing-device.

[8] has made the arrangement of a castellated barrier wall, vortex generators and surface roughness elements in the wind tunnel test section. The height (127 mm) and form of the castellated barrier wall and vortex generators, as well as the layout of surface roughness elements, were tuned to generate rural, suburban and urban ABL models.

[9] have made use of elliptic generators. They have followed the procedure and the design made by [10] but with a wedge angle of 5.7°.

2.2. Standard Mean velocity and turbulence intensity profile Mean velocity profiles
The ASCE standard mean velocity profile for the ABL in rural and suburban areas are shown in Fig. 2
Using the following formula to plot the graph

\[
\frac{V_{z,TC}}{V_{10,TC}} = \left( \frac{z}{10} \right)^{\alpha_Tc}
\]  

(1)

Where \( \alpha \) values are 0.13, 0.15, and 0.18 for exposure D, C, and B respectively. Meanwhile, \( V \) is the mean velocity and \( z \) is the height. Subscript \( Tc \) stands for terrain category in the ASCE standard.

**Turbulence intensity profiles**

The ASCE standard turbulence intensity profiles for the ABL in exposures B, C, and D are shown in Figure 3.

**Figure 2**: Velocity profile for rural and suburban (ASCE-7, 2010)

**Figure 3**: Turbulence intensity profiles (ASCE-7, 2010)
\[ I_{x,Tc} = C_{Tc} \left( \frac{10}{z} \right)^{\frac{3}{2}} \]  

(2)

\( C_{Tc} \) is a constant for each exposure; 0.3, 0.2 and 0.15 for exposure B, C and D respectively.

2.3. Scaling the profile

Most of the previous studies simply assume the scale for modelling the atmospheric boundary layer in the wind tunnel[11] has defined the scale for simulation in wind tunnel to be 1/500 when the height of the atmospheric boundary layer produced in the wind tunnel is 2m by assuming the real typical boundary layer as 1000 m. Another researcher, [12] also has assumed, the scale to be 1:3000 when he simulates the atmospheric boundary layer is generated in a small wind tunnel with the height of 22.1cm and compare it with the height of 700 m atmospheric boundary layer in the real world.

3. Experiment Setup

The atmospheric boundary layer is generated in the International Islamic University Malaysia Low Speed Wind Tunnel. The IIUM LSWT is a closed-loop type wind tunnel having a test section of 1.5 m x 2.3 m x 6 m with maximum speed of 50 m/s. The arrangement of the devices has been classified into three cases. The details of the cases are as follows:

3.1. Case A:
In this case a combination of spires and blocks as surface roughness are used to generate the atmospheric boundary layer as shown in Figure 4.

![Figure 4: Spires and surface roughness installed (Case A)](image)

3.2. Case B:
In this case a combination of spires, fence and blocks as surface roughness are used to generate the atmospheric boundary layer as shown in Figure 5.
3.3. Case C:
In Case C, fence and blocks as surface roughness are used to generate the atmospheric boundary layer as shown in Figure 6.

3.4. Measurement device
A constant temperature anemometer (CTA) – also known as a hotwire was used to measure the mean and turbulent velocity as well as the turbulence intensity. A 1-D CTA probe was used. The tests were performed at free stream speeds of 15m/s, 20m/s and 30m/s.

4. Results
Empty wind tunnel test data: Figures 7 show the velocity profiles and turbulence intensity of the empty test section at various speeds. The measurements were carried out near the end of the test.
section (5.21 m from the beginning of the test section) using a 1D CTA probe. The results prove the thin boundary layer and low turbulence intensity even at the end of the test section.

![Figure 7: Free Stream Velocity profile for 15m/s](image1)

![Figure 8: Free Stream Turbulence intensity for 15m/s](image2)
Figure 9: Free Stream Velocity profile for 20m/s

Figure 10: Free stream Turbulence intensity for 20m/s

Figure 11: Free steam velocity profile 30m/s
4.1. Analysis of results

The measurements were made at a location 5.21m from the beginning of the test section. The tests have been divided into three cases that are; Case A, Case B and Case C for free stream speeds of 15m/s, 20m/s and 30m/s. Only for case A, a velocity of 30m/s could be attained. For case A, the installation of spires at height of 0.8m and blocks as the surface roughness produced a boundary layer of 750mm height. This method proves that, any desired height of boundary layer, can be produced by using spires of nearly the same height as the required boundary layer height. In all cases, the boundary layer height produced was nearly of the same height as of the spires used for all speeds tested. However, the turbulence intensity produced varied with the speed. Turbulence intensities of 5.88%, 11.65% and 16.133% were produced, near the floor at speeds of 15m/s, 20m/s and 30m/s respectively, in Case A.

For case B, all three devices were installed together that are, spires, fence and blocks as surface roughness. The data for velocity profile fluctuates more at low level of height that is below 200mm, than in case A. There is no change of height of boundary layer which is the same as in case A. However, there is a difference in turbulence intensity near the floor especially at a speed of 20m/s. The increase in turbulence intensity was substantial at 27.68%. For case C, only the fence and the blocks as the surface roughness were used. From the graph, velocity profile for velocity of 15m/s and 20m/s shows an increment until the height of 700mm and start decrease at the height of 750mm. This happens due to the absence of spires. At a speed of 15m/s, the turbulence intensity is smaller than at 20m/s. The percentage near the floor are 8.36% and 21.31% respectively. Therefore, we can say that, the turbulence intensity near the floor increases as the velocity increases, as well as when the fences are installed. The fence proves to be great device to increase the turbulence intensity as well as slow the air stream.

The experimental data is compared to the ASCE standard. From the comparison it seems that the best combination to simulate the ABL profile of ‘Exposure B’ is fence and blocks as the surface roughness at a tunnel speed of 20m/s. To simulate the ABL for ‘Exposure C’, the best combination should be spires, fence and blocks as the surface roughness at the tunnel speed of 20m/s. This combination is achieved by scaling the wind tunnel data to match with the ASCE standard. From the standard, the nominal height of atmospheric boundary layer is 365.76m. Thus, a scale of 1:488 is proposed to match with the velocity profiles of the ASCE 7-10 standard.

The measured turbulence intensity is lower than expected. The major cause seems to be the use of a 1-D probe measuring only the x-component of the turbulence intensity. The actual turbulence intensity would be higher if a 3D CTA probe is used.

Figure 12: Free stream turbulence intensity for 30m/s
**Figure 13:** The most suitable comparison between experimental and ASCE standard suburban velocity profile

**Figure 14:** The most suitable comparison between experimental and ASCE standard suburban turbulence intensity profile
Figure 15: A comparison between experimental and ASCE standard rural velocity profile

5. Conclusion
The results prove that by utilizing spires we can increase the height of the boundary layer and also increase its turbulence intensity. Also by adding fence upstream of the spire we can significantly increase the turbulence intensity. The blocks seem to have little effect on the turbulence intensity and velocity profile. The main function of the blocks is to retard air flow on the lower portion of the boundary layer. In conclusion, all the devices tested prove to be effective in altering the flow properties and simulating an ABL for ‘Exposures B and C’.

The suburban and rural atmospheric boundary layer was generated in the IIUM LSWT using the configuration of fence, spires and blocks as the surface roughness. The scale of the simulated ABL is 1:488 after unifying and finding a compromise between the scale of the velocity profile and the turbulence intensity. Further measurements should be made using a 3D CTA probe to obtain better results.

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