Investigation Of Wind Flow Characteristics Using Passive Devices in Boundary Layer Wind Tunnel

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Abstract

Atmospheric boundary layer (ABL) flow can be generated in an open-loop boundary layer wind tunnel (BLWT) to simulate a realistic rough-wall condition imposed on the natural wind. An open-loop BLWT experiment is performed in this work using a wall barrier and roughness elements as passive devices to create a rough-wall condition and reproduce a realistic neutral ABL flow. The roughness elements used are homogeneous cubic blocks with a side length of 25 mm arranged in a staggered layout at 12.5% packing density. Wind velocity data is measured in the upstream test section of the BLWT using a hot-wire anemometer (HWA) to obtain the wind velocity profiles. The height z was measured from z = 7 mm from the test section floor to z = 800 mm. The mean vertical velocity profile of the rough wall indicates a significant decrease within the height interval of z/zref < 1.0 due to the surface roughness. Additionally, the normalized mean wind velocity is approaching unity at z/zref = 1 with the rough wall, whereas the smooth wall (no roughness elements) is observed at z/zref = 0.1. Moreover, the standard deviation profile of the rough wall shows higher values in the near-wall region (z/zref ≤ 0.4), suggesting a higher level of turbulence in the wind flow due to surface roughness. Finally, the rough wall skewness profile is left-skewed, suggesting a non-Gaussian feature. The study found that roughness parameters affect vertical velocity profiles and create realistic atmospheric .boundary layer flows.

Keywords

wind tunnel; boundary layer; surface roughness

Introduction

Artificial atmospheric boundary layer (ABL) flows are used in boundary layer wind tunnel (BLWT) studies on natural event-related rough surface aerodynamics [1, 2]. Wind-surface interaction causes boundary layer flow that enhances surface turbulence, influenced by roughness. Friction makes the rough-wall boundary layer flow more turbulently.

ABL models in short-test-section BLWTs are often generated using surface roughness elements and other experimental devices. Researchers are known to employ the BLWT wall barrier to induce input turbulence flow. The wall barrier reduces the fetch needed for ABL small-scale model development. The barrier decreases momentum and increases turbulence in the lower ABL model [3]. The barrier creates horizontal eddies as air rushes over it. Barriers provide the layer's initial momentum deficit and depth [4]. Simulating the atmospheric boundary layer in the BLWT requires turbulence. The barrier also simulates airflow and turbulence patterns caused by buildings and terrain features, making the ABL more realistic. Use different surface roughnesses in BLWTs to study ABL development. This is necessary to obtain a characteristic wind velocity profile to predict boundary layer formation [5, 6]. The rough surface

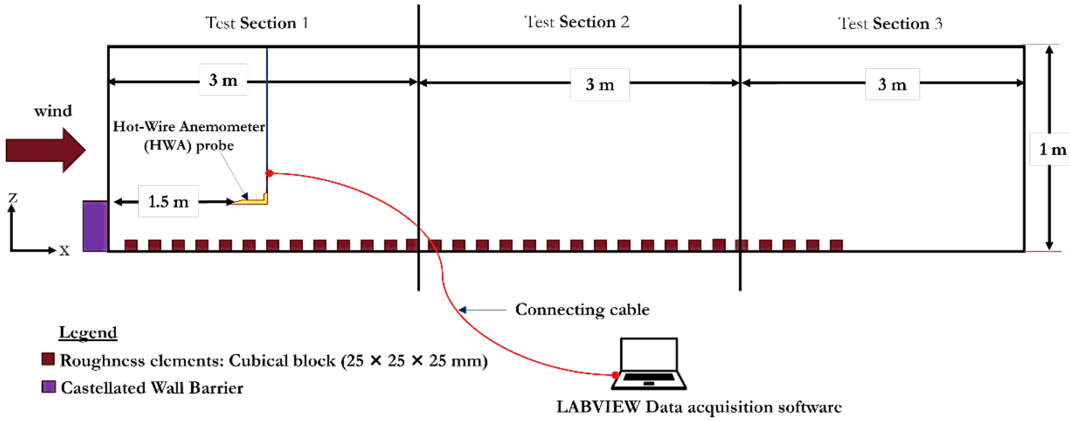

Figure 1: Side-view diagram of the open-loop BLWT

setup is arbitrary since cubic blocks [7, 8], and ribs [7] were used in previous studies to suit BLWT sizes and research targets. Mo et al. [9] noted the similarity of cubic block and rib results. The geometric configuration of roughness elements employed in boundary layer investigations has not been standardised.

This work aims to elucidate the rough-wall boundary layer through BLWT testing using homogeneous cubic blocks (i.e., uniform height) as roughness elements in the open-loop boundary layer BLWT. The change in the vertical velocity profile due to the surface roughness is focused on the upstream test section of the BLWT. The findings of this work will contribute to the literature on the aerodynamic effect of wind flow characteristics using passive devices with exclusivity to open-loop BLWTs.

METHODOLOGY

The experimental work was conducted in the open-loop boundary layer wind tunnel (BLWT) laboratory of Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia. In this work, the measurement of the vertical velocity profile was focused in test section 1 of the BLWT, as shown in Figure 1. To generate the artificial neutral ABL, a castellated wall barrier was installed at the inlet of test section 1 and the roughness elements were installed in its entire floor area, as in Figure 2.

The density of roughness elements is determined using packing density, λp which is defined as the ratio of the plan surface area of a block to the lot surface area. The roughness elements used were cubic blocks (side lengths of 25 mm) installed in the staggered layout with a λp of 12.5%. The setting of the castellated wall barrier and the 25 mm cubic roughness elements was adopted from H'ng et al. [5].

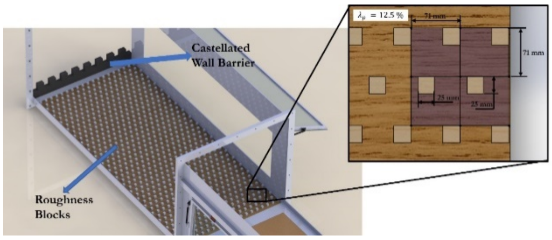

Figure 2: Layout of the roughness elements

The flow of processes involved in the BLWT experiment is shown in Figure 3. The work began with the passive device installation (wall barrier and roughness elements), followed by the calibration of the hot-wire anemometer (HWA), from which the wind velocity reading was compared with the pitot static tube reading.

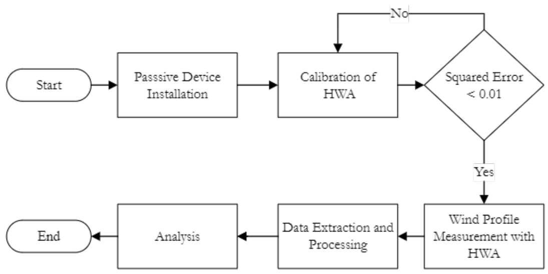

Figure 3: Process flow of BLWT experiment

A measurement frequency of 1000 Hz was set on the HWA to collect data for 10 seconds, and 10,000 data readings were collected from each measurement point. The squared error of the wind velocity data was set to be less than 0.01 to ensure data precision. Subsequently, to obtain the vertical velocity profile, the methodology of Vikneshvaran et al. [2], which used the same BLWT but without the roughness elements, was reproduced in this work. The measurement of vertical velocity profile was conducted at the test section's centre (y = 0). The measurement height z, is measured at z = 7 mm from the BLWT floor to z = 800 mm. Table 1 shows the measurement height was then increased vertically at several Δz intervals. The measured data was then extracted and processed using the LabVIEW software for further analysis.

Table 1: Vertical measurement points

z (mm)	Δz (mm)	Measured points
7 ≤ z ≤ 140	1	134
140 ≤ z ≤ 160	5	4
160 ≤ z ≤ 800	10	6
	Total	202

Results and Discussion

Mean Vertical Velocity Profile

The mean wind velocity profiles of the rough wall and the smooth wall from Vikneshvaran et al. [2] are shown in Figure 4. The mean wind velocity is normalized by the reference mean wind velocity taken at z_{ref} = 400 mm. The figure shows the increasing mean wind velocity from z/z_{ref} = 0 to 1 for the rough wall condition. As the height increases from z/z_{ref} = 1, the normalized wind velocity remains approximately constant, i.e., U/U_{ref} ~ 1.0. On the contrary, without the roughness elements, the profile over the smooth wall shows that the normalized mean wind velocity can achieve unity at a lower height, i.e., z/z_{ref} ~ 0.1. This suggests that the use of roughness elements has a significant effect on the wind flow characteristics.

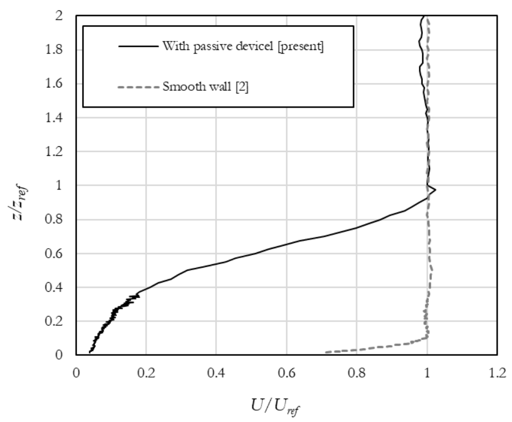

Figure 4: Mean vertical velocity profile

Standard Deviation and Skewness Profiles

The standard deviation and skewness profiles of the wind velocity data are shown in Figures 5 and 6, respectively. Figure 5 shows the distribution of the normalized standard deviation throughout the vertical height in the test section. The standard deviation of the streamwise velocity component variations, normalized by the mean streamwise velocity, is typically used to characterize the turbulence level. The standard deviation increases from z/zref = 0 to 0.4, at which the maximum standard deviation is observed, this corresponds to a high level of turbulence in the flow at this height, characterized by values ranging from 0.006 to 0.012. The standard deviation is relatively larger near the surface due to strong shear stress caused by wall barriers and roughness blocks [10]. From z/zref = 0.4, the standard deviation decreases close to zero, suggesting the diminishing effect of surface roughness on the flow.

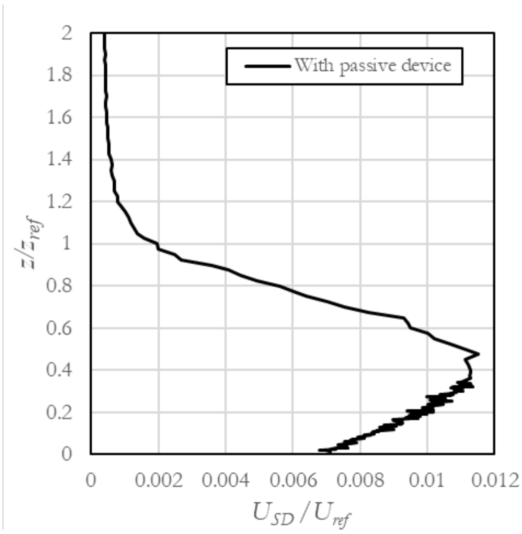

Figure 5: Standard deviation profile

On the other hand, the skewness profile shown in Figure 6 indicates that the wind velocity distribution is skewed left and displays the non-Gaussian characteristic [11]. In wind engineering, the skewness of a vertical velocity profile is a crucial parameter that provides insight into the turbulence and the distribution of wind velocities at various heights above the ground. The skewness of wind velocity data in BLWT with a rough-wall condition is related to the Gaussian or non-Gaussian characteristic because it helps determine the nature of the wind velocity data distribution. Gaussian distributions are symmetric and skewless. Thus, non-zero wind velocity skewness indicates a non-Gaussian distribution. A negative skewness number indicates a longer or thicker left tail than a right tail. Rough-wall turbulence can cause non-Gaussian distributions with non-zero skewness in wind velocity data. Turbulence can also cause non-Gaussian distributions with skewness in wind velocity data. The rough wall's skewness profile contradicts Vikneshvaran et al.'s [2] right-skewed distribution for the smooth wall. Therefore, it can be said that roughness affects BLWT wind flow.

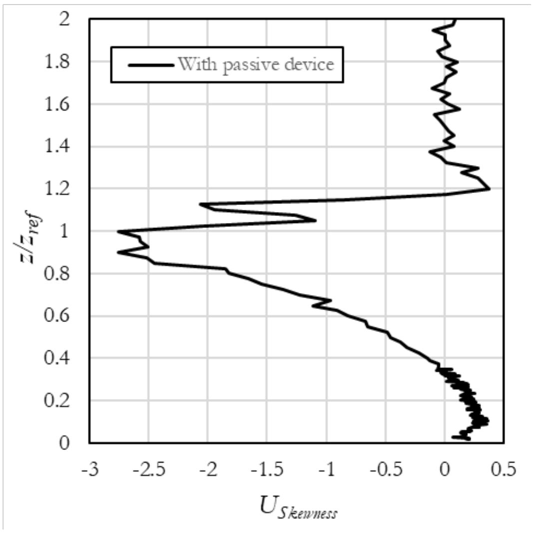

Figure 6: Skewness profile

Conclusion

BLWT experiments show that surface roughness parameters affect atmospheric boundary layer (ABL) flow dynamics. The mean wind velocity fell significantly when the z/zref ratio was less than 1.0 compared to the smooth wall condition at 0.1. Wind patterns have changed significantly. The roughness features make the skewness profile left-skewed, deviating from Gaussian. The standard deviation profiles indicate higher turbulence near the rough wall (z/zref < 0.4). This study shows that roughness elements in BLWT experiments duplicate ABL conditions and shed light on boundary layer dynamics and surface roughness. For future research, scaled model experiments inside BLWTs can evaluate turbulent flow across rough surfaces. Integrating passive devices like spires into BLWTs and collecting vertical velocity profiles at streamwise points should improve deep atmospheric boundary layer modelling.

Acknowledgement

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