Simulation of atmospheric boundary layer in the wind tunnel facility at University of Bristol

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1 INTRODUCTION

Air pollution studies are critical for understanding the dispersion of pollutants in urban environments and mitigating their adverse health effects. Accurate simulation of these processes in a controlled environment, such as a wind tunnel, is essential for advancing our knowledge and developing effective pollution control strategies. The atmospheric boundary layer (ABL) plays a pivotal role in influencing pollutant dispersion due to its complex flow dynamics and turbulence characteristics. Therefore, replicating the ABL accurately in wind tunnel experiments is crucial for reliable urban air pollution studies.

At the University of Bristol, the new national Boundary Layer Wind Tunnel (BLWT) Facility provides a state-of-the-art platform for such investigations. A number of previous works have reported on characterising new wind tunnel facilities. For instance, Kuznetsov et al. [1] detailed the climatic wind tunnel at the Institute of Theoretical and Applied Mechanics (ITAM), specifically for precipitation and freezing effects, focusing on the streamwise effect of each Counihan method component. Kozmar [2] characterised the Technische Universität München (TUM) boundary layer wind tunnel to replicate rural, suburban, and urban flows. Various methods exist for generating an ABL in a BLWT, including active methods like air injection [3], spires with slats for limited space tunnels [4], and mesh grid and barrier combinations [5]. However, the most widely used approach is Counihan's method [6], with further modifications [7].

Our research began by characterising the wind tunnel's capabilities through baseline measurements of smooth-wall configurations to establish a reference point. The main focus was to generate the ABL using Counihan's method [5], involving a castellated barrier, quarter-elliptic wedge spires, and scaled roughness elements (Lego blocks) to simulate urban surface roughness. We systematically investigated the effects of these components on boundary layer dynamics. Extensive measurements using hot-wire anemometry (HWA) characterised the flow properties, including mean velocity, velocity fluctuations, turbulence intensity, and integral length scales. These measurements were compared with established datasets from sources such as the Engineering Sciences Data Unit (ESDU) [8] and Walshe [9] to validate the flow characteristics and ensure the reliability of our ABL simulations for future wind engineering research.

2 EXPERIMENTAL SETUP

The BLWT at the University of Bristol, spans $30\,m$ and is equipped with 9 axial, with a power requirement of $240\,kW$. Its multi-fan configuration allows for variable operational modes, achieving a steady flow velocity ranging from $0.5\,m/s$ to $35\,m/s$ with low free-stream turbulence levels. The test section measures $2\,m$ in width, $1\,m$ in height, and approximately $18\,m$ in length. It can naturally develop a boundary layer exceeding $200\,mm$ thickness ($Re_x \sim 9.5 \times 10^6$) [14].

For the experimental setup simulating the ABL, components were designed based on [6, 7 ,10], detailed in Figure 1, with $H = 900\,mm$ being the height of vortex generators, with a spacing of $0.6H$, and the height of the castellated barrier is $200\,mm$. The Lego blocks have a height of $60\,mm$, and they were in a staggered pattern with a spacing of $140\,mm$. The instrumentation included Dantec 55P15 single-wire probes for smooth wall configurations, and 55P51 cross-wire hotwire probes for ABL configurations, that were mounted on the linear traverse system SMC-LEFS32 of $1000\,mm$ stroke and a $0.01\,mm$ precision (along y-direction). The data acquisition was controlled using Labview. The calibration of the probes was conducted using a 54H10 calibrator and StreamWare Pro v6.00 software. Hotwire measurements were executed using a Dantec Streamline ProSystem equipped with a CTA91C10 module, interfaced with a National Instruments PXIe-4499 module housed in a PXIe-1082Q chassis for data acquisition. Data was sampled at a rate of $2^{16}\,Hz$, with sampling times initially estimated using [11], then optimised based on

DOI 10.5258/WES/P0016

several tests to be $100\,s$ per measurement point. The streamwise distance between the last row of roughness elements and the probe is $700\,mm$.

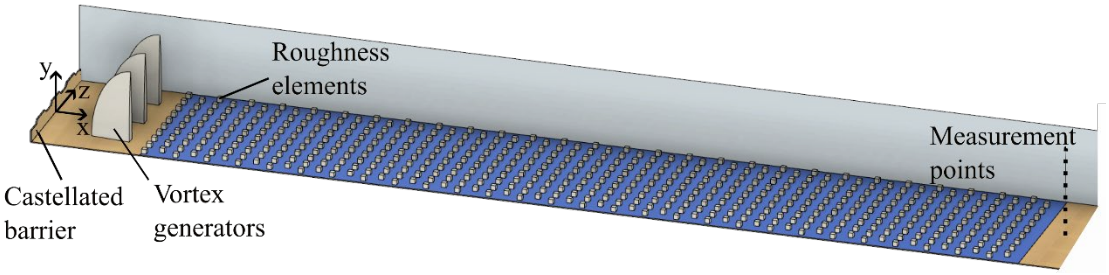

Figure 1: BLWT with arrangement of castellated barrier, vortex generators, and roughness elements .

3 RESULTS AND DISCUSSION

3.1 Empty test section

By measuring the velocity distributions along vertical lines (31 points in total) at *x=15.5 H* downstream of the entrance of the test section, at three different velocities $U_\infty = 10\,m/s$, $15\,m/s$, and $20\,m/s$, the airflow properties in the empty tunnel are evaluated. The mean flow velocities normalised by the free-stream velocity U_∞, turbulence intensities $I_u = \sqrt{u'^2}\,/U$, with u' and U the fluctuating and mean velocity at each vertical position, respectively, and the spanwise homogeneity are illustrated in Figure 2.

The boundary layer thickness δ is estimated to be around $200\,mm$, based on $U = 0.99U_\infty$ at $y = \delta$, in an empty wind tunnel, which is in good agreement with the theory ($\delta = 0.37\,x\,Re_x{}^{-1/5}$). The turbulence intensity in the outer layer is less than 0.3%. The good collapse of the mean velocity profiles and turbulence intensities at different free-stream velocities is an indication of the stability of the wind tunnel performance.

To evaluate the spanwise homogeneity of the flow, we conducted HWA measurements at $z = -400\,mm, 0\,mm, 400\,mm$. The maximum deviation in mean velocity from the centre of the test section was found to be less than 3% of the free-stream velocity, which falls within the acceptable range [12]. This confirms that the flow is spanwise homogeneous.

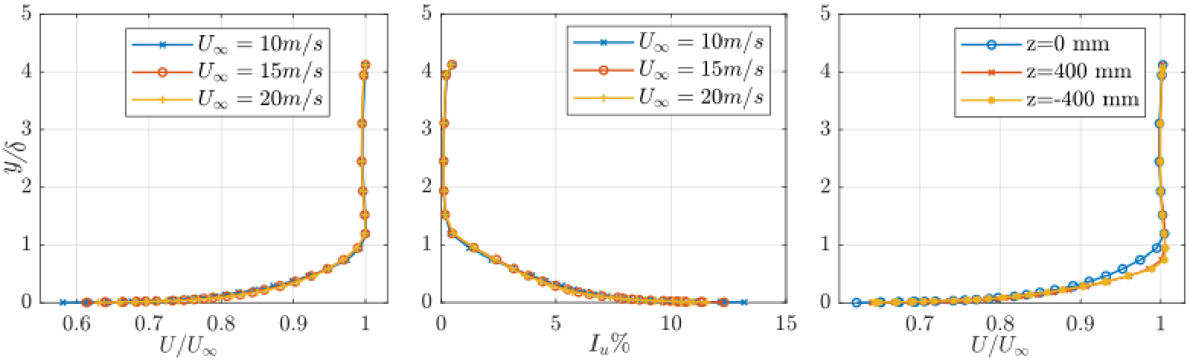

Figure 2: Profiles of (a) Normalised mean velocities at z=0, x=15.5H , (b) Turbulence intensities percentage at z=0, x=15.5H, and (c) Normalised mean velocities in three spanwise positions at x=15.5H .

3.2 Atmospheric boundary layer

Four boundary layer configurations were tested in the BLWT, to further investigate the individual effect of each component of the Counihan's method on the ABL profile parameters. The details of each test are described in Table 1.

Figure 3 shows mean velocity profiles, turbulence intensities, and integral length scales L_{ux} for the four different boundary layers tested. The integral length scales were estimated by calculating the integral of the autocorrelation ($L_{ux} = U \int R_{uu}(t)dt$, with R_{uu} being the autocorrelation) , and then were compared against those calculated using Walshe's method [9], i.e. $L_{ux} = 101\,(y/10)^{\alpha}$, with $\alpha = 0.3$ for urban flows.

DOI 10.5258/WES/P0016

Table 1: Conditions of each Boundary Layer (BL) tested.

BL	*Surface treatment*	U_∞ *(m/s)*	*Location*
BL1	*Vortex generators, roughness elements, and castellated barrier.*	*10*	*z=0 and x=15.5H*
BL2	*Roughness elements and castellated barrier.*	*10*	*z=0 and x=15.5H*
BL3	*Vortex generators and roughness elements.*	*10*	*z=0 and x=15.5H*
BL4	*Vortex generators and castellated barrier.*	*10*	*z=0 and x=15.5H*

As shown in Figures 3(a) & 3(b), and by comparing BL1 and BL4 profiles, the roughness elements effect is more prominent in the near-wall region through introducing higher velocity defect and enhanced turbulent energy in accordance with previous findings [5], and increased integral length scales. The outer region remains relatively comparable for the mean velocity. The effect of vortex generators or castellated barrier is less pronounced, by comparing BL2 & BL3 against BL1, as only a small increase in velocity deficit is observed in the absence of barriers. For the case with no castellated barrier BL3, there is a decrease in the turbulence in the outer region, compared to BL1, as confirmed in Hohman et al. [5], which shows that the castellated barrier improves the turbulence generation.

The effect of the barrier can also be seen in Figure 3(c), where the integral length scales of BL3 are out of the confidence interval of Walshe [9], which highlights its importance in ABL. There is a larger influence in generating turbulent energy with the barrier compared to the vortex generators. Further investigation on their effect on the spanwise homogeneity is necessary.

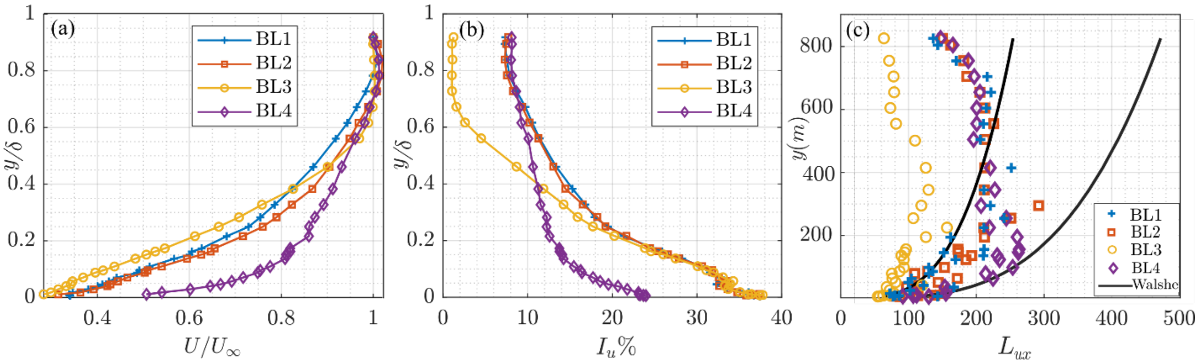

Figure 3: Profiles of the four boundary layers, (a) Normalised mean velocities, (b) Turbulence intensities , and (c) Integral length scales compared to ±30% Walshe confidence interval (y in full scale, with scale 1:800) .

To further investigate the suitability of BL1 as a representation of ABL in urban flow, Figure 4 (a) illustrates the power law, i.e. $U/U_{ref} = ((y-d)/(y_{ref}-d))^{\alpha}$, $with\ U_{ref}$, and y_{ref} being the mean velocity and height at a reference point.The power law exponent reached a value of $\alpha = 0.318$ that is in the range of urban flows according to ESDU [8], with d representing the zero-displacement height. In this study the zero-displacement height was found to be about $d = 9.32\ mm$. The turbulence intensity, shown in Figure 4 (b), is within the 30% confidence interval of the ESDU 85020 [8] up to a height of $300\ m$ in full-scale, which is widely used. The power sepctral density at $y = 255\ mm$, shown in Figure 4 (c), follows the Kolmogorov's $-5/3$ law [13], the spectra has a strong inertial subrange which is useful for structures wind loading future studies.

4 CONCLUSION

The BLWT at the University of Bristol was characterised for simulating urban ABL flows using Counihan's method. Measurements showed effective replication of ABL characteristics, with roughness elements enhancing near-wall turbulence and castellated barriers improving outer region turbulence. Validated against established datasets, the BLWT is considered suitable for urban air pollution and wind engineering research.

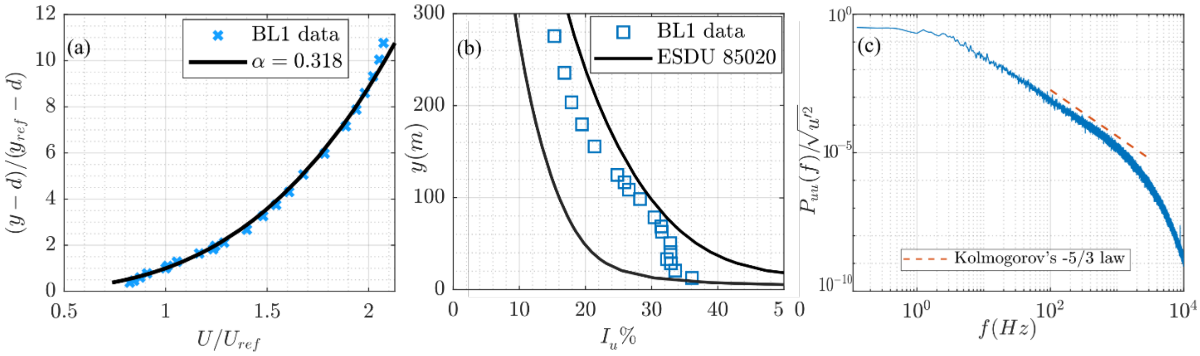

Figure 4: (a) Mean velocity profile compared to the power law with α=0.318, (b) Turbulence intensity compared to ±30% ESDU 85020 confidence interval (y in full scale, with scale 1:800), and (c) Power spectral density of BL1 at y=255 mm.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon Europe research and innovation program under the MODELAIR project grant agreement No.101072559.

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