Turbulent boundary layers over multiscale urban arrays

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Abstract

Wind tunnel experiments were conducted on multiscale building model arrays immersed in a deep turbulent boundary layer. A reference cuboid model of aspect ratio 3 was used, with two fractal iterations which systemically added smaller model length scales, totalling in three building models and in turn three roughness arrays of varying length scales. Through these fractal iterations, the frontal and plan solidities, λ_f and λ_p respectively, are kept the same to isolate the effects of the additional length scales on the flow structure and the aerodynamic parameters. Three-dimensional Laser Doppler Anemometry measurements were taken to measure the velocity fields along with a pressure tapped model in each array allowing for a direct calculation of the friction velocity, u_τ, and an estimation of the virtual origin, d, using Jackson's [1] interpretation. Preliminary results suggest that d increases with the addition of smaller length scales while the roughness length, z_o shows significant changes across iteration, despite the fixed λ_f and λ_p. The friction velocity calculated from pressure is found to be within 10% of that estimated from the Reynolds shear stress method [2]. The pressure also gives a good approximation for the virtual origin when compared to its evaluation from customary log-law fitting procedures.

1 Introduction

Understanding and modelling the flow field around tall urban environments is becoming increasingly important as more of the world's population begin to live in cities where tall buildings predominate. Despite significant improvements in morphometric methods, models remain relatively poor particularly when assessing more complex geometries with multiple length scales. There has been some shift in research towards multiscale roughness and considering different geometric parameters with a particular focus on predicting the aerodynamic parameters of a roughness surface such as drag and the roughness length, z_0 [3, 4, 5]. Even so, a clear understanding of how smaller length scales can affect atmospheric turbulence around urban arrays is needed.

To explore this, we employ a tall building model array of AR = 3. The model has two fractal iterations obtained using a Minkowski sausage-type generator which add a length scale roughly an order of magnitude lower than the previous totalling in three roughness arrays. Through these iterations λ_f and λ_p are kept constant (as well as the average height and width of the budlings). Herein, we examine how the surface characteristics change with additional length scales via an indirect method, using the Clauser chart method and Reynolds stress approximation, and a direct method, obtaining the shear stress, μ_τ and d with a pressure tapped building model.

2 Experimental facility and details

2.1 Experimental facility and boundary layer development

The experiments were carried out in the University of Surrey Environmental Flow Research Centre (EnFlo) 'Aero' wind tunnel. This tunnel's working section covers 9000 mm (length) x 1060 mm (width) x 1270 mm (height). It is a closed-circuit wind tunnel with a maximum velocity of 40 m s^{-1}. A Pitot-static probe at the tunnel inlet measures the free-stream velocity. The tunnel velocity was set to 10 m s^{-1}, resulting in a Reynolds number of 6×10^4 , based on the building height. Irwin spires, along with floor roughness elements are employed to produce a thick velocity profile similar to that of an urban boundary layer (Fig. 1). The spires have a height of 245 mm and a base width of 35 mm, with a centre spacing of 130 mm. The 2 mm tall and 8 mm wide floor roughness elements are spaced 16 mm apart in a staggered array. These give a boundary layer depth at the building location of $\delta \approx$ 221 mm and, using the approximation $u_\tau \approx \sqrt{u'w'}$ [6], a u_τ = 0.45 m s^{-1}.

DOI 10.5258/SOTON/WES/P0003

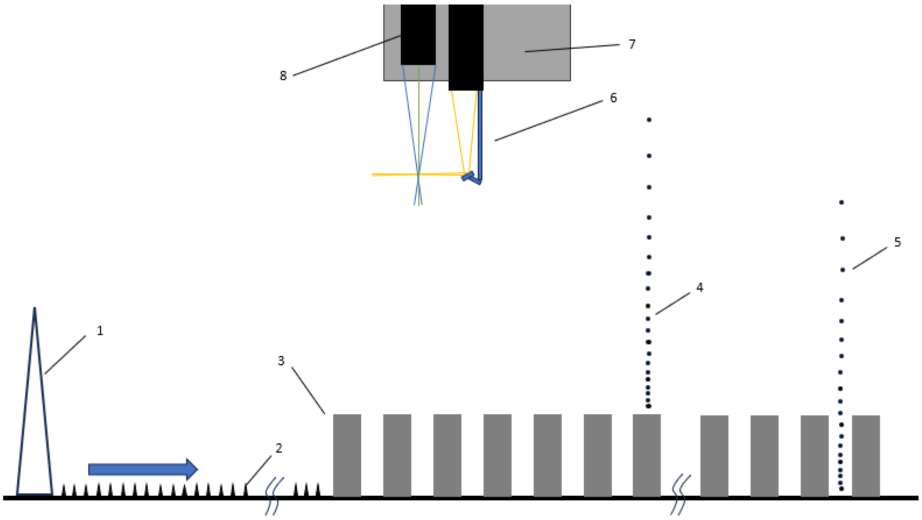

Figure 1: Tunnel side on view with LDA set up showing [1] Irwin spires, [2] floor roughness, [3] building models, [4] streamwise location of vertical profiles, [5] In canopy vertical profile, [6] mirror, [7] LDA probe shroud, [8] LDA probes. Not to scale. [7]

2.2 Rough wall models

A flat-surface tall square cylinder with AR = 3 is used as a reference case. From this form, two iterations of geometric complexity are added, each an order of magnitude more detailed or lower than the previous one. Thus, three building models are used (Fig. 2), all with a mean building height (H_B) 90 mm and width of 30 mm. Through each iteration the frontal and plan area, λ_f (0.5) and λ_p (0.2) respectively, remain the same, isolating the effects of the smaller length scales. Thus, all models have a H_B / δ of 0.41. The building model arrays started 2000 mm downwind of the spires (Fig. 1). The fractal iterations are obtained using a Minkowski Sausage-type generator [8] to decrease the minimum length scale characterising the building at each iteration (see Fig. 2). Although more iterations are possible, the length scales rapidly become smaller than the sensor's spatial measurement resolution rendering any differences undetectable. 3D printed building models, used for drag estimation, have embedded pressure ports using grey resin from i.materlise (Technologielaan 15, 3001 Leaven, Belgium) and the rest of the models were manufactured from laser cut wood.

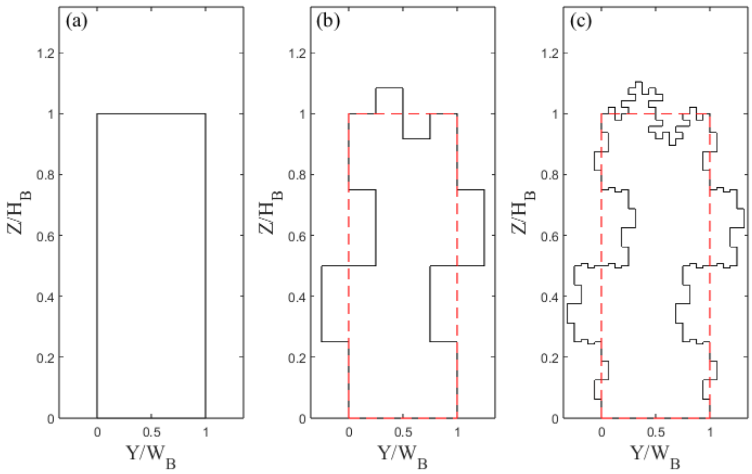

Figure 2 Building models normalised with mean height (H_B) and width (W_B), for (a) zero, (b) first, and (c) second iterations, with average width and height of models (red dashed lines). [9]

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2.3 LDA

A three-component Laser Doppler Anemometer (LDA, Fibreflow, Dantec Dynamics, Denmark) is used to simultaneously measure the mean (U, V, W) and fluctuating (u', v', w') velocity components, corresponding to the streamwise (x), spanwise (y) and wall-normal (z) directions, respectively. The laser beams are converged by a 300 mm focal length lens. An acquisition frequency of 500 Hz is set as the minimum target for the flow seeder. Each data point is recorded for 30 s to allow for sufficient statistical convergence, while constraining experiment run time. We define X= 0 mm at the start of the rough wall models, Y = 0 mm at the centre line of the tunnel and Z= 0 mm at the top of the baseboard the rough wall models are placed on. For each array, vertical profiles are taken at several streamwise locations from 0 mm to 4000 mm, from the top of the canopy to Z = 550 mm. Once fully-rough flow is reached, 12 to 18 in-canopy profiles are taken within a repeating unit (depending on model and iteration) to be spatially averaged.

3 Preliminary results

This paper presents some preliminary results for the surface characteristics of each array which come from a manuscript currently in preparation for publication [7]. In spatially-developing flow, z_0 has a dependency on the boundary layer fetch [10], and so to accurately assess the surface characteristics the flow must be fully rough and adjusted to the roughness below. This was determined to occur by a fetch of x ≈ 4000 mm for all building arrays. The surface characteristics for each rough wall are presented in Table 1. The surface characteristics are obtained with 2 separate methods, the first of which is and indirect method where μ_τ is calculated from the Reynolds shear stress and using the suggested correction factor from Cheng and Castro 2002, $u_\tau = 1.12\sqrt{u'w'}$. The Clauser chart method is then used where d and z_0 are unknown variables and are found by fitting the viscous scaled spatially averaged streamwise velocity, U^+, to a logarithmic region of the boundary layer [11] (Fig. 3). The second method calculates μ_τ and d directly from a pressure tapped building using the method outlined in [12] for the former and Jackson's (1981) interpretation of d as the point at which the mean surface drag appears to act for the latter. z_0 is then found by again fitting U^+ to the logarithmic region of the boundary layer (Fig. 3).

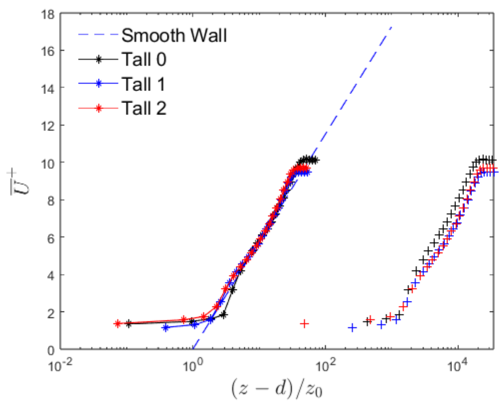

Figure 3 Mean streamwise velocity profiles of Tall arrays. The dotted blue line represents a smooth wall and the crosses the unscaled data. [7]

Table 1 shows that the results from both methods are all within 10% of each other supporting the use of the correction factor for the Reynolds shear stress and Jackson's 1981 interpretation of d as well as the validity of both methods. d shows an increase with fractal iteration which is larger from iteration 0 to 1 than 1 to 2, suggesting that the virtual origin is, at least partly, a function of the maximum height of the buildings. The models show an overall increase in μ_{τ_p}, but this is not fully reflected in μ_τ. z_0 and z_{0_p} increase with each iteration, which is in contradiction to many morphometric methods that would suggest it should remain unchanged given the fixed frontal and plan solidities. Overall, the addition of the smaller length scales had a significant effect on the roughness length and results suggest that this could be an important factor in finding a more accurate morphometric method for complex rough walls.

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Table 1 Surface characteristics for each building array iteration. "$_p$" subscript denotes results from direct pressure measurements. [7]

Building Model	d (mm)	d_p (mm)	μ_τ	μ_{τ_p}	z_0 (mm)	z_{0_p} (mm)
Tall 0	60	62	1.02	1.06	7.1	7.0
Tall 1	63	66	1.09	1.12	9.5	9.3
Tall 2	66	67	1.07	1.15	9.8	9.7

4 Conclusion

3D LDA was carried out over rough walls with varying length scales to assess how these affect the surface characteristics. This was done using an indirect method, using the Clauser chat method and the Reynolds shear stress, and a direct method, using a pressure tapped building to calculate μ_τ and d. The compared data from both methods was all within 10% showing good validity. The roughness length scale in both methods was shown to change significantly with the additional length scales highlighting the importance of multiscale information when considering morphometric methods for rough walls modelling.

This paper briefly covered some of the preliminary mean results from the flow. This experiment has also investigated similarity across each of the rough walls as well as changes seen in the fluctuating flow and the spectra which will be covered in future work.

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DOI 10.5258/SOTON/WES/P0003