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Influence of spacing between buildings on wind characteristics above rural and suburban areas

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Abstract. A wind tunnel study has been carried out to determine the influence of spacing between buildings on wind characteristics above rural and suburban type of terrain. Experiments were performed for two types of buildings, three-floor family houses and five-floor apartment buildings. The atmospheric boundary layer (ABL) models were generated by means of the Counihan method using a castellated barrier wall, vortex generators and a fetch of roughness elements. A hot wire anemometry system was applied for measurement of mean velocity and velocity fluctuations. The mean velocity profiles are in good agreement with the power law for exponent values from $\alpha = 0.15$ to $\alpha = 0.24$, which is acceptable for the representation of the rural and suburban ABL, respectively. Effects of the spacing density among buildings on wind characteristics range from the ground up to 0.6δ. As the spacing becomes smaller, the mean flow is slowed down, whilst, simultaneously, the turbulence intensity and absolute values of the Reynolds stress increase due to the increased friction between the surface and the air flow. This results in a higher ventilation efficiency as the increased retardation of horizontal flow simultaneously accompanies an intensified vertical transfer of momentum.

Keywords: wind characteristics; spacing between buildings; wind tunnel simulation.

1. Introduction

A precise atmospheric boundary layer (ABL) wind tunnel simulation is a very important issue in studying the wind loading of structures, as the correct evaluation of near-ground winds can significantly improve the aerodynamic design of structures (e.g. Crandell, *et al*. 2000).

Several investigations have been performed recently into the effects of surface roughness on the boundary layer structure for a flat terrain. Their focus was on the study of air flow over an urban landscape and inside the urban canopy at constant spacing density of building models (Rafailidis 1997, Cheng and Castro 2002, Kastner-Klein and Rotach 2004, Castro, *et al.* 2006) and with variations of building areal density (Jia, *et al.* 1998, Macdonald 2000). Wind characteristics between buildings in a suburban environment were also studied (Becker, *et al.* 2002), as well as for a rural landscape (Sterling, *et al.* 2005). The determination of the dependence of the aerodynamic

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roughness length z_0 on the structure of surface roughness was the subject of previous investigations (Lettau 1969, Counihan 1971, Petersen 1997, Xian, *et al.* 2002, Minvielle, *et al.* 2003). Most studies were carried out in wind tunnels, but there are few important full-scale investigations which have shed additional light on the problems of wind/structure interaction (e.g. Hoxey, *et al.* 2002).

The influence of buildings in an urban landscape on the oncoming wind remains confined to within three overall building heights above the ground, while the effect of spacing between buildings on the wind at the roof level is relatively weak, Rafailidis (1997). The strong three-dimensionality of the turbulent flow in the roughness sublayer was confirmed by Cheng and Castro (2002) who reported that the roughness sublayer was much thicker for randomly distributed roughness elements than for the uniform surface, the friction velocity was higher and the roughness length significantly larger. Kastner-Klein and Rotach (2004) extended their study of wind flow structure over an urban landscape to the region inside the urban canopy. Within street canyons, the mean wind velocities are almost zero or negative below the roof level, while significantly higher close to intersections or open squares. The turbulent velocities inside the canopy for the latter case are also higher than at street-canyon locations, while the turbulence kinetic energy and shear stress profiles reach maxima in the flow region immediately above the roof level. Barlow and Belcher (2002) studied the ventilation characteristics of a street canyon in an urban environment and suggested that transfer within the canyon is entirely due to turbulent processes and is less sensitive to street geometry.

The simulation of neutrally stable urban ABL by Castro, *et al.* (2006) showed that eddies in the near-wall region differ significantly from those in regular smooth-wall flows. The dependence of the shear velocity, turbulence intensity and longitudinal turbulent length scale on the roughness element spacing density were experimentally evaluated by Jia, *et al.* (1998). Becker, *et al.* (2002) studied the structure of the flow field around three-dimensional obstacles and showed the dependence of the flow structure around the obstacle on its aspect ratio, the angle of attack, the Reynolds number, and the type of boundary layer. Macdonald (2000) used an example of urban canopy layer to show that the turbulence length scale decreases with increasing building areal density. Sterling, *et al.* (2005) analysed wind velocity and pressure data in a rural environment using both conventional analysis and conditional sampling and suggested that the extreme events occur as a result of the superposition of two independent mechanisms.

In the past, several methods for estimating surface roughness length as a function of physical dimensions of objects at the surface have been developed. Lettau (1969) and Counihan (1971) have provided analytical tools whereby the surface roughness length can be estimated directly from dimensions and spacing of structures. These two methods were recently discussed by Petersen (1997) and Minvielle, *et al.* (2003). Xian, *et al.* (2002) concluded that the aerodynamic roughness length z_0 values increase with increasing size and area density of roughness elements. The shape and height of roughness elements were found to affect roughness length more than other factors. The roughness length increases with the decreasing ratio of element horizontal surface area to the height of roughness elements. But at a higher free stream velocity, the height is more important than the shape in affecting the roughness length. Roughness elements' geometry required for experimental wind simulations can preliminarily be determined as suggested in Gartshore and De Cross (1977), and the final arrangements are usually obtained through trial and error.

This paper therefore describes a series of wind tunnel tests that have been carried out to determine wind characteristics above suburban and rural areas dependent on building areal density. Six ABL simulations were generated in the boundary layer wind tunnel by the means of the Counihan method, whereas the roughness elements correspond to family houses and apartment buildings. Results of velocity measurements are presented in form of mean velocity, turbulence intensity and Reynolds shear stress. The implications of the results are discussed in terms of air ventilation efficiency between the buildings, but they can also be valuable for studies on wind loading of structures.

2. Experimental details

The experimental program consisted of a detailed wind-tunnel study of mean velocity and velocity fluctuations above a suburban and rural type of terrain under neutral stratification conditions. Experiments were carried out in a 1.80 m high × 2.70 m wide × 21 m long test section of the boundary layer wind tunnel ('Rudolf-Frimberger-Windkanal') at the Technische Universität München (TUM), which is schematically shown in Fig. 1.

The wind tunnel can operate in an open or a closed circuit mode with suction configuration. The flow uniformity is achieved by means of a honeycomb, four sets of screens and the Börger nozzle with the contraction ratio of 2.12:1. As a result, the turbulence intensity of less than 0.5% at the entrance of the test section can be obtained. The test section ceiling is adjustable in height, which allows the zero pressure gradient to be achieved along the wind tunnel test section. Models of a structural object can be mounted at the turntable, whose centre is positioned 11.3 m downwind from the nozzle. The flow is produced by an axial flow fan driven by a 210 kW electric motor. The air speed through the test section can be set from 1 to 30 m/s. The simulation technique, originally introduced by Counihan (1969a, 1969b, 1973), was based on the use of quarter-elliptic, constant-wedge-angle spires and a castellated barrier wall, followed by a fetch of roughness elements. Tests were performed following standard wind-tunnel modelling procedures (Pernpeintner, *et al.* 1995 and Plate 1982) and assuming the adiabatic conditions, as suggested by Clarke (1982) and Rotach (1993),

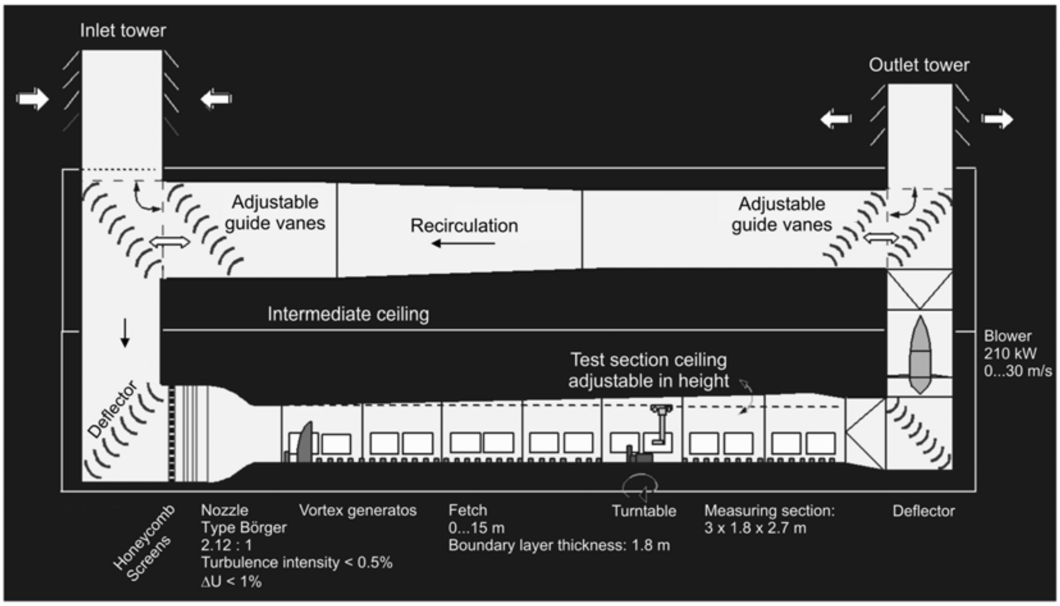

Fig. 1 Boundary layer wind tunnel at the Institute of Aerodynamics, TUM

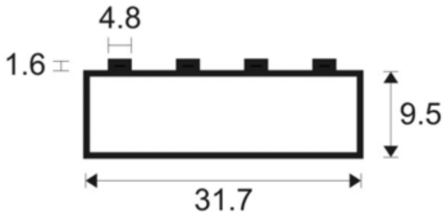

Fig. 2 LEGO brick (quotes in mm)

since in most urban sites the mechanical production of turbulence dominates over thermal effects.

LEGO plates (plan area 380 mm × 380 mm), having 1.6 mm high protrusions, were fitted to the floor of the wind tunnel, and were used as a basic surface roughness. 16 mm wide LEGO bricks, schematically shown in Fig. 2, were adjusted for LEGO plates in a staggered pattern. The side with dimensions 31.7 mm × 9.5 mm was in all configurations normal to the wind.

It should be noted that the effects of small round elements on the top of LEGO bricks on wind characteristics were not investigated here. However, it would be useful to check this issue in some future study. Configurations of LEGO bricks were varied in height and arranged in several different distribution densities (test section area covered with surface roughness elements/total test section area). Roughness elements' spacing and height in this study were preliminarily determined as suggested by Gartshore and De Croos (1977). The final arrangements were obtained through trial and error.

Gartshore and De Croos (1977) extended the study of Dvorak (1969) who related the roughness elements' height k and the spacing λ_e to the wall shear stress τ_0 and displacement height d, using the form proposed by Clauser (1954), as follows

$$\frac{\bar{u}_\delta}{u_\tau} = \frac{1}{\kappa}\ln\left(\frac{\bar{u}_\delta d}{u_\tau k}\right) + A - C, \tag{1}$$

where

$$\frac{u_\tau}{\bar{u}_\delta} = \left(\frac{\tau_0}{\rho \bar{u}_\delta^2}\right)^{1/2}, \tag{2}$$

with A = constant = 4.8, κ = constant = 0.41, and C is a constant depending on λ_e and κ as follows:

$$C = -5.95\left(0.48\ln\frac{\lambda_e}{k} - 1\right). \tag{3}$$

Assuming that the rectangular bodies imply a drag coefficient ratio of approximately one, Gartshore and De Cross (1977) suggested the form

$$\frac{\lambda_e}{k} \approx \frac{A_P}{A_F}, \tag{4}$$

which allows the shear stress correlation of Dvorak (1969) to be used for a variety of 2D and 3D roughness elements.

The logarithmic law suggested by Thuillier and Lappe (1964),

$$\bar{u} = \frac{u_\tau}{\kappa}\ln\left(\frac{z-d}{z_0}\right), \tag{5}$$

the power law proposed by Hellman (1916),

$$\frac{\bar{u}_z}{\bar{u}_\delta} = \left(\frac{z-d}{\delta-d}\right)^\alpha \tag{6}$$

and an equation proposed in Counihan (1975),

$$\alpha = 0.096\log z_0 + 0.016(\log z_0)^2 + 0.24 \tag{7}$$

were applied together with Eqs. (1) to (4) to estimate a preliminary relationship between the power law exponent and the roughness elements' geometry. Details of the final arrangements, which were obtained through trial and error, are shown in Table 1.

The simulations were made using a 127 mm high castellated barrier wall and five 1 m high elliptical vortex generators. A design of applied castellated barrier wall and vortex generator is shown in Fig. 3.

One typical setup of simulation hardware in the wind tunnel test section during the course of this study is shown in Fig. 4.

As expected when using the 1 m high "Counihan" spires, the boundary layer reached the gradient height at 1 m, which is comparable to previous studies (e.g. Balendra, *et al.* 2002). According to Counihan's review (1975), the full scale boundary layer thickness could be around 500 m. Ratio of the model boundary layer thickness (1 m) to the full scale boundary layer thickness (500 m) can be used to calculate a preliminary length scale factor (1:500). This preliminary length scale factor was

Table 1 Details of density and height of surface roughness elements

Configuration	Density of surface roughness elements, %	Height of surface roughness elements, mm
BL1	0.23	28.5
BL2	0.46	28.5
BL3	3.59	28.5
BL4	0.46	19.0
BL5	0.64	19.0
BL6	1.39	19.0

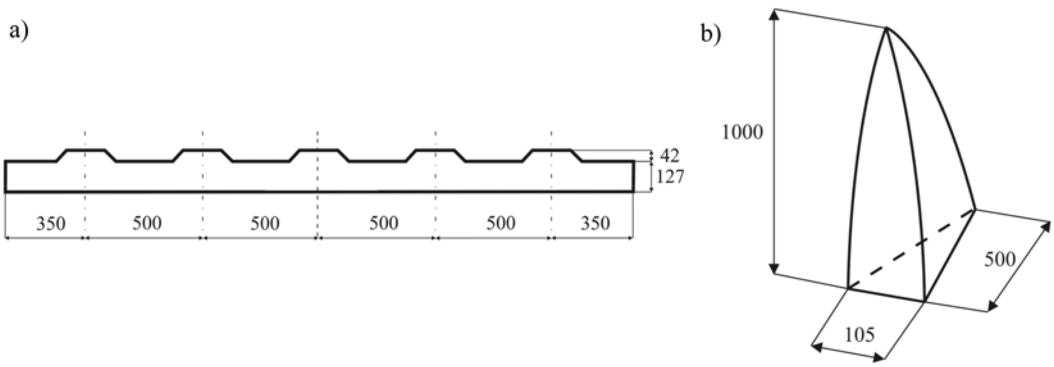

Fig. 3 Details of: (a) castellated barrier wall, (b) vortex generators' design (quotes in mm)

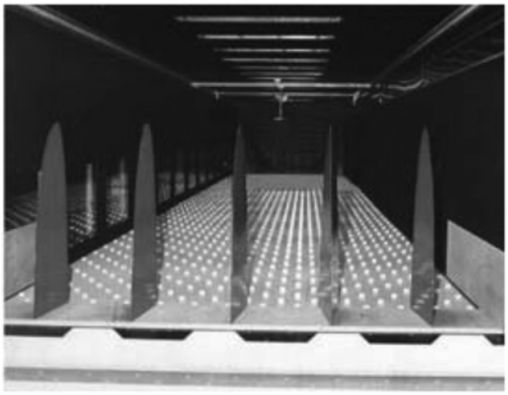

Fig. 4 Typical setup of simulation hardware in the wind tunnel test section

validated by comparing the obtained z_0 values and I_u profiles with the ESDU data (1985) using this scale factor. Similar procedure to determine the length scale factor was previously applied by Balendra, *et al.* (2002). Surface roughness elements, which were 19.0 mm and 28.5 mm high, represent three-floor family houses (scaled-up height = 9.5 m, i.e. approximately 0.02δ) and five-floor apartment buildings (scaled-up height = 14.25 m, i.e. approximately 0.03δ) at the scale of 1:500. Increasing the size of building models, i.e., roughness elements, would result in larger Reynolds numbers which would be closer to full scale values. However, blockage and wall effects could in that case deteriorate the obtained results. Nevertheless, it would be advantageous to simulate the wind characteristics above suburban and rural terrains at larger Reynolds numbers in the future. In this study, the blockage of the wind tunnel by the LEGO bricks representing buildings was in all cases far below 5%, which is an acceptable limit in wind-tunnel modelling, as suggested by Hucho (2002).

Velocities were measured using triple hot-wire probes DANTEC 55P91 and a ten-channel AALAB AN 1003 anemometer system. The velocity signals were sampled at 1.25 kHz using a 12-bit digitizer Data Translation DT2821 at total record length of 150 s. Complete calibrations of the hot-wire probes were obtained in the calibration tunnel by exposing them to uniform flows with 20 different velocities and 252 different yaw angles. Velocity measurements were carried out at a distance $x = 8.7$ m from the trailing edge of the vortex generators, where the flow is developed and uniform, as described in detail by Kozmar, *et al.* (2005), i.e. further downwind from this position, differences in mean velocity $\bar{u}$ are not larger than 2% and turbulence intensity I_u differs up to 1%.

3. Results

Experimental results were fitted to the logarithmic law to determine the roughness length z_0 and the friction velocity u_τ, and to the power law to estimate the power law exponent α and displacement height d. Table 2 presents the values obtained in this study, and Table 3 shows the characteristic values observed in full scale reported in ESDU (1985).

The obtained z_0 and d values shown in Table 2 were scaled up to full scale at the preliminary scale factor 1:500. In configurations BL1, BL2, BL4, and BL5 a reasonable agreement with the terrains (c) and (d) shown in Table 3 was obtained, while simulations BL3, BL6 agree better with terrains (a) and (b) from Table 3. Also, displacement heights in configurations BL3 and BL6 were

Table 2 Obtained values for parameters of generated boundary layers

Type of terrain	α	z_{0p}, m	d_p, m	u_τ, m/s
BL1	0.16	0.017	1.9	0.629
BL2	0.17	0.061	2.5	0.718
BL3	0.24	0.910	5.0	0.769
BL4	0.15	0.018	2.5	0.627
BL5	0.16	0.051	1.5	0.721
BL6	0.22	0.225	5.0	0.625

Table 3 Characteristics of rural and suburban terrain, ESDU (1985)

	Type of terrain	z_{0p}, m	d_p, m
(a)	Small towns Suburbs of large towns and cities Wooded country (many trees)	0.3	5 to 10
(b)	Outskirts of small towns Villages Countryside with many hedges, some trees and some buildings	0.1	0 to 2
(c)	Open level country with few trees and hedges and isolated buildings; typical farmland	0.03	0
(d)	Fairly level grass plains with isolated trees	0.01	0

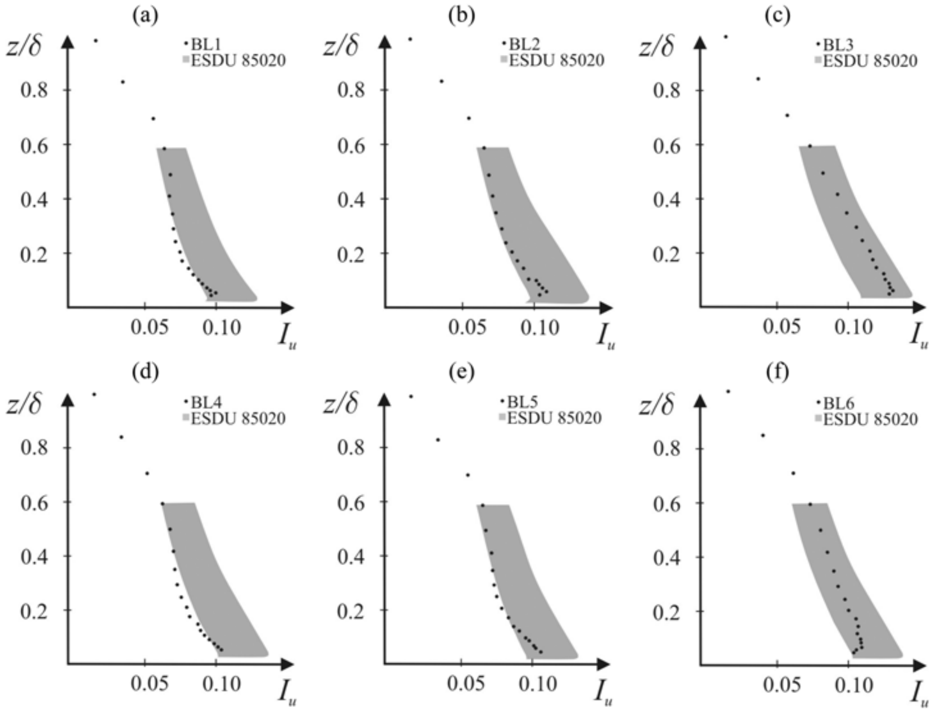

Fig. 5 Comparison of obtained turbulence intensity I_u profiles with the ESDU (1985) data

larger than in configurations BL1, BL2, BL4, and BL5. The validity of the preliminary length scale 1:500 can be additionally checked by comparing the obtained turbulence intensity profiles with the

ESDU (1985) data using this length scale. The results of this comparison are shown in Fig. 5.

The experimental results agree well with the ESDU (1985) data when the preliminary length scale factor 1:500 was used, with exception of few points in the middle part of the profile in BL1, BL4, and BL5 configurations. The agreement of z_0 and I_u values obtained in this study with the ESDU (1985) data using the preliminary length scale of 1:500 justifies the choice of this scale and indicates that this scale can be accepted for the presented wind simulations. Furthermore, the boundary layer thickness for this length scale factor would be 500 m, which is a reasonable agreement with data reported in Counihan (1975).

The effect of spacing between buildings on the mean velocity component $\bar{u}$ above roofs is shown in Figs. 6 and 7.

The obtained mean velocities in x-direction are compared with the power law which is commonly used for the representation of mean velocities in the outer layer of the ABL (e.g. Stathopoulos and Surry 1983, Sockel 1984). The mean velocities profiles are in good agreement with the power laws from $\alpha = 0.15$ to $\alpha = 0.24$, which can be accepted as a good approximation of the rural and suburban ABL, respectively. The velocity gradients near the top of the vortex generators are very low, i.e. in all six configurations differences between the two highest measuring points ($z/\delta = 0.84$ and 1) were less than 1.5%. Since it is possible to define the boundary layer thickness as that

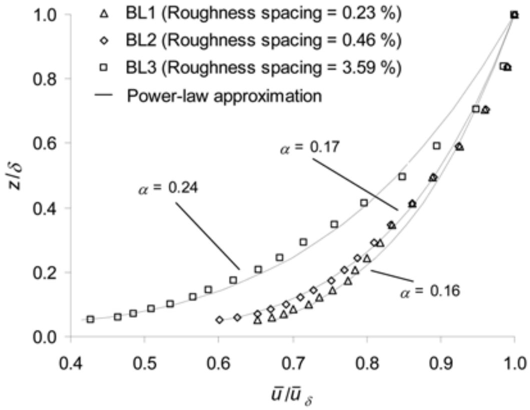

Fig. 6 Mean velocity profiles in x-direction dependent on the spacing between apartment buildings

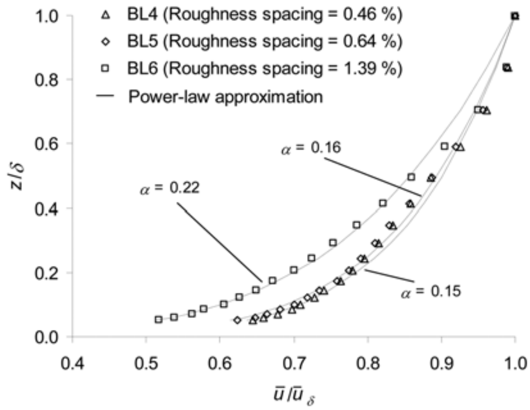

Fig. 7 Mean velocity profiles in x-direction dependent on the spacing between family houses

distance from the surface where the mean velocities in x-direction differs by 1% from the freestream velocity (Schlichting 2000), it seems reasonable to accept for the purposes of this study that $\delta \approx 1$ m. These results also correspond with Balendra, *et al.* (2002) who reported that the thickness of generated boundary layers matches with the spires' height.

In the medium part of the boundary layer ($0.2 < z/\delta < 0.5$) there is a slight reduction in experimental results compared with the power law, which is characteristic for the Counihan method. As the spacing among buildings becomes smaller, the mean flow near the surface adjusts itself to local surface conditions and the retardation of the flow can be clearly seen due to the increased friction between the surface and the air flow, which is comparable to the previous results (e.g. Krogstad and Antonia 1999, Coceal and Belcher 2005). These results extend the study of Theurer (1993), who concluded that the wind shows little sensitivity to the frontal density of a group of flat-roofed buildings. Plate (1995) suggested that the effect of obstacles on the wind disappears above 3–5 combined building heights above the ground, while in an urban environment the boundary layer above approximately 2–3 total building heights from the ground recovers to that developing above a flat plate (Rafailidis 1997). In this study, the retardation effects of buildings extend up to 0.6δ, as presented in Figs. 6 and 7, for both family houses and apartment buildings, whereas the difference of obtained results near the surface is greater for apartment buildings due to a wider range of applied spacing densities. Above this level, differences between the non-dimensional velocities are small. In order to improve the ventilation among buildings it is of interest that the retardation of a horizontal velocity component is accompanied by a simultaneous vertical transfer of momentum, which can be described in form of turbulence intensity and Reynolds stress.

Figs. 8, 9 and 10 show the turbulence intensity profiles in x-, y-, z-directions normalized with local velocities, respectively, dependent on the spacing between buildings for both family houses and apartment buildings.

The presented results compare well with the ESDU (1985) field measurements, which are reported elsewhere (Kozmar 2000 and 2005). The effects of the building spacing density on turbulence intensities can be clearly seen, which extends the findings of Rafailidis (1997) for an urban type of terrain, who stated that turbulent winds are quite independent of the building areal density and are predominantly driven by a different roof shape. When the spacing density among

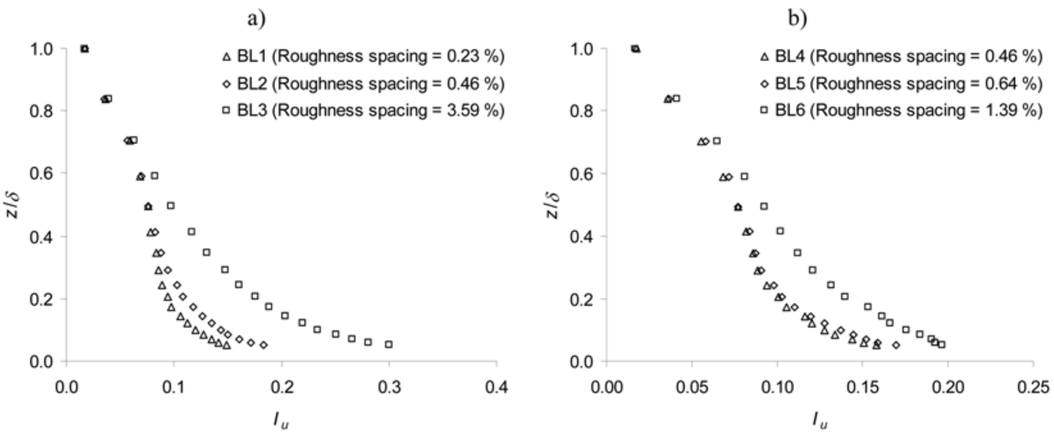

Fig. 8 Turbulence intensity profiles I_u dependent on the spacing between buildings; a) apartment buildings, b) family houses

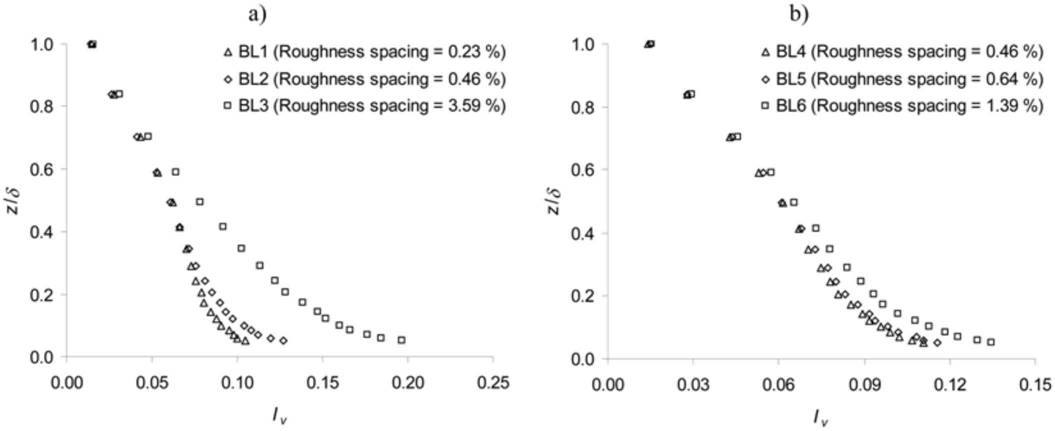

Fig. 9 Turbulence intensity profiles I_v dependent on the spacing between buildings; a) apartment buildings, b) family houses

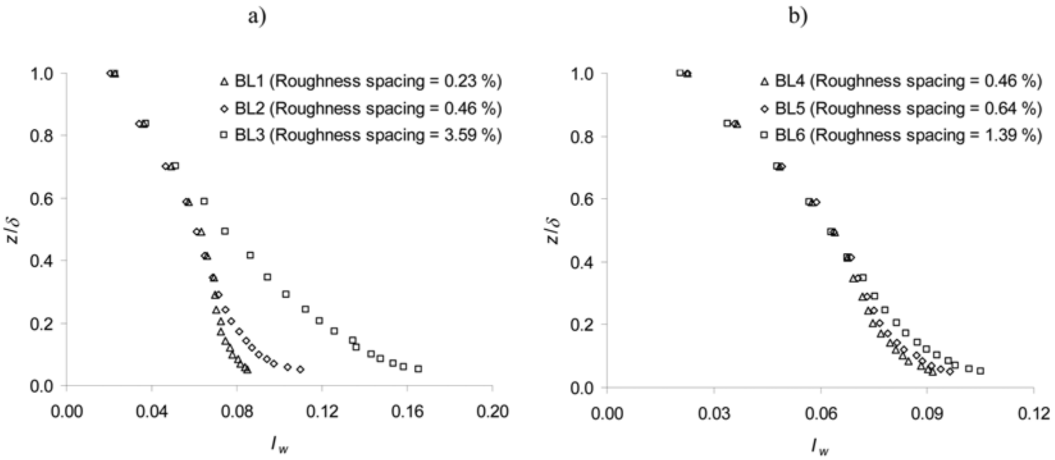

Fig. 10 Turbulence intensity profiles I_w dependent on the spacing between buildings; a) apartment buildings, b) family houses

buildings becomes higher, the turbulence intensity increases as a result of intensified friction between the surface and the air, which corresponds well with the results of Tieleman (1990). The influence of the surface roughness is greater in the lower part of the boundary layer ($z/\delta \leq 0.6$). At $z/\delta \geq 0.6$ differences between obtained values become smaller, i.e., the influence of surface roughness on the boundary layer structure is not significant. The difference of turbulence intensities is greater for apartment buildings than for family houses due to a greater range of simulated spacing densities, i.e., for apartment buildings from 0.23% to 3.59%, for family houses from 0.46% to 1.39%.

The Reynolds stress profiles are presented in Fig. 11, where $\bar{u}_{\mathrm{ref}}$ is the mean velocity in the x-direction in the reference height $z_{\mathrm{ref}} = 0.05$ m.

As one approaches the ground from above, the Reynolds stress increases significantly. This suggests an intensified vertical transfer of momentum. The obtained results, except BL6, correspond well with the results of Gong, *et al.* (1996), which reach a maximum about 10 mm away from the surface of the obstacles. The near surface profile of Reynolds stress for BL6 will be investigated in

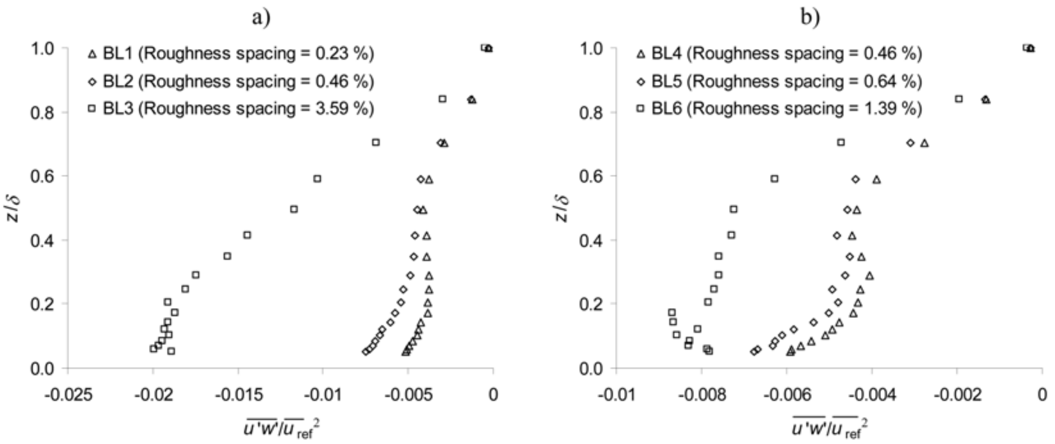

Fig. 11 Reynolds stress profiles dependent on the spacing between buildings; a) apartment buildings, b) family houses

greater detail in the future. Perry and Li (1990) and Flack, *et al.* (2005) suggest that the major local effect of roughness is simply to increase the shear at the surface, which is consistent with the results presented in Fig. 11, i.e., the absolute value of the Reynolds stress increases when the air is streaming over an area with larger spacing density of buildings. Differences in obtained Reynolds stresses are larger for a complex of apartment buildings than for family houses, due to a wider range of simulated spacing densities.

4. Conclusions

Wind characteristics above suburban and rural areas were experimentally studied in the boundary layer wind tunnel for various spacing densities between buildings. The study was performed for two types of buildings, i.e., three-floor family houses and five-floor apartment buildings. The rural and suburban ABL models were generated by means of the Counihan method using a castellated barrier wall, vortex generators and a fetch of roughness elements.

The mean velocity profiles are in good agreement with the power law for exponent values from $\alpha = 0.15$ to $\alpha = 0.24$, which is a good approximation for the simulation of the rural and suburban ABL, respectively. In the medium part of the boundary layer ($0.2 < z/\delta < 0.5$) there is a slight reduction in experimental results compared with the power law, which is characteristic for the Counihan method. Effects of the spacing density among buildings range from the ground up to 0.6δ. As the spacing becomes smaller, the mean flow is slowed down, whilst, simultaneously, the turbulence intensity and the absolute value of the Reynolds stress increase due to the increased friction between the surface and the air flow. This results in a higher ventilation efficiency as the increased retardation of horizontal flow simultaneously accompanies an intensified vertical transfer of momentum.

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Nomenclature

A	: constant
A_F	: frontal area of one roughness element
A_P	: plan area associated with one roughness element
C	: constant
d	: displacement height
d_p	: displacement height in the full scale
I_u, I_v, I_w	: turbulence intensity in the x-, y-, z-directions
k	: roughness element height
u, v, w	: absolute velocity in the x-, y-, z-directions
u', v', w'	: fluctuating velocity component in the x-, y-, z-directions
$\bar{u}$	: mean velocity component in the x-direction
$\bar{u}_{ref}$	: mean velocity component in the x-direction in the reference height
$\bar{u}_z$	: mean velocity component in the x-direction in the height z
$\bar{u}_\delta$	: freestream velocity
u_τ	: shear velocity
x	: distance in the direction of the flow
y	: spanwise distance from test section centerplane
z	: vertical distance from wind tunnel floor
z_0	: aerodynamic roughness length
z_{0p}	: aerodynamic roughness length in the full scale
α	: power law exponent
δ	: boundary layer thickness
κ	: von Kármán constant
λ_e	: effective streamwise spacing of roughness elements
ρ	: air density
τ_0	: wall shear stress

References

Balendra, T., Shah, D.A., Tey, K.L., Kong, S.K. (2002), "Evaluation of flow characteristics in the NUS-HDB Wind Tunnel", *J. Wind. Eng. Ind. Aerod.*, **90**, 675-688.

Barlow, J.F. and Belcher, S.E. (2002), "A wind tunnel model for quantifying fluxes in the urban boundary layer", *Bound-Lay Meteorol.*, **104**, 131-150.

Becker, S., Lienhart, H. and Durst, F. (2002), "Flow around three-dimensional obstacles in boundary layers", *J. Wind. Eng. Ind. Aerod.*, **90**, 265-279.

Castro, I.P., Cheng, H. and Reynolds, R. (2006), "Turbulence over urban-type roughness: deductions from wind-tunnel measurements", *Bound-Lay Meteorol.*, **118**, 109-131.

Cheng, H. and Castro, I.P. (2002), "Near wall flow over urban-like roughness", *Bound-Lay Meteorol.*, **104**, 229-259.

Clarke, C.F. (1982), "An experimental study of turbulence in an urban environment", US E.P.A. Technical Report, EPA 600 S3-82-062.

Clauser, F.H. (1954), "Turbulent boundary layers in adverse pressure gradients", *J. Aeronaut. Sci.*, **21**, 91-108.

Coceal, O. and Belcher, S.E. (2005), "Mean winds through an inhomogeneous urban canopy", *Bound-Lay Meteorol.*, **115**, 47-68.

Counihan, J. (1969a), "A method of simulating a neutral atmospheric boundary layer in a wind tunnel", *AGARD Conference Proceedings*, **43**.

Counihan, J. (1969b), "An improved method of simulating an atmospheric boundary layer in a wind tunnel", *Atmos. Environ.*, **3**, 197-214.

Counihan, J. (1971), "Wind tunnel determination of the roughness length as a function of the fetch and the roughness density of three-dimensional roughness elements", *Atmos. Environ.*, **5**, 637-642.

Counihan, J. (1973), "Simulation of an adiabatic urban boundary layer in a wind tunnel", *Atmos. Environ.*, **7**, 673-689.

Counihan, J. (1975), "Adiabatic atmospheric boundary layers: a review and analysis of data from the period 1880-1972", *Atmos. Environ.*, **9**, 871-905.

Crandell, J.H., Farkas, W., Lyons, J.M. and Freeborne, W. (2000), "Near-ground wind and its characterization for engineering application", *Wind Struct.*, *An Int. J.*, **3**, 143-158.

Dvorak, F.A. (1969), "Calculation of turbulent boundary layers on rough surfaces in pressure gradient", *AIAA J.*, **7**, 1752-1759.

ESDU (1985), "Characteristics of wind speed in the lower layers of the atmosphere near the ground. Part II: single point data for strong winds (neutral atmosphere)", Engineering Sciences Data Unit 85020.

Flack, K.A., Schultz, M.P. and Shapiro, T.A. (2005), "Experimental support for Townsend's Reynolds number similarity hypothesis on rough walls", *Phys. Fluids.*, **17**, 035102.

Gartshore, I.S. and De Croos, K.A. (1977), "Roughness element geometry required for wind tunnel simulations of the atmospheric wind", *J. Fluids Eng.*, **9**, 480-485.

Gong, W., Taylor, P.A. and Dörnbrack, A. (1996), "Turbulent boundary-layer flow over fixed aerodynamically rough two-dimensional sinusoidal waves", *J. Fluid Mech.*, **312**, 1-37.

Hellman, G. (1916), "Über die Bewegung der Luft in den untersten Schichten der Atmosphäre", *Meteorol. Z.*, **34**, 273.

Hoxey, R.P., Richards, P.J. and Short, J.L. (2002), "A 6m cube in an atmospheric boundary layer flow. Part I. Full-scale and wind-tunnel results", *Wind Struct.*, *An Int. J.*, **5**, 165-176.

Hucho, W-H. (2002), "Aerodynamik der stumpfen Körper", Vieweg & Sohn, Wiesbaden.

Jia, Y., Sill, B.L. and Reinhold, T.A. (1998), "Effects of surface roughness element spacing on boundary-layer velocity profile parameters", *J. Wind. Eng. Ind. Aerod.*, **73**, 215-230.

Kastner-Klein, P. and Rotach, M. (2004), "Mean flow and turbulence characteristics in an urban roughness sublayer", *Bound-Lay Meteorol.*, **111**, 55-84.

Kozmar, H. (2000), "Modelling the atmospheric boundary layer in the wind tunnel (in Croatian)", Master Thesis, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb.

Kozmar, H. (2005), "Scale effects on the structure of the atmospheric boundary layer model (in Croatian)", Ph.D. Thesis, University of Zagreb.

Kozmar, H., Džijan, I. and Šavar, M. (2005), "Uniformity of atmospheric boundary layer model in the wind tunnel (in Croatian)", *Strojarstvo*, **47**, 157-167.

Krogstad, P-A. and Antonia, R.A. (1999), "Surface roughness effects in turbulent boundary layers", *Exp. Fluids.*, **27**, 450-460.

Lettau, H. (1969), "Note on aerodynamic roughness-parameter estimation on the basis of roughness-element description", *J. Appl. Meteorol.*, **8**, 828-832.

Macdonald, R.W. (2000), "Modelling the mean velocity profile in the urban canopy layer", *Bound-Lay Meteorol.*, **97**, 25-45.

Minvielle, F., Marticorena, B., Gillette, D.A., Lawson, R.E., Thompson, R. and Bergametti, G. (2003), "Relationship between the aerodynamic roughness length and the roughness density in cases of low roughness density", *Environ. Fluid. Mech.*, **3**, 249-267.

Pernpeintner, A., Schnabel, P., Schuler, A. and Theurer, W. (1995), "Appendix 17: Qualifizierungsversuch", WTG-Merkblatt über Windkanalversuche in der Gebäudeaerodynamik, in E. J. Plate (ed.), WTG-Berichte Nr.

3, Windtechnologische Gesellschaft WTG e.V.

Perry, A.E. and Li, J.D. (1990), "Experimental support for the attached eddy hypothesis in zero pressure-gradient turbulent boundary layers", *J. Fluid. Mech.*, **218**, 405-438.

Petersen, R.L. (1997), "A wind tunnel evaluation of methods for estimating surface roughness length at industrial facilities", *Atmos. Environ.*, **31**, 45-57.

Plate, E.J. (1982), "Wind tunnel modelling of wind effects in engineering", *Engineering Meteorology* (Elsevier, Amsterdam).

Plate, E.J. (1995), "Urban Climates and Urban Climate Modelling: An Introduction", in J. E. Cermak, A. D. Davenport, E. J. Plate, and D. X. Viegas (eds.), Wind Climate in Cities, Kluwer Academic Publishers, Dordrecht, pp. 23-39.

Rafailidis, S. (1997), "Influence of building areal density and roof shape on the wind characteristics above a town", *Bound-Lay Meteorol.*, **85**, 255-271.

Rotach, M.W. (1993), "Turbulence close to a rough urban surface, Part II: Variances and gradients", *Bound-Lay Meteorol.*, **66**, 75-92.

Schlichting, H., Gersten, K. (2000), *Boundary Layer Theory*, Springer, 8th edition.

Sockel, H. (1984), "Aerodynamics of buildings (in German)", Vieweg & Sohn.

Stathopoulos, T. and Surry, D. (1983), "Scale effects in wind tunnel testing of low buildings", *J. Wind. Eng. Ind. Aerod.*, **13**, 313-326.

Sterling, M., Baker, C.J., Quinn, A.D. and Hoxey, R.P. (2005), "Pressure and velocity fluctuations in the atmospheric boundary layer", *Wind Struct.*, *An Int. J.*, **8**, 13-34.

Theurer, W. (1993), "Ausbreitung bodennaher Emissionen in komplexen Bebauungen", Dissertation, Institut für Hydrologie und Wasserwirtschaft, Universität Karlsruhe, Germany.

Thuillier, R.H. and Lappe, U.O. (1964), "Wind and temperature profile characteristics from observations on a 1400 ft tower", *J. Appl. Meteorol.*, **3**, 299-306.

Tieleman, H.W. (1990), "Wind tunnel simulation of the turbulence in the surface layer", *J. Wind. Eng. Ind. Aerod.*, **36**, 1309-1318.

Xian, X., Tao, W., Qingwei, S. and Weimin, Z. (2002), "Field and wind-tunnel studies of aerodynamic roughness length", *Bound-Lay Meteorol.*, **104**, 151-163.

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