



WIND TUNNEL MODELLING OF VENTILATION IN AN URBAN SQUARE

by

András TOMOR
/IDTP8W/

Submitted to the
Department of Fluid Mechanics of the
Budapest University of Technology and Economics
in partial fulfillment of the requirements for the degree of
Master of Science in Mechanical Engineering Modelling

on the 12th of December, 2014

MSc Thesis

Final Project /BMEGEÁTMWD2/

Supervisor:
Márton BALCZÓ, assistant research fellow

Evaluation Team Member, advisor:
Márton BALCZÓ, assistant research fellow

Department of Fluid Mechanics
Faculty of Mechanical Engineering
Budapest University of Technology and Economics

DECLARATION

Full Name (as in ID):	András TOMOR
Neptun Code:	IDTP8W
University:	Budapest University of Technology and Economics
Faculty:	Faculty of Mechanical Engineering
Department:	Department of Fluid Mechanics
Major/Minor:	MSc in Mechanical Engineering Modelling Fluid Mechanics major / Solid Mechanics minor
Project Report Title:	Wind Tunnel Modelling of Ventilation in an Urban Square
Academic year of submission:	2014 / 2015 - I.

I, the undersigned, hereby declare that the Project Report submitted for assessment and defence, exclusively contains the results of my own work assisted by my supervisor. Further to it, it is also stated that all other results taken from the technical literature or other sources are clearly identified and referred to according to copyright (footnotes/references are chapter and verse, and placed appropriately).

I accept that the scientific results presented in my Project Report can be utilised by the Department of the supervisor for further research or teaching purposes.

Budapest, 12th of December, 2014

(Signature)

FOR YOUR INFORMATION

The submitted Project Report in written and in electronic format can be found in the Library of the Department of Fluid Mechanics at the Budapest University of Technology and Economics. Address: H-1111 Budapest, Bertalan L. 4-6. „Ae” building of the BME.

ABSTRACT

József Nádor Square in downtown Budapest is located next to the extremely busy József Attila Street and surrounded by buildings from all sides; the square has unfavorable ventilation and it is heavily polluted with concentration levels well above limit values.

A small-scale model of the quarter surrounding József Nádor Square in downtown Budapest was prepared and with this 1:350 scale model flow field measurements were carried out in the Large Horizontal Wind Tunnel (LHWT) of the Department of Fluid Mechanics at the Budapest University of Technology and Economics (BME) using Laser-Doppler Velocimetry (LDV).

Two main wind directions were investigated, parallel to the square axis (northern wind direction) and 90 degree to the square axis (western wind direction). In each of them, flow velocities were measured along vertical profiles and horizontal planes at $0.25h$ and $0.5h$ height where h is the mean building height (28 m in full scale). In the case of the northern wind direction one more horizontal plane was investigated at $1h$ height. The flow field results show the evidence of low air exchange between the square and the neighboring areas and also between the square and the atmospheric boundary layer. The air exchange is comparable to that in street canyons. Mean flow structures responsible for the complex airflow in the square could be identified. The results of the measurements could be used as reference data set for validation of urban wind field models.

An in-depth analysis of flow field results was performed and the measurement data were compared to – previously obtained – CFD simulation results. The CFD results agree fairly with the experimental results; however, certain flow structures are not properly resolved by the model.

KIVONAT

A Budapest belvárosában található József nádor tér a rendkívül forgalmas József Attila utca mellett helyezkedik el, és a teret minden oldalról magas épületek veszik körül. A kedvezőtlen átszellőzés miatt a téren igen jelentős a légszennyezettség, a határértékeket nagymértékben meghaladó szennyezőanyag koncentrációk is előfordulnak.

Munkám során elkészítettem a Budapest V. kerületében található József nádor tér és a körülötte elhelyezkedő városrész 1:350 léptékű modelljét, és ezen a modellen szélmező méréseket végeztem az Áramlástan Tanszék nagy vízszintes szélcsatornájában Lézer Doppler Anemometriát alkalmazva.

A környéken leggyakrabban előforduló északi és nyugati szélirányok mellett végeztem méréseket. A vizsgált városrész különböző pontjaiban időátlagolt sebességprofilokat és szórásprofilokat határoztam meg, valamint a tér felett a $0,25h$, $0,5h$ és $1h$ magasságban lévő síkokon az időátlagolt sebesség és a turbulens kinetikus energia eloszlását vizsgáltam; h az átlagos épületmagasság, melynek értéke 28 m valós léptékben. A szélmező mérések eredményeiből jól látható, hogy a tér és a környező városrész között valamint a tér és az atmoszférikus határréteg között csak kismértékű légsere jön létre. Ez a jelenség megfigyelhető az utcakanyonok esetében is. A téren kialakuló, összetett légáramlásért felelős áramlási struktúrák jól azonosíthatóak. A mérési eredmények alapjául szolgálhatnak CFD modellek validálásának.

Az eredmények alapos és részletes elemzése után a mérési eredményeket – korábbi munkák eredményeképpen rendelkezésre álló – CFD szimulációk eredményeivel vetettem össze. A különböző módszerekkel kapott eredmények között jó egyezés figyelhető meg, bizonyos áramlási struktúrákat azonban nem sikerült megfelelően felbontani a CFD modellel.

CONTENTS

ABSTRACT	II
KIVONAT	III
CONTENTS.....	IV
NOMENCLATURE.....	V
1 INTRODUCTION	1
1.1 Motivation.....	1
1.2 Former studies focused on the investigation of József Nádor Square	2
2 ATMOSPHERIC BOUNDARY LAYER GENERATION AND MODEL CONSTRUCTION	3
2.1 Modelling an urban-type atmospheric boundary layer.....	3
2.2 Model construction.....	6
3 FLOW FIELD MEASUREMENTS ON THE MODEL OF JÓZSEF NÁDOR SQUARE	8
3.1 Measurements with northern wind direction.....	11
3.1.1 Vertical profile measurements with northern wind direction	11
3.1.2 Investigation of horizontal planes with northern wind direction.....	18
3.1.3 Analysis using wind roses	22
3.2 Measurements with western wind direction	25
3.2.1 Vertical profile measurements with western wind direction	25
3.2.2 Investigation of horizontal planes with western wind direction	33
4 COMPARISON OF MEASUREMENT DATA TO CFD SIMULATION RESULTS	37
4.1 CFD setup	38
4.2 Analysis of vertical profiles	39
4.3 Flow field in horizontal planes.....	42
4.4 Three-dimensionality of the flow	47
4.5 Square vs. street canyons	49
5 CONCLUSIONS	51
BIBLIOGRAPHY	53

NOMENCLATURE

d_0	displacement height [m]
f	frequency [1/s]
h	mean building height [m]
I_u	turbulence intensity in the x -direction [-]
I_v	turbulence intensity in the y -direction [-]
I_w	turbulence intensity in the z -direction [-]
K_d	dimensionless turbulent kinetic energy [-]
$L_{u,x}$	longitudinal integral length scale of turbulence [m]
R_{uu}	autocorrelation coefficient of the velocity fluctuation in the x -direction [-]
S_{uu}	power spectral density of longitudinal velocity fluctuations [m^2/s]
t	time [s]
T	total record length [s]
TKE	turbulent kinetic energy [m^2/s^2]
u	absolute velocity in the x -direction [m/s]
u_d	dimensionless mean velocity in the x -direction [-]
u_{href}	reference velocity at h [m/s]
u_p	u component of the velocity of a tracer particle [m/s]
u_{ref}	mean velocity at the reference height [m/s]
$\bar{u}$	mean velocity into the main flow direction [m/s]
v	absolute velocity in the y -direction [m/s]
v_d	dimensionless mean velocity in the y -direction [-]
v_{md}	dimensionless mean velocity magnitude [-]
v_p	v component of the velocity of a tracer particle [m/s]
v_{pd}	magnitude of the dimensionless velocity of a tracer particle [-]
$\bar{v}$	mean velocity in the y -direction [m/s]
$\underline{v}$	flow velocity vector [m/s]
$\underline{v}_{hor d}$	dimensionless velocity vector in horizontal (xy) plane [-]
w	absolute velocity in the z -direction [m/s]
w_d	dimensionless mean velocity in the z -direction [-]
$\bar{w}$	mean velocity in the z -direction [m/s]
z	height, z coordinate [m], [mm]
z_{ref}	reference height [m], [mm]

GREEK INDICES

α	exponent [-]
Δv_{md}	difference of dimensionless velocity magnitude between two cases [-], [%]
ρ	fluid density [kg/m^3]
σ_u	standard deviation of the u velocity component [m/s]
σ_{ud}	dimensionless standard deviation in the x -direction [-]
σ_v	standard deviation of the v velocity component [m/s]
σ_{vd}	dimensionless standard deviation in the y -direction [-]
σ_w	standard deviation of the w velocity component [m/s]
σ_{wd}	dimensionless standard deviation in the z -direction [-]

1 INTRODUCTION

1.1 Motivation

The air quality of our environment is significantly deteriorated by traffic pollution. Dispersion of air pollutants is determined by various flow phenomena. These flow phenomena take place in the atmospheric boundary layer, so the characteristics of the atmospheric boundary layer play an important role in air pollutant dispersion. The parameters of the boundary layer are measurably affected by the terrain conditions, vegetation and buildings. In urban areas, surrounding buildings have the most significant effect on flow characteristics.

Concentration of contaminants increases dramatically in the vicinity of the emission of pollutants, so busy roads and nearby squares could be the most contaminated areas. The relevant studies in connection with microscale air pollution research focused mainly on the investigation of urban street canyons, street intersections and regular arrangements of building blocks. Air pollution and flow phenomena at urban squares were much less dealt with. Only a few papers [1, 2] paid attention to flow and dispersion specifically at urban squares. The study of wind and concentration fields at squares is also included in larger scale investigations of whole districts [3]. Investigation of flow and dispersion phenomena at urban squares is worth dealing with because this is an untapped research area.

József Nádor Square in downtown Budapest is located next to the extremely busy József Attila Street; moreover, the square is surrounded by buildings from all sides. In case the square has favorable ventilation, the pollutants do not enter the square or the entered pollutants disperse quickly and the air quality complies with the requirements. However, measurements at the nearby Erzsébet Square have proven very high pollutant concentrations, indicating similar situation at József Nádor Square.

In this thesis, the ventilation around József Nádor Square was investigated with wind tunnel measurements. A small-scale (1:350) model was prepared and Laser-Doppler Velocimetry (LDV) was used for the measurements. The model was placed in an urban-type boundary layer, which was modelled in the wind tunnel and checked by vertical profile measurements. The fiber-optic LDV probe accessed to the flow from below through a pane of glass. With the applied method the flow was absolutely not disturbed by the

probe. A two-component LDV system was applied, so with the mentioned arrangement the u and v velocity components could be determined.

An in-depth analysis of flow field results was performed and the measurement data were compared to CFD simulation results. The CFD simulation data were available from a former BSc thesis [4] and a recent research [5]; however, these data had to be thoroughly evaluated again in order to prepare the results for journal publication.

1.2 Former studies focused on the investigation of József Nádor Square

During a recent research [5] of the Department of Fluid Mechanics at the BME, CFD simulations were performed to analyze pollutant dispersion and flow phenomena around József Nádor Square. Every building, vegetation and significant pollutant source was modelled in the vicinity of the square within an 1100x900 m domain.

A very simplified small-scale model of József Nádor Square was prepared and with this 1:650 scale model flow field measurements were carried out in the NPL Wind Tunnel of the Department of Fluid Mechanics within the confines of an MSc thesis [6]. Tracer dispersion concentration measurements were also carried out on this wind tunnel model [7]. Moreover, a CFD model with the same geometry was constructed and a validation procedure was attempted [7].

Mean flow structures in the square could be identified with the mentioned very simplified wind tunnel model [6]; however, due to the small test section of the NPL Wind Tunnel and the 1:650 scale model the accuracy of the measurements was limited and there was not any possibility to validate the previously prepared [5] CFD model.

In order to obtain more accurate and reasonable results, a much more complex wind tunnel model of József Nádor Square was constructed and with this 1:350 scale model wind tunnel measurements were carried out in the LHWT.

2 ATMOSPHERIC BOUNDARY LAYER GENERATION AND MODEL CONSTRUCTION

2.1 Modelling an urban-type atmospheric boundary layer

Experiments were carried out in a 3.8 m long open test section with a diameter of 2.6 m of the LHWT at the BME. This Göttingen-type wind tunnel is operable in a closed circuit mode with a suction configuration. In order to model an urban-type boundary layer, vortex generators, crossbars and roughness elements were placed into the preparatory section of the wind tunnel in an appropriate arrangement. The mentioned arrangement can be seen in Fig. 2.1.

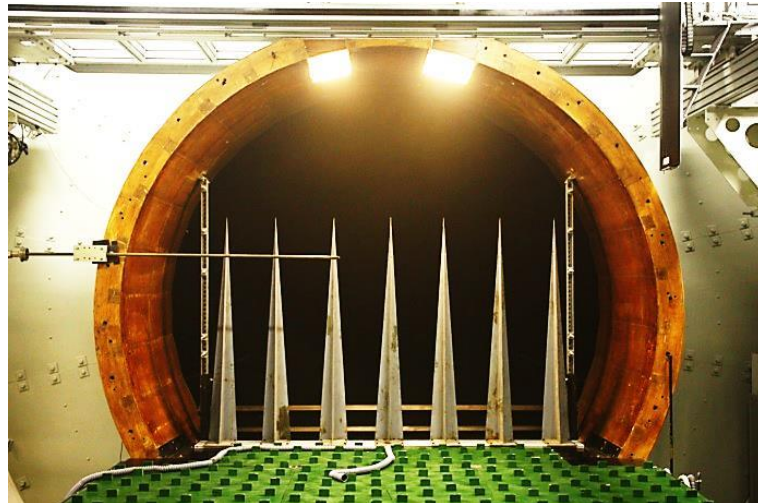


Fig. 2.1: Arrangement of the vortex generators, crossbars and roughness elements in the preparatory section of the wind tunnel

The inlet profile of the modelled atmospheric boundary layer was checked by two-component LDV measurements. At the incoming boundary layer measurement about 200000 velocity samples (bursts) were collected at each of the measurement points during the selected 5 min averaging time. The boundary layer parameters discussed herein are given in the following equations:

Mean velocity in the x - and y -direction

$$\bar{u}(z) = \frac{1}{T} \int_0^T u(z,t) dt, \quad \bar{v}(z) = \frac{1}{T} \int_0^T v(z,t) dt \quad (2.1)$$

with $u(z,t)$ - time dependent absolute velocity in the x -direction, $v(z,t)$ - time dependent absolute velocity in the y -direction and T - total record length.

Turbulence intensity in the x - and y -direction

$$I_u(z) = \frac{\sigma_u(z)}{\bar{u}(z)}, \quad I_v(z) = \frac{\sigma_v(z)}{\bar{v}(z)} \quad (2.2)$$

with $\sigma_u(z)$ - standard deviation of the u velocity component and $\sigma_v(z)$ - standard deviation of the v velocity component.

Longitudinal integral length scale of turbulence

$$L_{u,x} = \int_0^\infty R_{uu}(\Delta x) d\Delta x \quad (2.3)$$

with R_{uu} - autocorrelation coefficient of the velocity fluctuation in the x -direction and Δx - the shifting.

Power spectral density of longitudinal velocity fluctuations $S_{uu}(f)$, where

$$\sigma_u^2 = \int_0^\infty S_{uu}(f) df. \quad (2.4)$$

Fig. 2.2 shows mean velocity $\bar{u}$ into the main flow direction, as well as turbulence intensities I_u and I_v determined for the longitudinal and lateral flow directions, respectively.

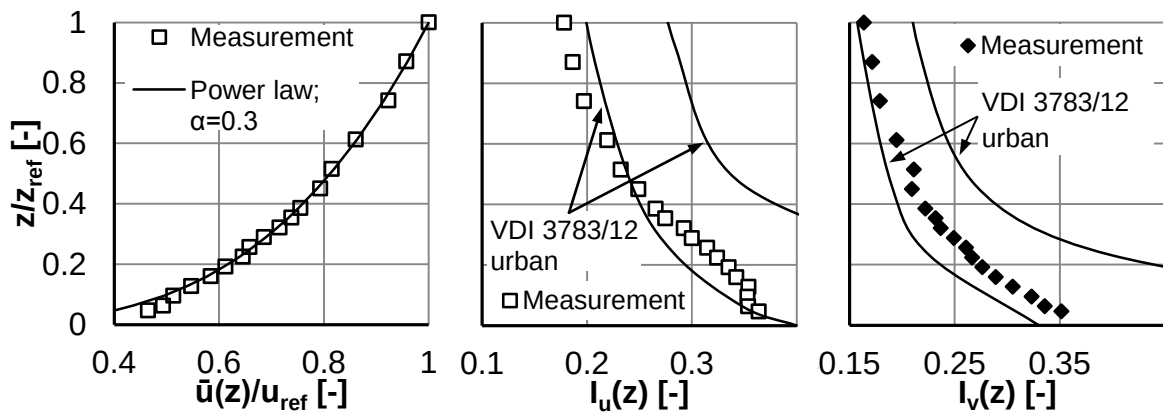


Fig. 2.2: Inlet profiles of dimensionless mean velocity and turbulence intensity

Mean velocity u was compared with the power law [8] in the form

$$\frac{u(z)}{u_{ref}} = \left(\frac{z - d_0}{z_{ref} - d_0} \right)^\alpha \quad (2.5)$$

where α is the exponent, z is the height, z_{ref} is the reference height, u_{ref} is the mean velocity at the reference height and d_0 is the displacement height. In order to obtain dimensionless mean velocities, local velocities, $u(z)$, were divided by the reference velocity $u_{ref} = 4.60$ m/s, which was measured at the reference height $z_{ref} = 309.50$ mm. Displacement height was considered to be zero in all cases.

The above parameters of an urban boundary layer are described in several guidelines and standards. According to ESDU 72026 [9], the power law exponent $\alpha = 0.3$ can be accepted for the representation of the urban atmospheric boundary layer; thus the measured mean velocity profile was adequate. Turbulence intensity I_u profile shows some differences compared to VDI 3783/12 [10] data; however, turbulence intensity profiles could also be accepted.

The integral length scale profile $L_{u,x}$ is shown in Fig. 2.3. The $L_{u,x}$ values were compared with ESDU 85020 [11] data. The ESDU data were scaled down using the scale factor 1:350.

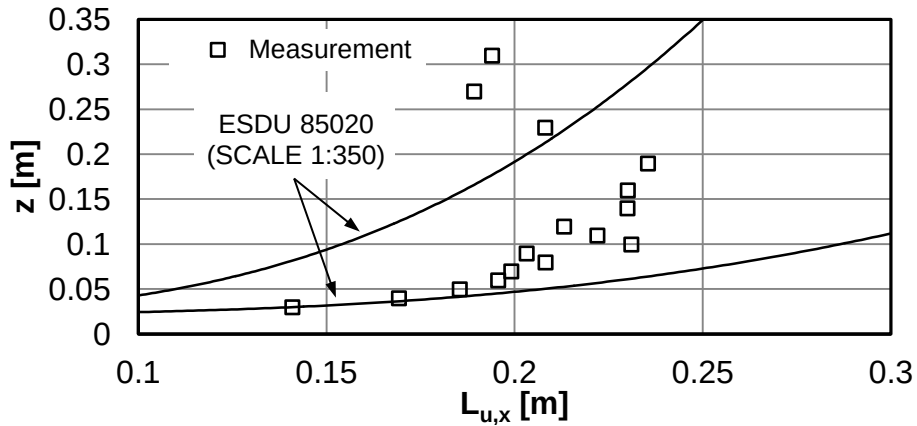


Fig. 2.3: Longitudinal integral length scale of turbulence $L_{u,x}$ compared with ESDU 85020 [10] data

The integral length scale profile $L_{u,x}$ shows some differences compared to ESDU 85020 [11] data at the three highest measurement points, below this level the agreement is perfect. The longitudinal integral length scale profile could also be accepted.

Fig. 2.4 shows the power spectral density of longitudinal velocity fluctuations at $z = 189.5$ mm, $z = 89.5$ mm and $z = 29.5$ mm, respectively. Experimental results were compared with the von Karman spectrum [10] over the whole frequency range.

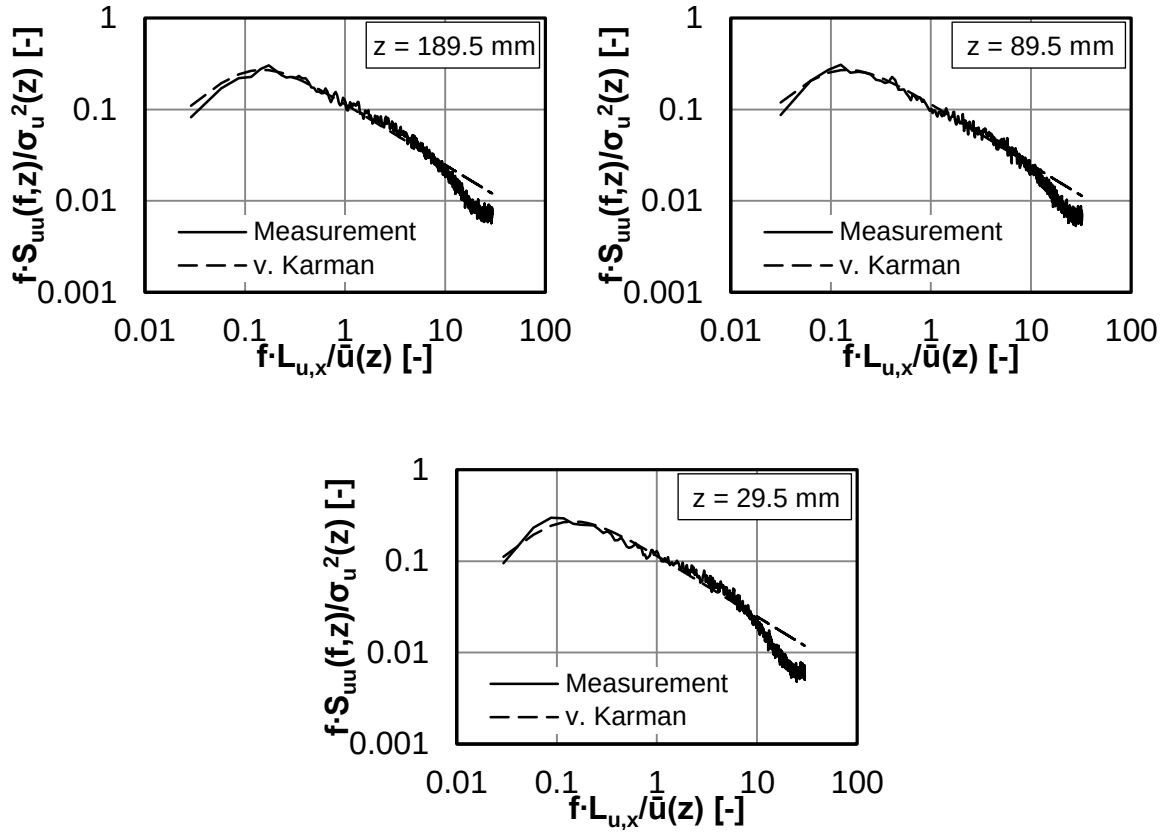


Fig. 2.4: Power spectral density of longitudinal velocity fluctuations at $z = 189.5$ mm, $z = 89.5$ mm and $z = 29.5$ mm

Measured spectra show a good agreement with the von Karman spectrum (except for the highest frequencies affected by Heisenberg's viscous dissipation subrange) at all three heights.

Based on the profile measurements, the generated atmospheric boundary layer was considered to be applicable for the investigation of flow and dispersion around an urban square.

2.2 Model construction

A 1:350 scale model of the quarter around József Nádor Square in downtown Budapest was prepared of rigid foam and the whole model was placed on a wooden circular plate with a diameter of 2 m. There was an 800x800 mm opening in the middle of the plate

covered by a pane of glass. This pane provided optical access to the flow from beneath the model. The buildings were modelled as blocks with flat rooftops and classified heights in 1.5 m steps. Although roof shape has a certain influence on the flow, for the cause of a simple CFD model / mesh generation, this effect is neglected similarly to the effect of urban vegetation. József Nádor Square and the surrounding quarter can be seen in Fig. 2.5.

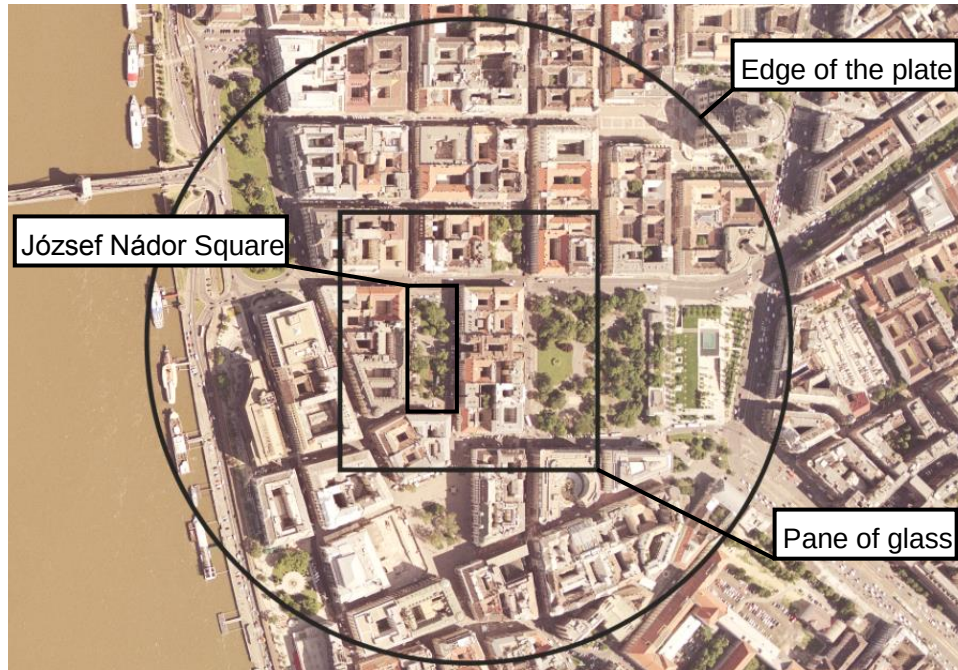


Fig. 2.5: József Nádor Square and the surrounding quarter; the edge of the wooden plate and the pane of glass are also marked

The complete model can be seen in Fig. 2.6.

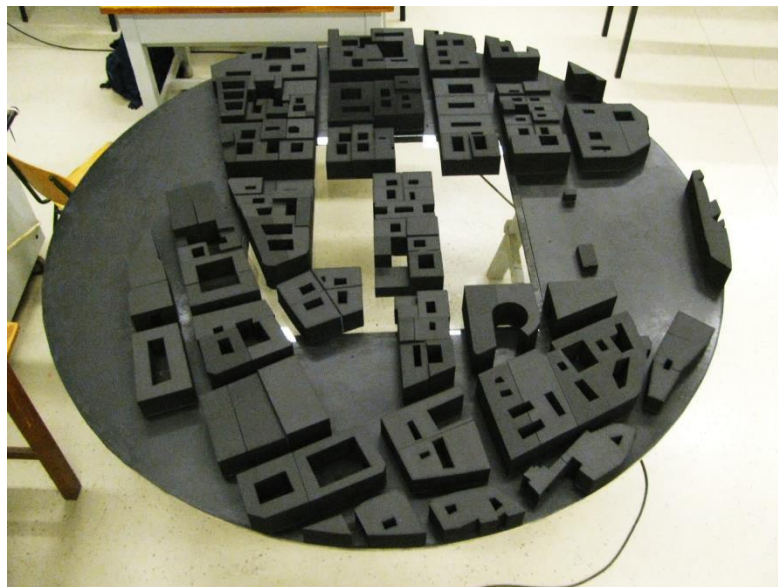


Fig. 2.6: The complete model

3 FLOW FIELD MEASUREMENTS ON THE MODEL OF JÓZSEF NÁDOR SQUARE

Fig 3.1 shows the model arranged in the test section of the wind tunnel.



Fig. 3.1: The model arranged in the test section of the wind tunnel

The final measurement layout can be seen in Fig. 3.2.

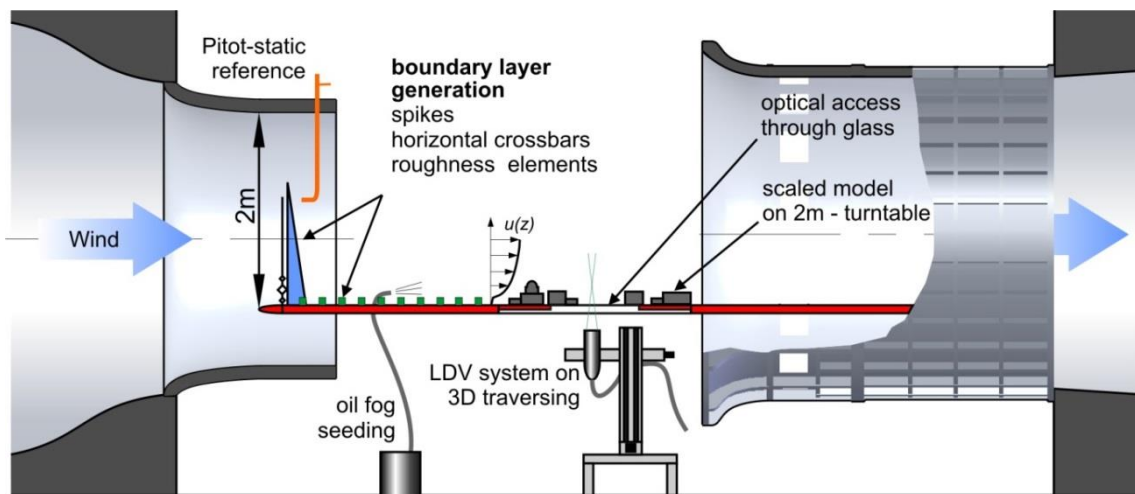


Fig. 3.2: The measurement layout including vortex generators, crossbars and roughness elements in the preparatory section of the wind tunnel, the model arranged in the test section of the LHWT and the LDV probe below the test section

During the flow field measurements in the model of József Nádor Square, two wind directions were investigated: approximately northern wind direction, 351.7 degree to North, and 261.7 degree to North, approximately western wind direction. Wind statistics were available from neighbouring meteorological stations, which are 2.5 - 10 km distance (Fig. 3.3). Their average wind rose shows North and West-Northwest as the prevailing wind directions. It must be noted, however, that the Buda mountains, less than 1 km in westerly direction from the area of investigation, must have a local influence both on the station 2.5 km south and the actual site as well, thus a simple averaging can only give an approximation of the local wind statistics.

The selected two wind directions means that wind blows at ‘northern’ wind exactly along the long axis of the square, at which its length to height ratio l/h is 5.3, and at ‘western wind’ exactly along the short axis of the square with l/h equalling 2.1. Thus, two distinctly different flow fields are expected.

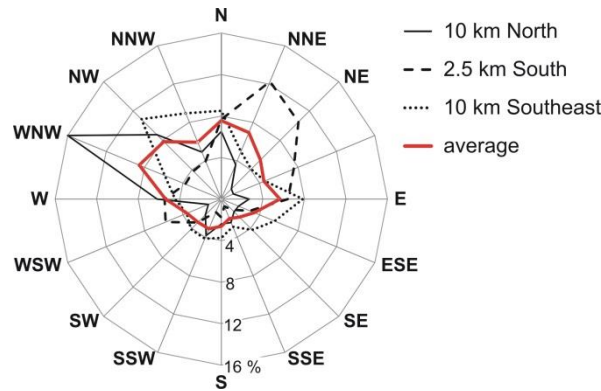


Fig. 3.3: Annual wind statistics at meteorological stations close to József Nádor Square. Wind speeds less than 1 m/s are excluded.

Flow velocities were measured along 23 vertical profiles and three horizontal planes (see in Fig. 3.4). During the flow field measurement of the square about 5000 samples were collected at each of the measurement points during the selected 50 s averaging time. The representativeness of measured velocity averages and standard deviations was checked during a few measurements of longer duration. Local mean velocities, $\bar{u}$ and $\bar{v}$, were normalized to the reference velocity $u_{href} = 3.02$ m/s, which was measured at the mean building height $h = 80$ mm during the boundary layer measurements; h is the mean building height in model scale (28 m in full scale).

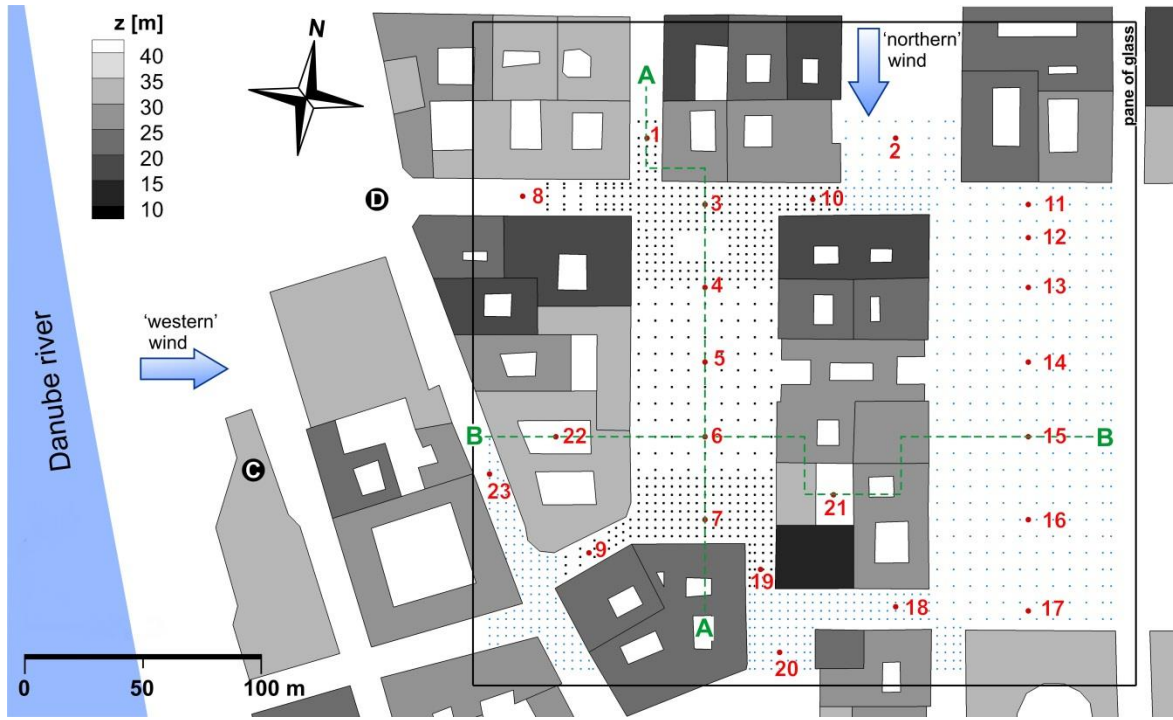


Fig. 3.4: Wind directions and measurement locations on the wind tunnel model. Buildings are coloured by their full scale height. Red circles: vertical profile (VP) measurements; black dots: horizontal plane measurements at $0.25 h$, $0.5 h$ and h height; blue dots: additional horizontal plane measurements at $0.5 h$ height.

The parameters discussed herein can be calculated with the following formulas:

Dimensionless mean velocity u_d and v_d

$$u_d = \frac{\bar{u}}{u_{href}}, \quad v_d = \frac{\bar{v}}{u_{href}}. \quad (3.1)$$

Dimensionless mean velocity magnitude

$$v_{md} = \sqrt{u_d^2 + v_d^2}. \quad (3.2)$$

Dimensionless velocity fluctuations σ_{ud} and σ_{vd}

$$\sigma_{ud} = \frac{\sigma_u}{u_{href}}, \quad \sigma_{vd} = \frac{\sigma_v}{u_{href}}. \quad (3.3)$$

Turbulent kinetic energy

$$TKE = \frac{1}{2} \cdot (\sigma_u^2 + \sigma_v^2). \quad (3.4)$$

Dimensionless turbulent kinetic energy

$$K_d = \frac{1}{2} \cdot (\sigma_{ud}^2 + \sigma_{vd}^2). \quad (3.5)$$

It must be noted that the calculated turbulent kinetic energy, dimensionless turbulent kinetic energy and dimensionless velocity magnitude values differs from the real values, because the vertical velocity component w and its standard deviation σ_w could not be measured using the applied arrangement. Thus, K_d is the contribution of horizontal velocity components to turbulent kinetic energy.

3.1 Measurements with northern wind direction

3.1.1 Vertical profile measurements with northern wind direction

In the first part of the flow field measurement series which was carried out on the model of József Nádor Square, northern wind direction was prescribed. Dimensionless mean velocities and velocity standard deviations were determined along 23 vertical profiles (VP1 to VP23). The results of the profile measurements with northern wind direction can be seen in Fig. 3.5, Fig. 3.6, Fig. 3.7, Fig. 3.8 and Fig. 3.9, respectively.

Analyzing the dimensionless mean velocity profiles above József Nádor Square (VP3 to VP7 in Fig. 3.5) a separation bubble evolved after the northern block can be clearly observed. The boundary layer after the middle of the square – at about $2-3h$ distance – penetrates the square and hits the southern block. The value of the v velocity component can differ from zero below the height of the buildings; this indicates remarkable cross-flow.

The VP1, VP8, VP9 and VP10 profiles are located in street canyons. The street in which profile VP1 can be found is parallel to the ambient wind direction; however, significant velocities were not measured here and neither in the case of VP2. In the streets perpendicular to the ambient wind direction the flow is parallel to the street axis. Although expected in VP8 and VP10, a clear street canyon vortex could not be observed.

Analyzing the standard deviation profiles in Fig. 3.6 it can be said that the standard deviation of the u velocity component is usually larger than the standard deviation of the v velocity component. The standard deviations of the velocity components decrease below the mean building height almost in all cases. In the case of the profiles VP3, VP8, VP9 and VP10 the standard deviation of the u velocity component decreases by leaps and bounds at the mean building height – decreases below the standard deviation of the v velocity component. This phenomenon absolutely agrees with our expectations, because these profiles are located in street canyons or in the wake of a building.

Seeing the dimensionless mean velocity profiles above Erzsébet Square (VP11 to VP17 in Fig. 3.7) it can be said that the appeared phenomenon is similar to the phenomenon occurred at József Nádor Square. A separation bubble evolved after the northern block can be clearly observed and the boundary layer at about $2-3h$ distance penetrates the square and hits the southern block.

The street in which profile VP19 can be found is parallel to the ambient wind direction; however, the value of the u velocity component is less than zero below the mean building height, so in the south-eastern connecting street of József Nádor Square backflow is detected. In the street in which VP18 is located the flow is parallel to the street axis and a clear street canyon vortex could not be observed. At the location where profile VP20 can be found flow velocities are relatively low; not only below the mean building height but also above it.

Analyzing the standard deviation profiles in Fig. 3.8 it can be stated that the standard deviation of the u velocity component is usually larger than the standard deviation of the v velocity component – similarly to the profiles in Fig 3.6. Almost all of the σ_u profiles have a maximum around the mean building height. In the case of the profiles VP11 and VP18 the σ_u values decrease significantly around the mean building height; VP11 is located in the wake of the northern building block and VP18 is located in a street canyon perpendicular to the ambient wind direction. The largest σ_u value was measured in VP19 at $1.5h$.

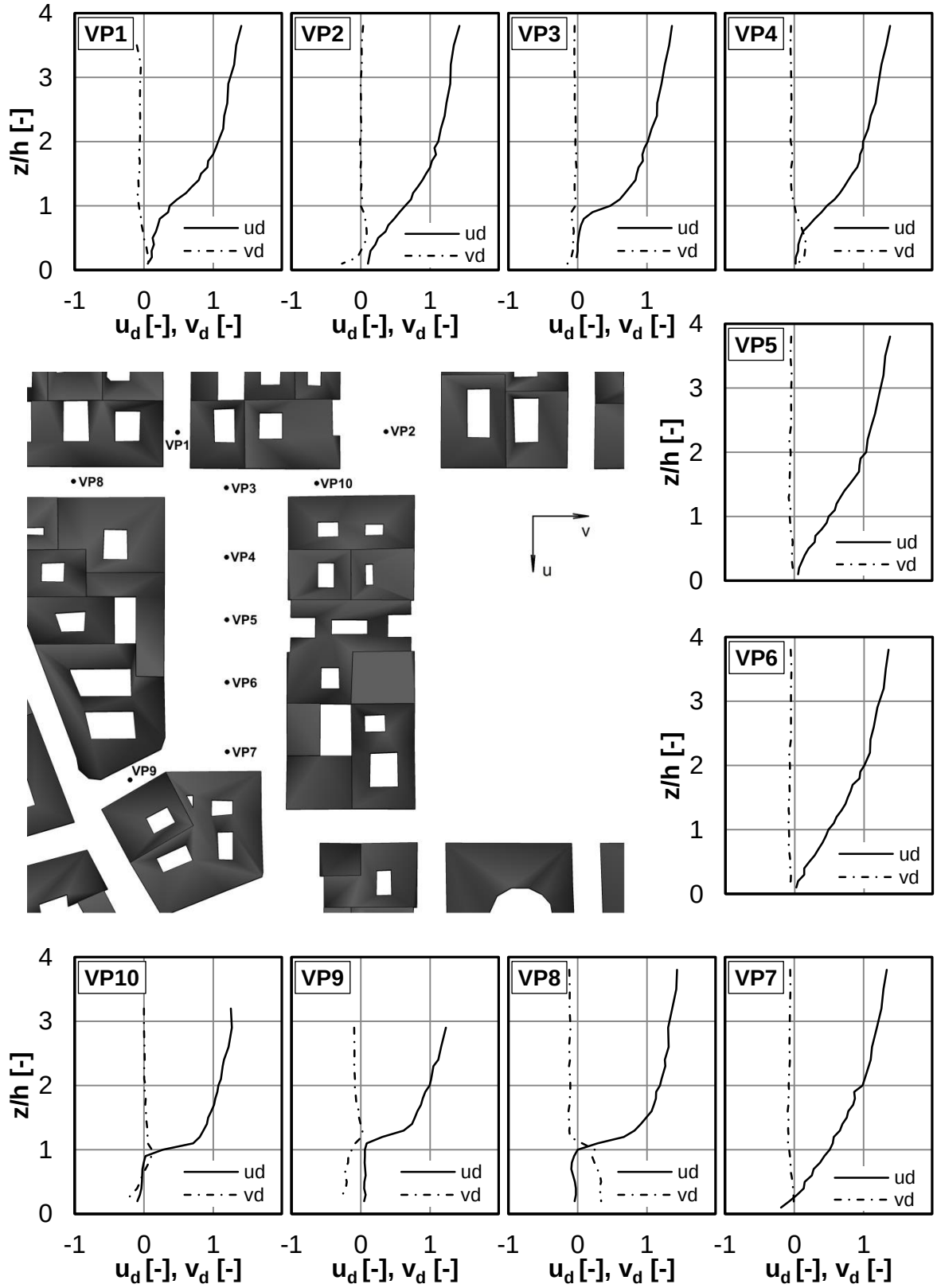


Fig. 3.5: Dimensionless mean velocity profiles (VP1-VP10) – northern wind direction

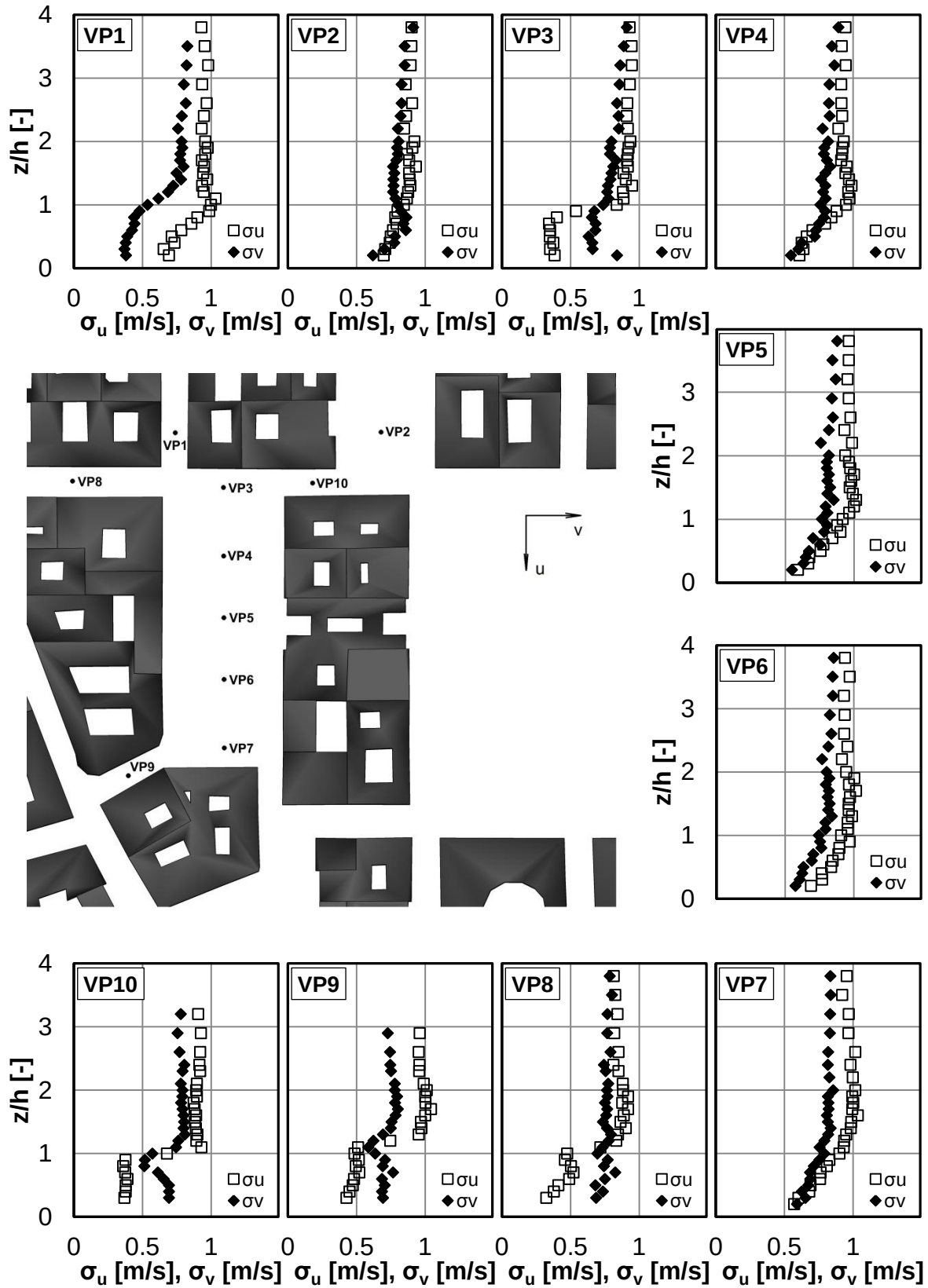


Fig. 3.6: Velocity standard deviation profiles (VP1-VP10) – northern wind direction

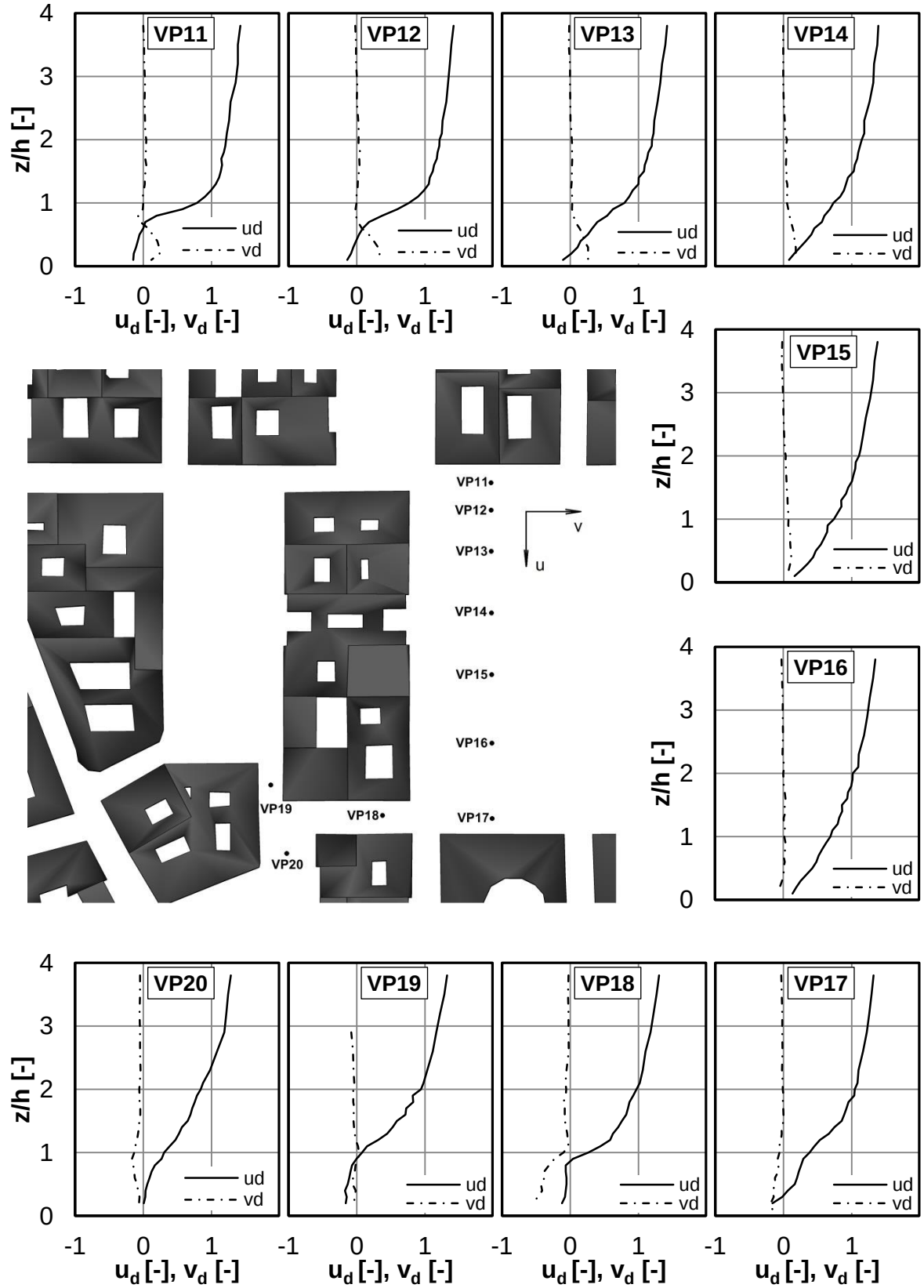


Fig. 3.7: Dimensionless mean velocity profiles (VP11-VP20) – northern wind direction

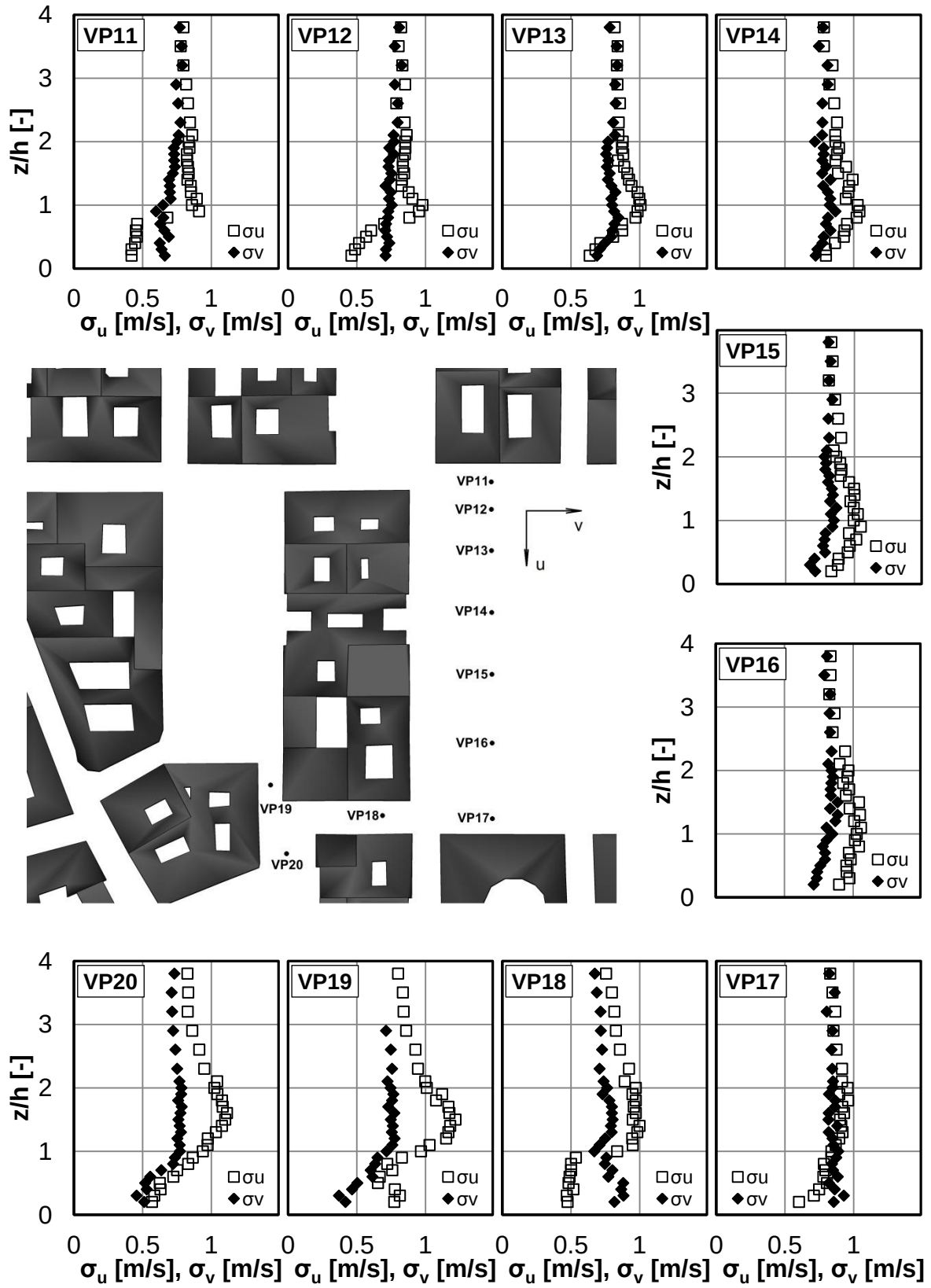


Fig. 3.8: Velocity standard deviation profiles (VP11-VP20) – northern wind direction

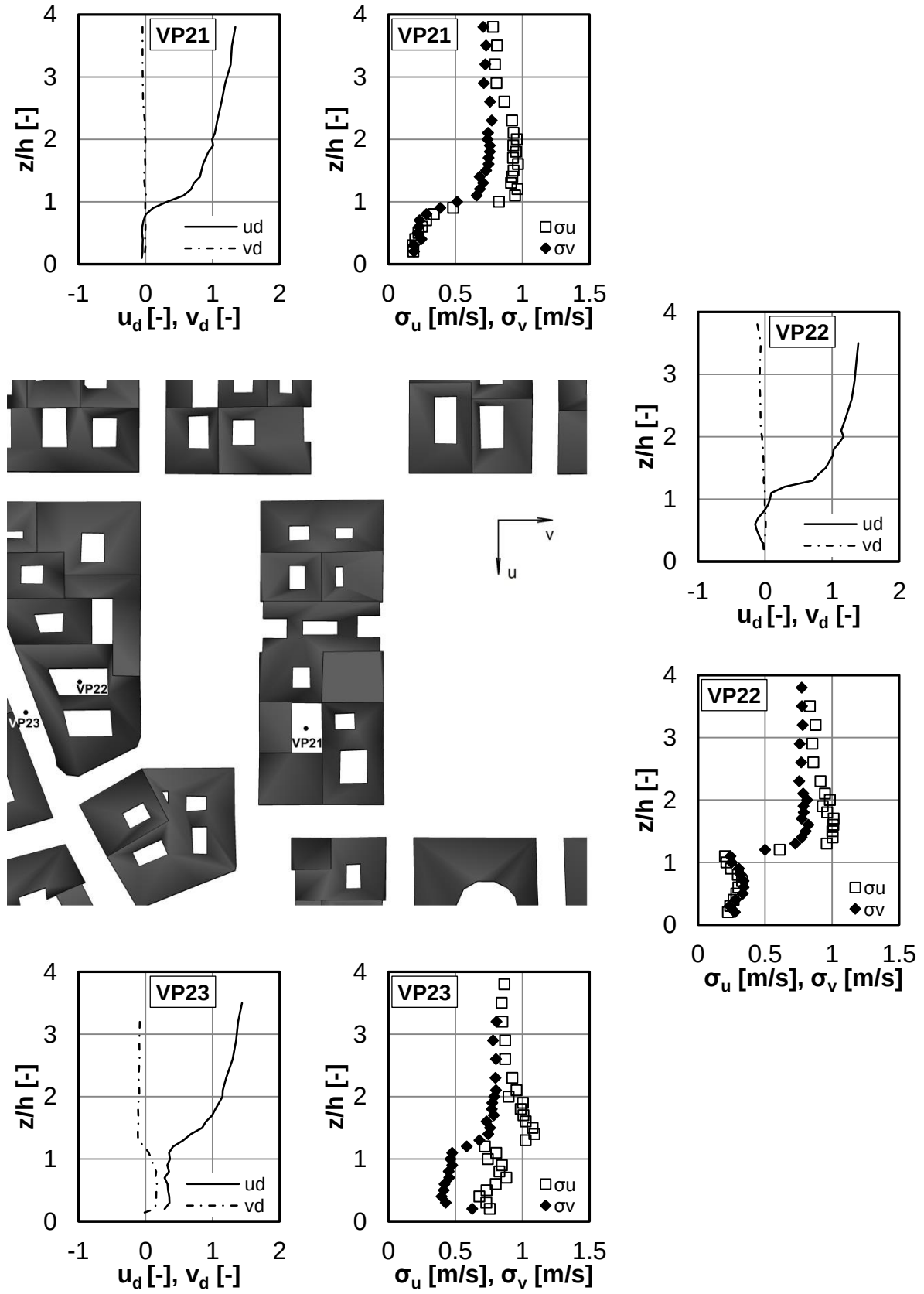


Fig. 3.9: Dimensionless mean velocity and velocity standard deviation profiles (VP21-VP23) – northern wind direction

Seeing the dimensionless mean velocity profile VP22 in Fig. 3.9 a vortex can be observed below the height of the buildings. This phenomenon is similar to a clear street canyon vortex; however, this profile can be found in an inner yard so the mentioned phenomenon is not exactly a street canyon vortex. In the case of profile VP21 the absolute values of the u velocities are smaller, almost zero below the height of the buildings. In the street in which VP23 is located the flow is parallel to the street axis.

The standard deviation profiles agree well with the expectations; the σ_u profiles have a maximum around the mean building height and the standard deviations of the velocity components decrease by leaps and bounds below this height. The σ_u values are generally larger than the σ_v values. In the inner yards (VP21 and VP22), the differences between the σ_u and σ_v values are almost zero below the height of the buildings.

3.1.2 Investigation of horizontal planes with northern wind direction

Flow velocities were measured along three horizontal planes at $z = 20$ mm ($0.25h$), $z = 40$ mm ($0.5h$) and $z = 80$ mm (h). The velocity and turbulent kinetic energy distributions on the three horizontal planes can be seen in Fig. 3.10.

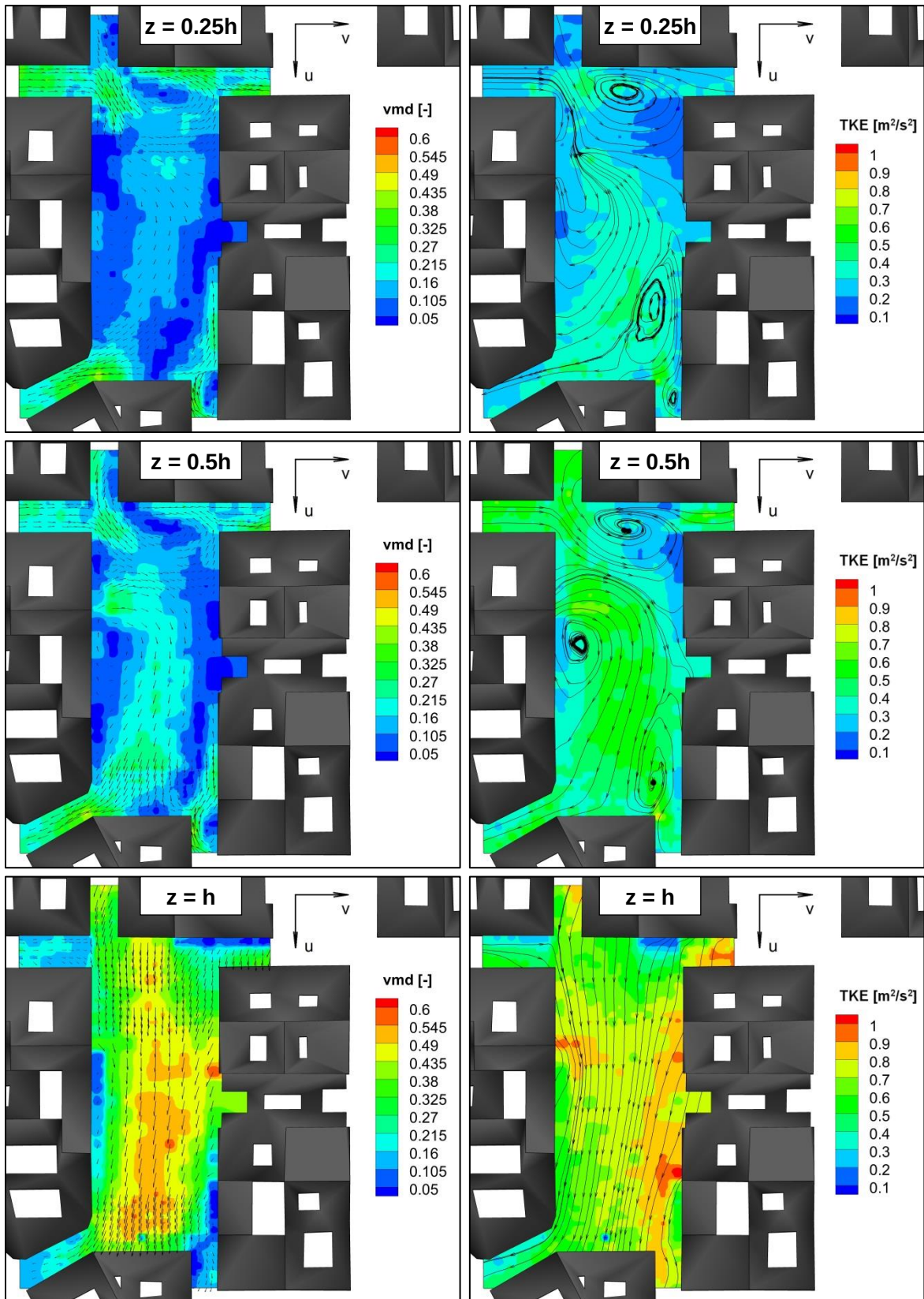


Fig. 3.10: Velocity and turbulent kinetic energy distributions on three horizontal planes – northern wind direction

As regards the velocity fields in northern wind direction (Fig 3.10), the highest velocity values were measured at $z = h$. No backflow is observable at this height. At lower heights, mean velocity values are also lower, at $0.25h$ less than 15% of the reference wind speed, with the exception of corners, where up to 30% can be observed.

Analyzing the streamlines, it can be stated that the flow forms three major vortices. Their vertical extension does not reach the reference height h but is clearly present at $z = 0.25h$ and $z = 0.5h$. The northern vortex is in the separation zone of the northern block, and the middle one is obviously caused by the second, taller building of the western building block.

Air enters the square from the northern streets and leaves it by passing through the south-western connecting street. Interestingly, backflow is detected in the south-eastern connecting street, so the outflow is blocked here. A stagnation point can be found in the front of the southern building. A significant proportion of the air, which arrives from northern connecting streets, is trapped into the first (north-eastern) vortex of the square.

Studying the turbulent kinetic energy distributions it can be unequivocally stated that turbulent kinetic energy increases with the height and it has a maximum at the average building height (h). Values of the turbulent kinetic energy are usually smaller in the vicinity of the walls. This agrees well with the expectations, because both the mean velocity and standard deviation values are lower near the walls.

At $z = 40$ mm ($0.5h$), measurement points were located not only at József Nádor Square and in the streets crossing the square but also at the nearby Erzsébet Square and in all the streets where the flow was accessible by the fiber-optic LDV probe through the pane of glass. The velocity distribution on the full plane at $0.5h$ can be seen in Fig. 3.11.

Analyzing the velocity distribution on the full plane (Fig. 3.11) it can be clearly seen that the measured velocities at Erzsébet Square are significantly larger than the velocities at József Nádor Square. Air enters Erzsébet Square from Hild Square (from the northern square) and goes through the square with high velocity. Large velocity values were measured also in the southern street (in Harmincad Street) which is perpendicular to the ambient wind direction; air flows from Erzsébet Square with high velocity and hits the southern building block of József Nádor Square. A certain proportion of the air turns north and this phenomenon is responsible for the backflow in the south-eastern connecting street of József Nádor Square. Separation bubbles evolved next to the southern building blocks can be observed in Bécsi Street and Vörösmarty Square. A significant proportion of the air leaves Erzsébet Square by passing through Bécsi Street (the south-western connecting

street which is parallel to the ambient wind direction) with high velocity; the largest velocity values were measured in this street and near the north end of the street at the edge of the southern building block.

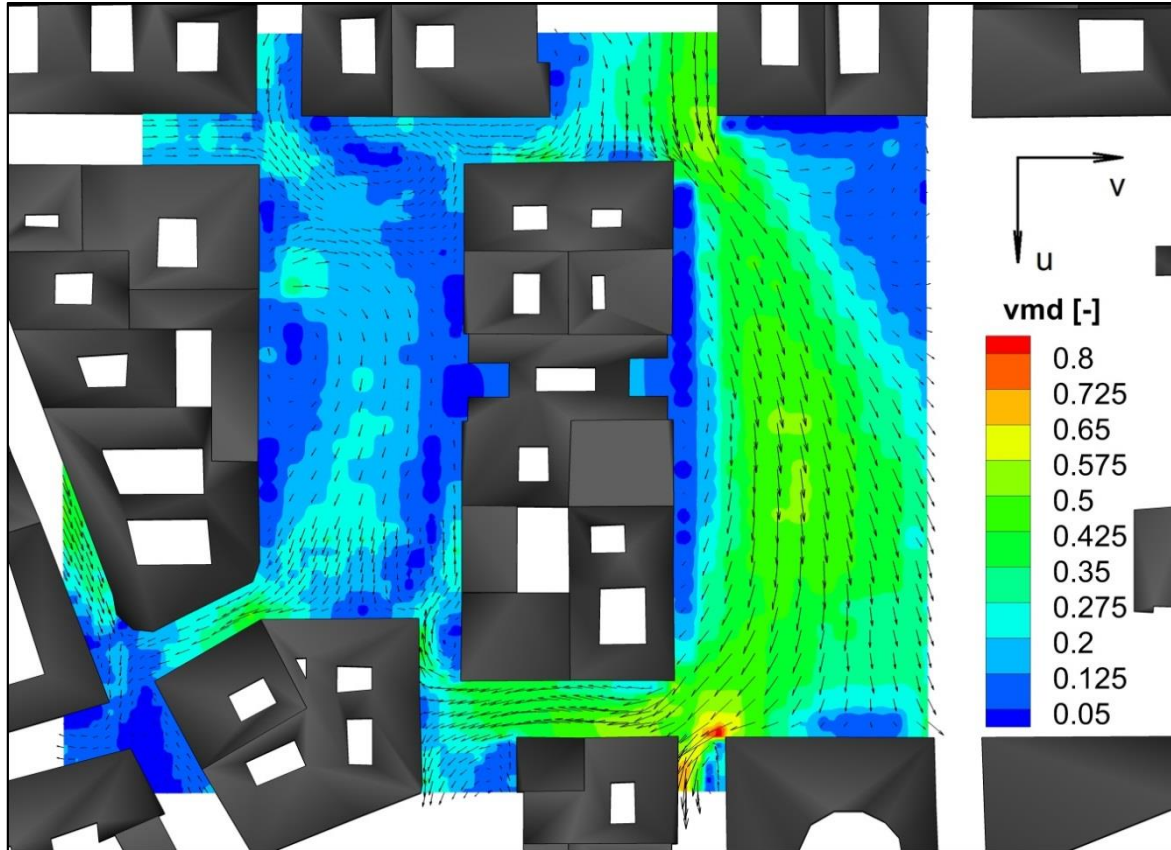


Fig. 3.11: Velocity distribution on the full plane at $0.5h$ – northern wind direction

The turbulent kinetic energy distribution on the full plane at $0.5h$ can be seen in Fig. 3.12.

Analyzing the streamlines in Fig. 3.12 it can be seen that the flow does not form any major vortices at Erzsébet Square. A certain proportion of the air, which arrives from the northern square (from Hild Square), does not enter Erzsébet Square but turns west towards József Nádor Square and it is trapped into the first (north-eastern) vortex of the square. A stagnation point can be found on the northern wall of the building block between József Nádor Square and Erzsébet Square. Stagnation points can be found also in the front of the southern building of Erzsébet Square and on the eastern wall of the southern building block of József Nádor Square.

An interesting part of the investigated area is the street intersection in the south-western corner of the pane of glass. Air arrives at the intersection from three directions and leaves it by passing through Szende Pál Street; backflow is detected in Dorottya Street.

Studying the turbulent kinetic energy distribution on the full plane it can be stated that the largest turbulent kinetic energy values were measured near the southern building block at Erzsébet Square. Values of the turbulent kinetic energy are usually smaller in the vicinity of the walls for the full investigated area.

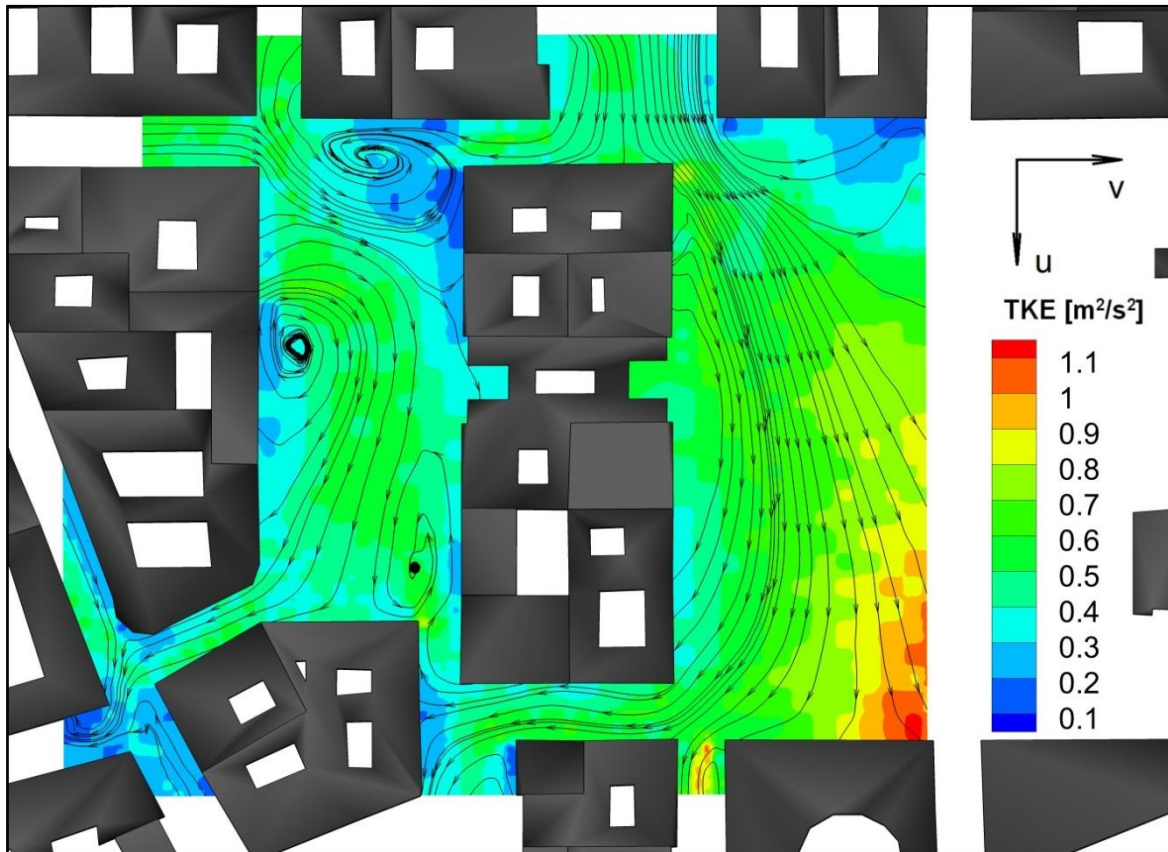


Fig. 3.12: Turbulent kinetic energy distribution on the full plane at $0.5h$ – northern wind direction

3.1.3 Analysis using wind roses

The time-resolved LDV data captured simultaneously for both horizontal wind directions contain information about turbulence anisotropy and spectral properties. Up to this point, from the turbulent quantities, only turbulent kinetic energy was utilised.

For a more detailed analysis simultaneous u and v time series were captured at a horizontal plane at $0.5 h$ height at several measurement locations, and the occurrence frequency of the instantaneous horizontal wind vector $\underline{v}_{i,d}$ at a certain location was

visualised by wind roses (polar area diagrams). Thirty one selected wind roses are shown in Fig. 3.13, coloured by the instantaneous velocity magnitude. Also, streamlines coloured by the average horizontal velocity magnitude v_{md} are shown.

- Each illustrated wind rose is placed at the location of the given measurement point – the exact location is the centre of the wind rose.
- The roses are divided into 10-degree spokes representing the probability of 10-degree wind direction sectors.
- Each spoke is subdivided into colour-coded bands that show velocity ranges.
- The spokes show the direction of the flow velocity vector.

It is important to point out that as opposed to the usual application of wind roses – representing annual wind statistics – the current wind roses show the statistics of wind speed and direction at a single incident wind direction. The wind roses presented in Fig. 3.13 can be organised into different groups based on their shape:

1. Wind roses with a single dominant wind direction and small deviations can be found in streets with one-directional flow (WR2, 23, 24) channelled along the streets' main axis. Backflow (90-270 degree to the main wind direction) is negligible. While the average velocity magnitude is 0.3-0.4, wind velocities of larger than 1 (wind gusts) have also a significant probability.
2. Fan-tail shaped wind roses appear in several locations on the square, but not in the connecting streets (WR 7, 8, 10, 12, 14-16, 19, 20, 31). Obviously, far from walls which restrict perpendicular movements, velocities can fluctuate in all directions. Deviations of up to +/-90 degree from the main wind direction can occur; also, a low percentage of backflow can be seen.
3. Wind roses with more than one peak can be observed in streets (WR 3, 21, 26, 27). The double peaks mean that at a given wind direction flow is coming once from one end of the street, once from the other end. WR 26, located in an intersection, shows peaks 90 degree to each other, which can be explained by the angle of the connecting streets.
4. Wind roses with more than one peak can be seen also near the core of vortices of the mean wind field (WR 5, 11, 21). This can be explained by the slight movement of the vortex core, meaning that the measurement location is once on one side, and once on the other side of the vortex core, thus flow direction is reversed.

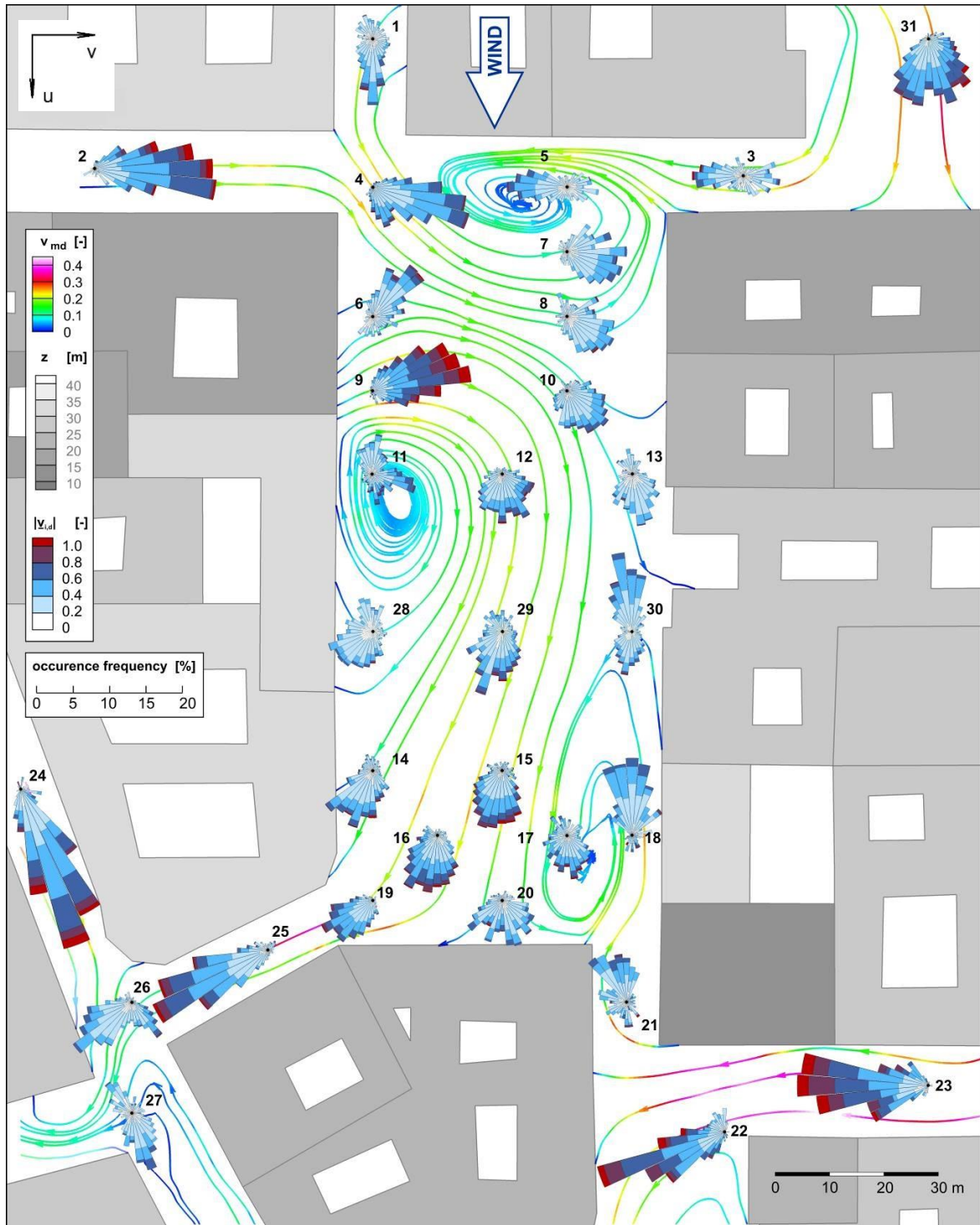


Fig. 3.13: Flow field and wind roses in the investigated area in northern wind direction at $0.5 h$ height. Streamlines are coloured by normalised average velocity magnitude v_{md} , buildings by their full scale height and wind roses by the magnitude of the instantaneous normalised wind vectors $v_{i,d}$. Note that the two velocity scales are different. The wind roses show the occurrence frequency of 10-deg wind direction sectors.

5. Finally, points on the boundary of a vortex of the mean flow can have multiple peaks, again explained by the slight movement of the cores as in WR 30. Here, velocity magnitude reaches 0.6, while average velocity is 0.05.

Regarding the temporal sequence of velocity fluctuations, double peaks in the velocity histogram in location types 4 and 5 prove the periodic switching between wind directions. Fig. 3.14 shows the continuous velocity histograms of the u_d stream-wise velocity component. The type 2 wind rose WR 15 shows a more Gaussian-like distribution; in contrast to this, the type 5 wind rose WR 30 shows double peaks indicating periodic or mode-locking flow switching between a northern (positive u_d) and a southern (negative u_d) flow state. The direct consequence of flow switching on smoke plume dispersion was observed in wind tunnel flow visualisations by [12].

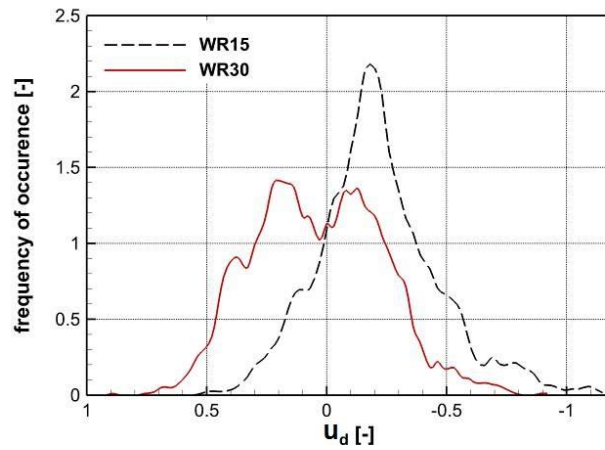


Fig. 3.14: Comparison of type 2 (WR 15) and type 5 (WR 30) wind velocity distributions (northern wind direction)

3.2 Measurements with western wind direction

3.2.1 Vertical profile measurements with western wind direction

After the flow field measurements with northern wind direction, western wind direction was prescribed and the measurement series was continued. Dimensionless mean velocities and velocity standard deviations were determined along 22 vertical profiles (VP1 to VP22). The results of the profile measurements with western wind direction can be seen in Fig. 3.14, Fig. 3.15, Fig. 3.16, Fig. 3.17 and Fig. 3.18, respectively.

Analyzing the dimensionless mean velocity profiles in Fig. 3.14 it can be seen that in the case of profiles VP3, VP8 and VP10 very large velocity values were measured below

the mean building height; in József Attila Square, the flow is parallel to the street axis and the flow velocity is extremely high.

In VP1 and VP2, negative u velocities were measured below the mean building height. Although expected in VP1, a clear street canyon vortex could not be observed.

Seeing the other profiles above József Nádor Square (VP4 to VP7) it can be noticed that the v velocity component can significantly differ from zero below the height of the buildings; this indicates remarkable cross-flow. In the case of profiles VP5, VP6 and VP7 the u velocity is zero at the mean building height and increases above this height.

Negative u velocities were measured below the height of the buildings also in VP9. In the street where VP9 can be found the flow is parallel to the street axis and air flows against the ambient wind direction.

Analyzing the standard deviation profiles in Fig. 3.15 it can be said that there are usual and unusual profiles. In the case of the usual profiles (VP1, VP2 and VP5 to VP9) similar phenomena can be observed as before; the standard deviation of the u velocity component is usually larger than the standard deviation of the v velocity component and the σ_u profiles have a maximum around the mean building height. In the case of the unusual profiles (VP3, VP4 and VP10) the standard deviation of the u velocity component is usually larger than the standard deviation of the v velocity component but σ_u does not have a maximum around the mean building height; actually it has a minimum (local or global) at the mean building height in these profiles. In VP3 and VP10, σ_u increases below the mean building height and has a local maximum at the lowest measurement point – local maximum in the case of VP3 and global maximum in the case of VP10. In VP4, the largest σ_u value was measured at $0.5h$. The mentioned phenomena are very important and will play a big role in the concentration measurements.

Negative u velocities were measured below a certain height in all of the profiles in Fig. 3.16. The value of the v velocity component can differ from zero below the height of the buildings; backflow or cross-flow is detected at all locations of the profiles. The street in which VP19 can be found is perpendicular to the ambient wind direction; however, a clear street canyon vortex cannot be observed here.

Surprising phenomena could not be observed in the case of the standard deviation profiles in Fig. 3.17; all of these profiles agree well with the expectations and also with the previously introduced usual profiles.

Seeing the dimensionless mean velocity profile VP22 in Fig. 3.18 a vortex can be observed below the height of the buildings – similarly to the vortex arose here in the case of the northern wind direction. In the case of profile VP21 the absolute values of the u velocities are slightly smaller than zero below the mean building height.

Profiles VP21 and VP22 are located in inner yards; as it was expected, the differences between the σ_u and σ_v values are almost zero below the height of the buildings. Above the mean building height, the σ_u values are normally larger than the σ_v values.

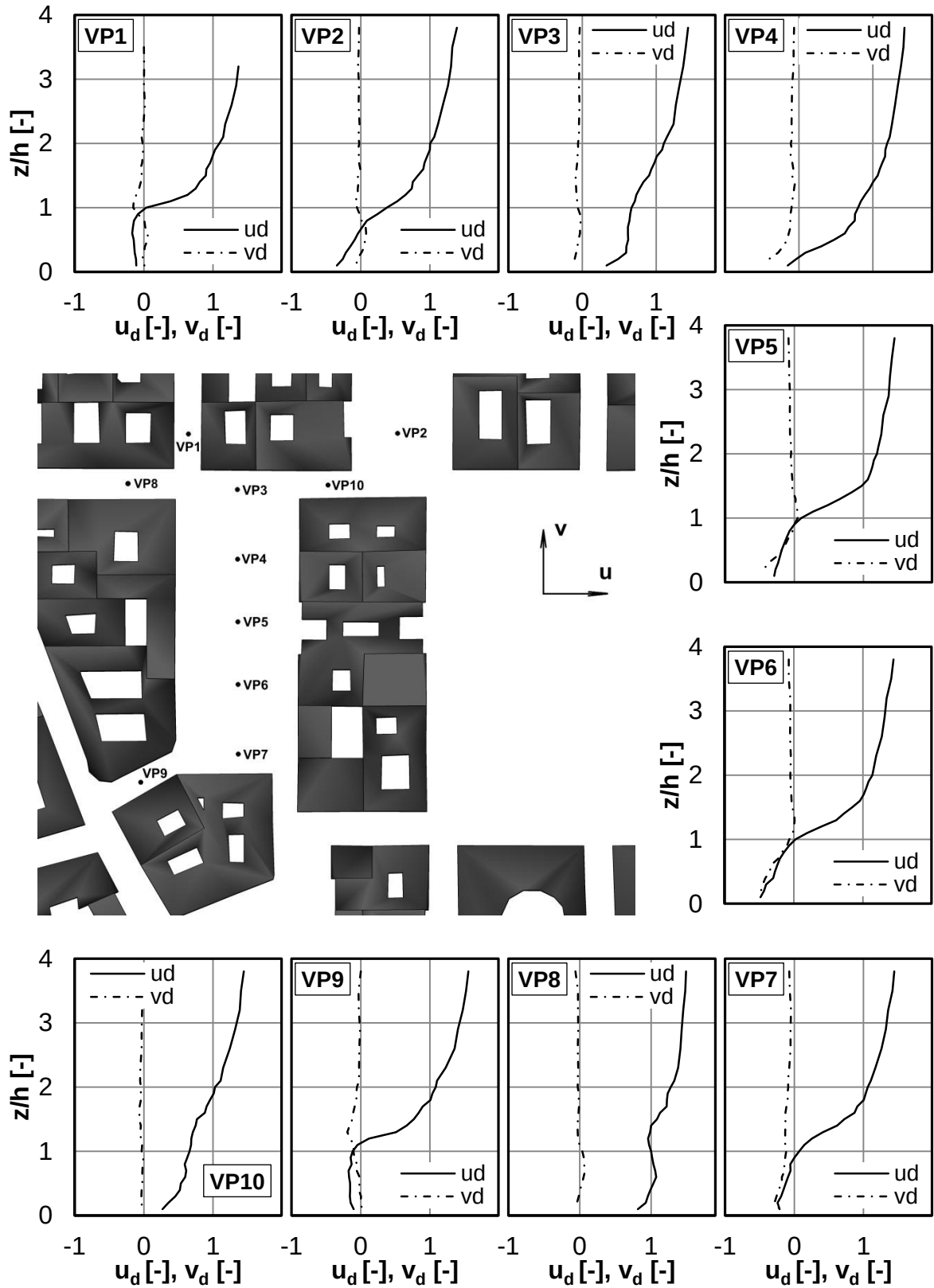


Fig. 3.14: Dimensionless mean velocity profiles (VP1-VP10) – western wind direction

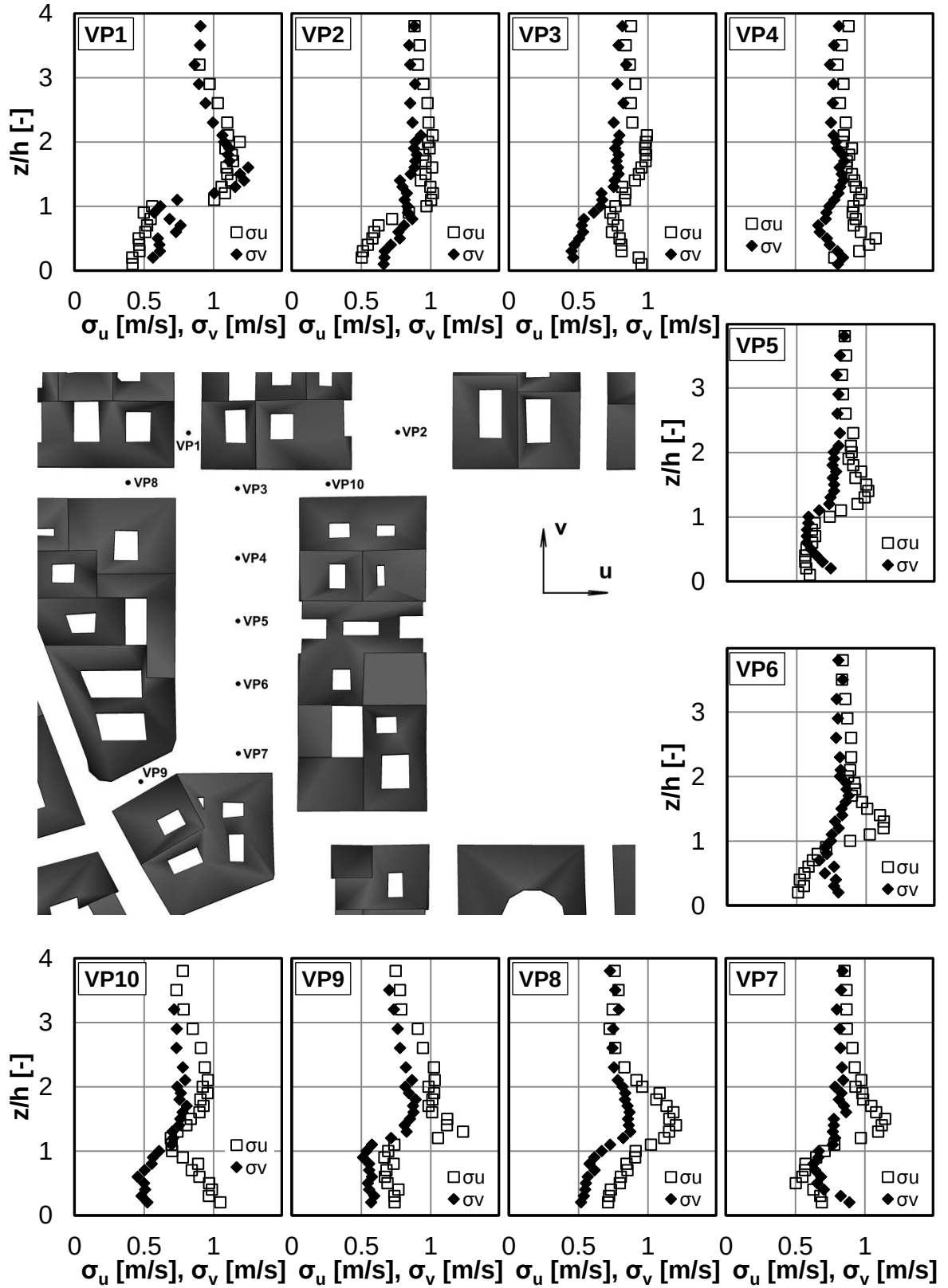


Fig. 3.15: Velocity standard deviation profiles (VP1-VP10) – western wind direction

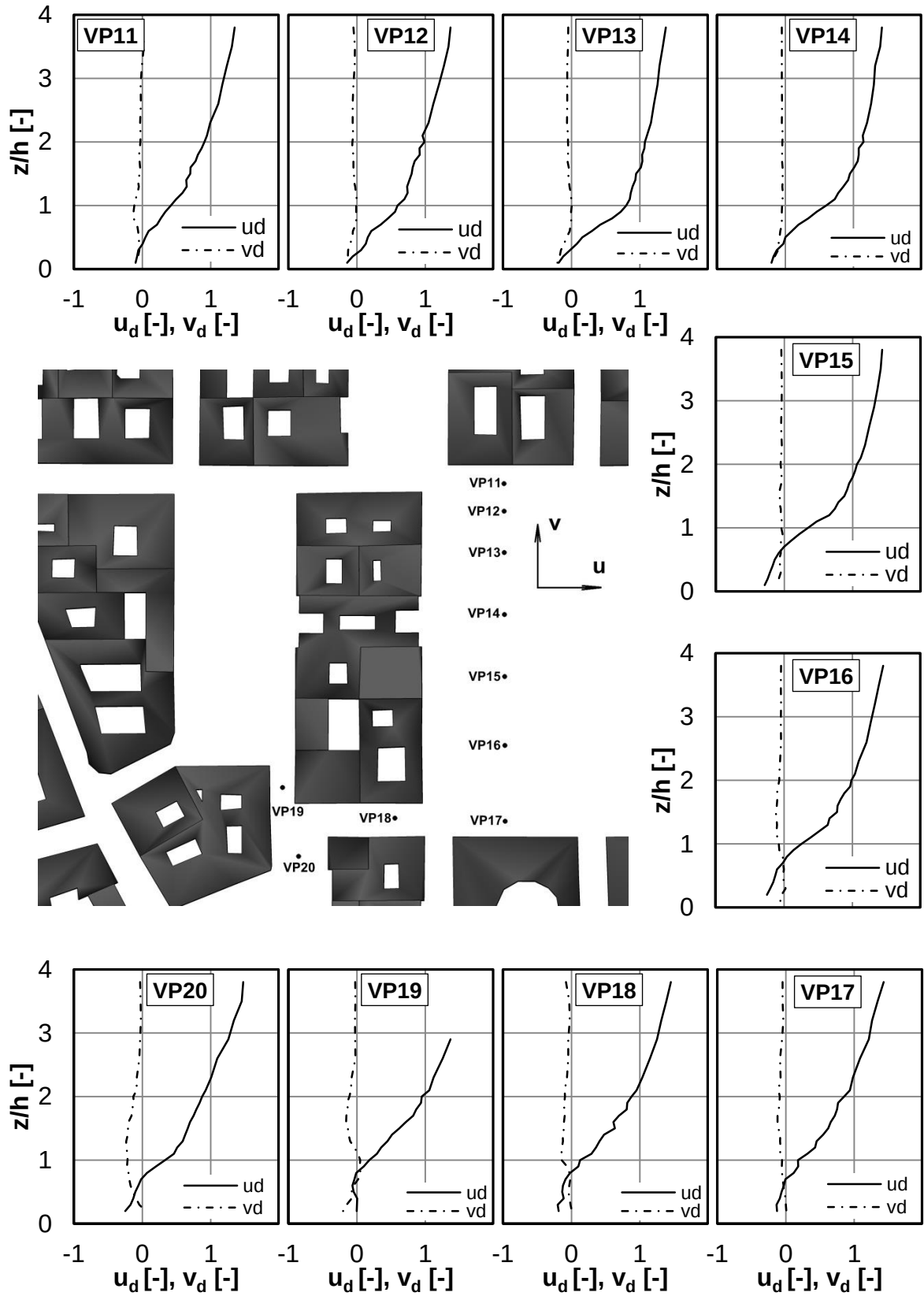


Fig. 3.16: Dimensionless mean velocity profiles (VP11-VP20) – western wind direction

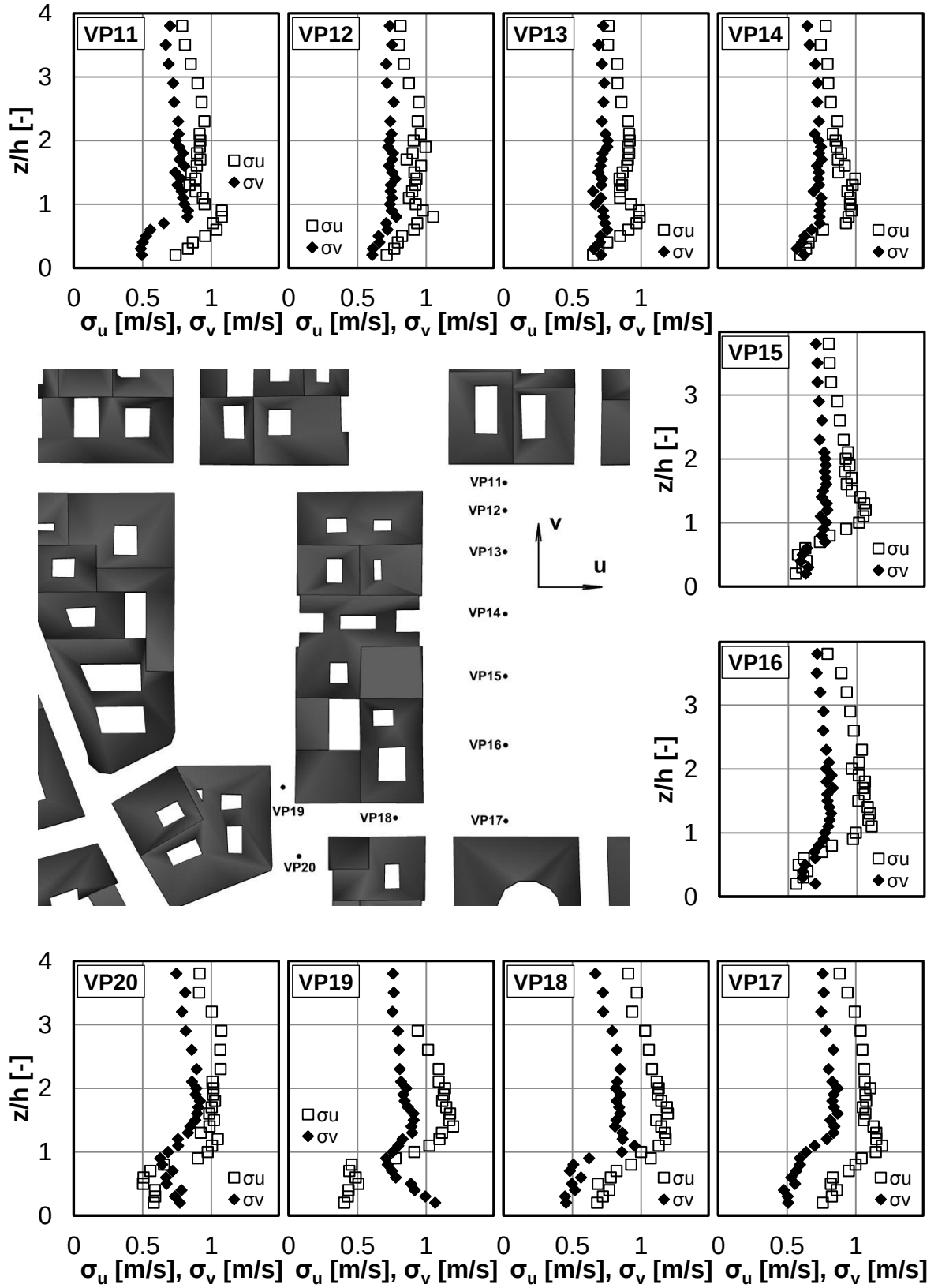


Fig. 3.17: Velocity standard deviation profiles (VP11-VP20) – western wind direction

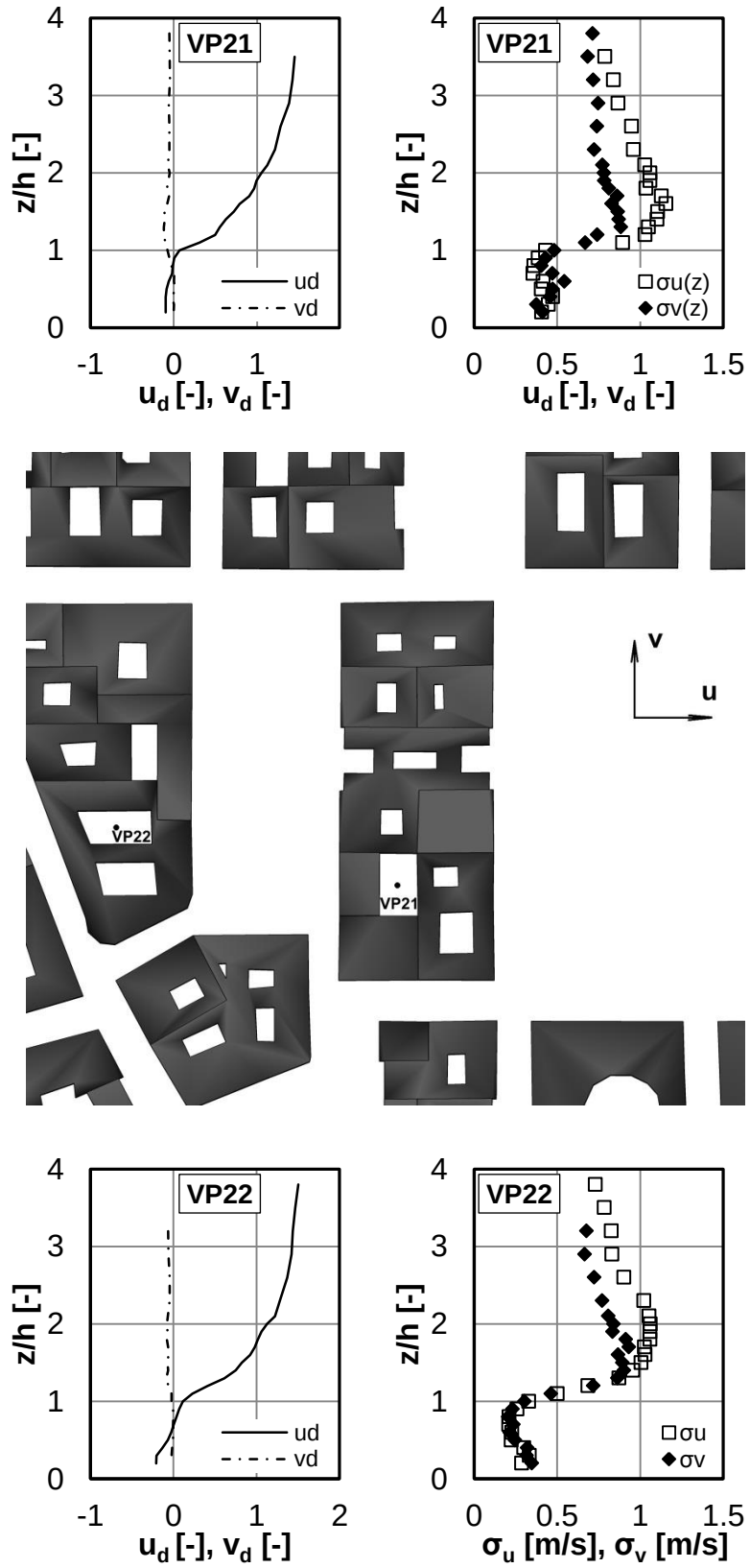


Fig. 3.18: Dimensionless mean velocity and velocity standard deviation profiles (VP21 and VP22) – western wind direction

3.2.2 Investigation of horizontal planes with western wind direction

Flow velocities were measured along two horizontal planes at $z = 20 \text{ mm}$ ($0.25h$) and $z = 40 \text{ mm}$ ($0.5h$). The velocity and turbulent kinetic energy distributions on the two horizontal planes can be seen in Fig. 3.19.

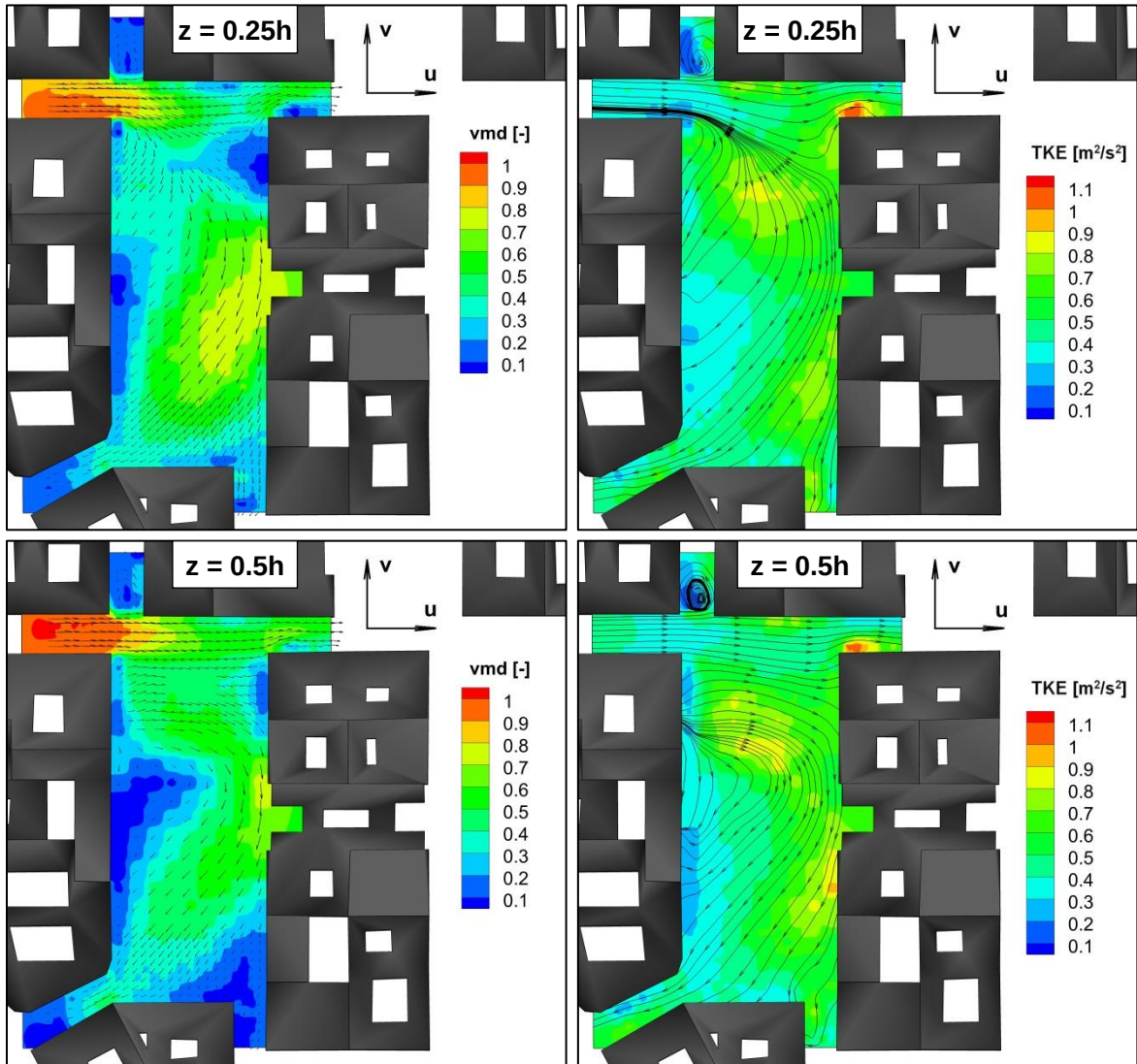


Fig. 3.19: Velocity and turbulent kinetic energy distributions on two horizontal planes – western wind direction

Seeing the velocity fields on the horizontal planes (Fig. 3.19) it can be said that the measured velocity values at $0.5h$ are not significantly larger than the values at $0.25h$; moreover, in the middle and in the eastern part of the square velocity values at $0.25h$ are larger than the values at $0.5h$. The highest velocities were measured in József Attila Street at both heights; mean velocity values approximate the reference wind speed in the western

part of the investigated section of the street. A separation bubble evolved after the western building block can be observed; low velocities were measured in the wake of this block. Mean velocity values are almost zero in the south-eastern connecting street at $0.5h$. Moderately low negative v velocities were measured in this street at $0.25h$. The outflow is neither blocked here nor in the south-western connecting street.

Analyzing the streamlines, it can be stated that the flow forms only one major vortex and it can be found in the northern connecting street which is perpendicular to the ambient wind direction (Nádor Street). At $0.25h$, a certain proportion of the air which arrives from József Attila Street enters József Nádor Square, goes through the square and leaves it by passing through the southern connecting streets; air flows against the ambient wind direction in the south-western connecting street. At $0.5h$, there are no common streamlines between József Attila Street and any of the southern connecting streets. This means that there are not any particles moving directly from József Attila Street to the southern connecting streets. However, the roughly unidirectional, high-velocity flow in József Attila Street governs the flow at József Nádor Square. Flowing air arrived from another height changes direction near the eastern building block, turns back and leaves the square by passing through the south-western connecting street. The outflow through the south-eastern connecting street is not significant at this height (at $0.5h$).

Studying the turbulent kinetic energy distributions it can be stated that the turbulent kinetic energy values at $0.5h$ are not significantly larger than the values at $0.25h$. Values of the turbulent kinetic energy are smaller in the wake of the western building block. The largest turbulent kinetic energy values were measured in József Attila Street near the north-western edge of the eastern building block at both heights.

At $z = 40 \text{ mm}$ ($0.5h$), measurement points were located not only at József Nádor Square and in the streets crossing the square but also at the nearby Erzsébet Square and in all the streets where the flow was accessible by the fiber-optic LDV probe through the pane of glass. The velocity distribution on the full plane at $0.5h$ can be seen in Fig. 3.20.

Analyzing the velocity distribution on the full plane (Fig. 3.20) it can be clearly seen that the measured velocities at Erzsébet Square are significantly smaller than the velocities at József Nádor Square. Flow in József Attila Street decelerates and air enters Erzsébet Square with very low velocities. Ventilation around Erzsébet Square is extremely poor. Air exchange is low between the square and the neighboring areas and also between the square and the atmospheric boundary layer. Backflow is detected in the southern half of Erzsébet Square almost everywhere and also in the southern street (in Harmincad Street) which is

parallel to the ambient wind direction. The south-western building of the western block of Erzsébet Square is a relatively low building – lower than $0.5h$. The measurement points were located at $0.5h$, so the effect of the flow above the mentioned low building could be observed; flowing air arrives at this building and is pushed by the flow above the building. This phenomenon causes increased absolute velocities. Both the u and v velocity components are negative in this area.

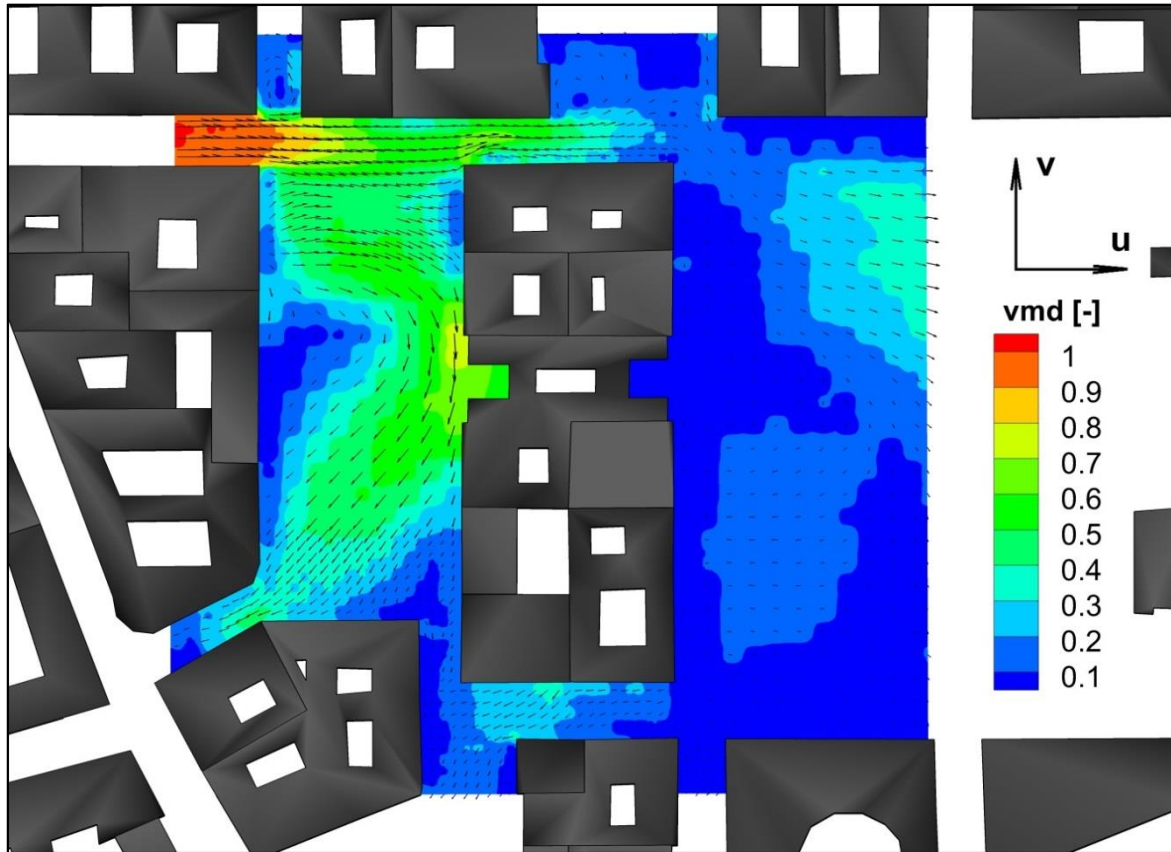


Fig. 3.20: Velocity distribution on the full plane at $0.5h$ – western wind direction

The turbulent kinetic energy distribution on the full plane at $0.5h$ can be seen in Fig. 3.21. Analyzing the streamlines in Fig. 3.21 it can be seen that the flow forms two major vortices – one in Nádor Street and one at Hild Square. Air enters Erzsébet Square from József Attila Street. The previously mentioned backflow is clearly observable in the southern half of Erzsébet Square and also in Harmincad Street.

Studying the turbulent kinetic energy distribution on the full plane it can be stated that the turbulent kinetic energy values at Erzsébet Square are not larger than the values at József Nádor Square. The smallest turbulent kinetic energy values were measured in the vicinity of the vortices and in the wake of the western building block of Erzsébet Square.

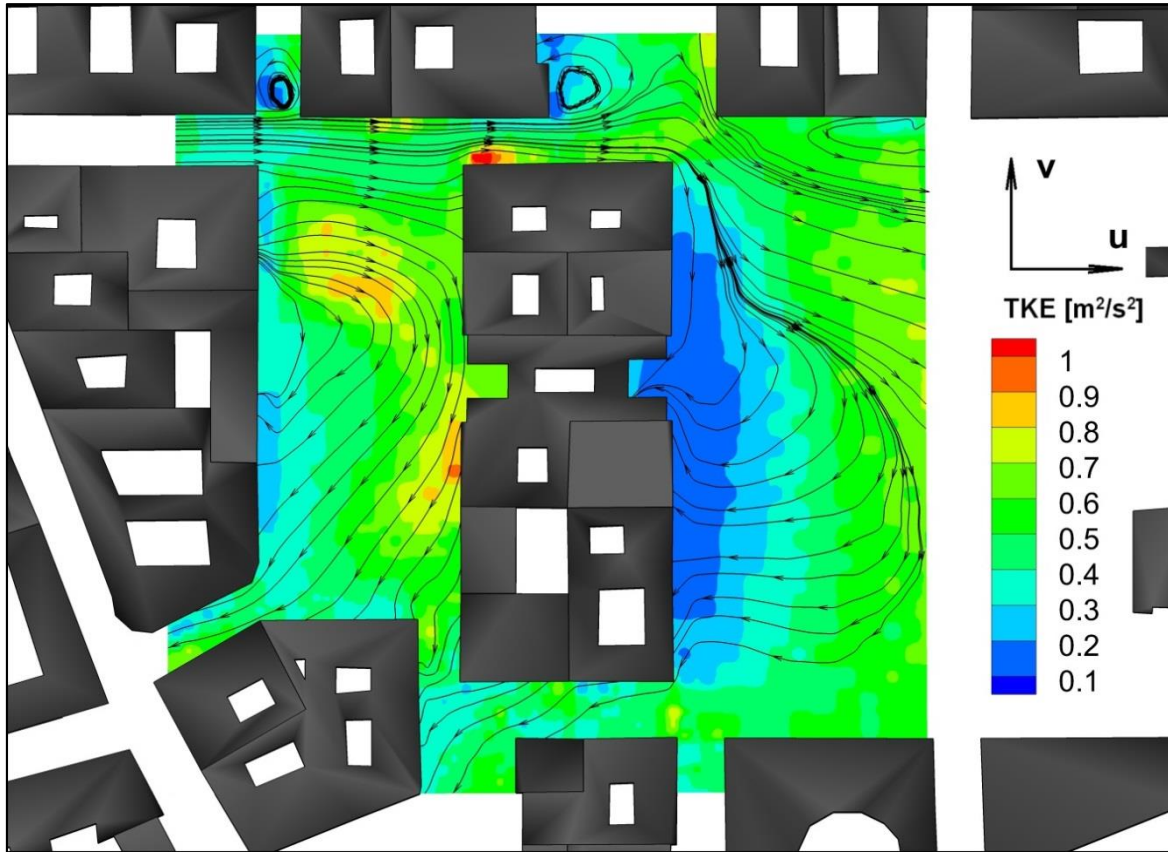


Fig. 3.21: Turbulent kinetic energy distribution on the full plane at $0.5h$ – western wind direction

4 COMPARISON OF MEASUREMENT DATA TO CFD SIMULATION RESULTS

During the evaluation of the measurement data, the x coordinate – and the u velocity component – was always parallel to the ambient wind direction; however, a fixed coordinate system is used in this section in order to provide an opportunity to perform a consistent and clear comparison of measurement data to CFD simulation results. The fixed coordinate system was added to Fig. 3.4 and the complete figure of the investigated area can be seen in Fig. 4.1.

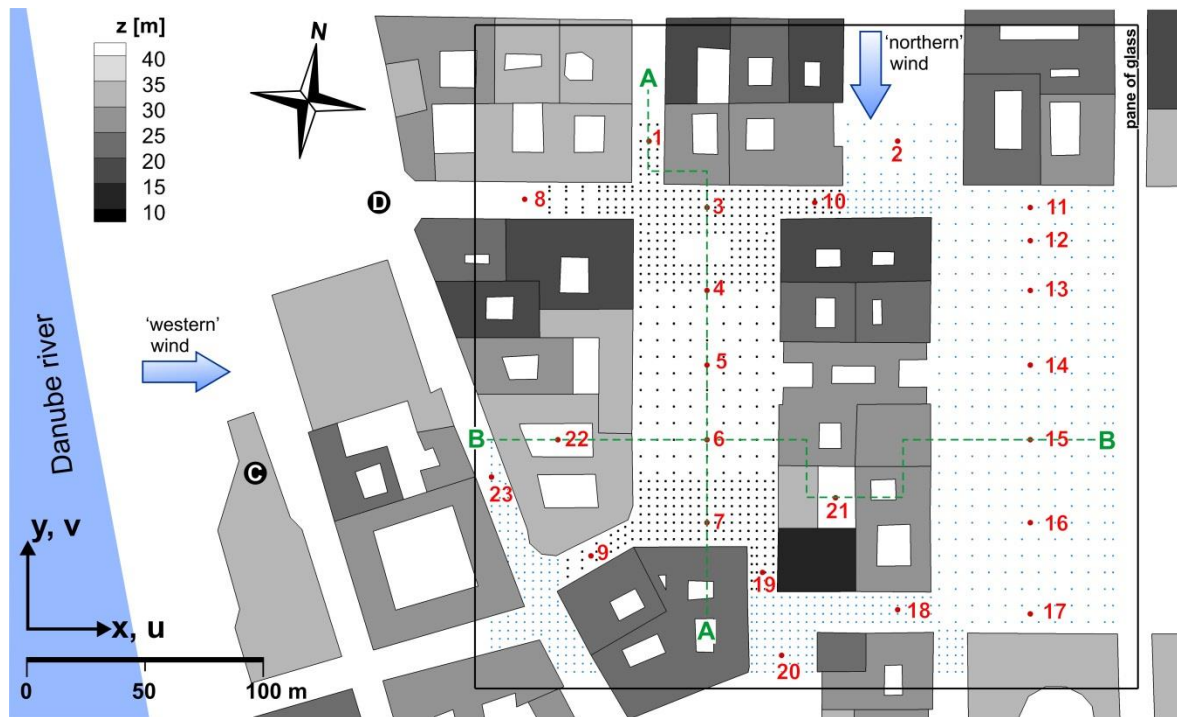


Fig. 4.1: The investigated area – the fixed coordinate system is also illustrated

The CFD simulation data were available from a former BSc thesis [4] and a recent research [5]; these data had to be thoroughly evaluated again in order to prepare the results for journal publication. The execution of CFD simulations is not included in this thesis; however, the CFD setup has to be introduced briefly.

4.1 CFD setup

Setup of the CFD simulations carried out in the mentioned previous projects [4, 5] followed the Best Practice Guideline given by [13]. The computational domain included the buildings modelled in the wind tunnel in full scale inside a 700 m diameter circle around József Nádor Square corresponding to the 2 m diameter turntable, with proper inlet, outlet and side distances to the domain boundary. Domain size was thus $1000 \times 1100 \times 500$ m. Grid resolution of the non-equidistant Cartesian grid applied by MISKAM varied from 4 - 6 m horizontally and 1 m vertically between buildings down to 1.5 m horizontally and 0.6 m vertically around József Nádor Square near the ground, up to a total of approximately 5 million grid cells.

Regarding grid independency of the computational mesh, earlier MISKAM simulations of a simplified symmetrical street canyon geometry by [14] showed that it can be reached at an average of 0.5 m cell size (with refinements of 0.1 m at building leading edges). However, this resolution could not be replicated in the current complex, large-domain case with hundreds of buildings due to memory limitations of the 32 bit code. The current resolution can be seen as typical for the MISKAM model when applied in environmental impact assessment studies by agencies on a daily basis.

The predefined boundary condition types of MISKAM (see [15]) were used: buildings represented as block outs from the Cartesian grid, on the surfaces no-slip conditions applied using wall functions, the roughness length on the surfaces set to 0.01 m. At the inlet boundaries an equilibrium logarithmic profile was generated by MISKAM automatically with initial roughness length z_0 of 0.2 m. The reference velocity was set to 3.02 m/s at $h = 28$ m, as measured in wind tunnel.

The comparison of the CFD approaching flow profile to the profile measured in the empty wind tunnel shows certain disagreement in terms of both mean velocity and turbulence (Fig. 4.2). Turbulence underestimation in boundary layer profiles over flat terrain is a common error of K- ϵ turbulence closures as shown e.g. by [16]. It is expected, however, that the first few rows of buildings will act as boundary condition generators, and the profiles will be assimilated to each other. This will be checked later comparing CFD and wind tunnel vertical velocity profiles at locations near the square.

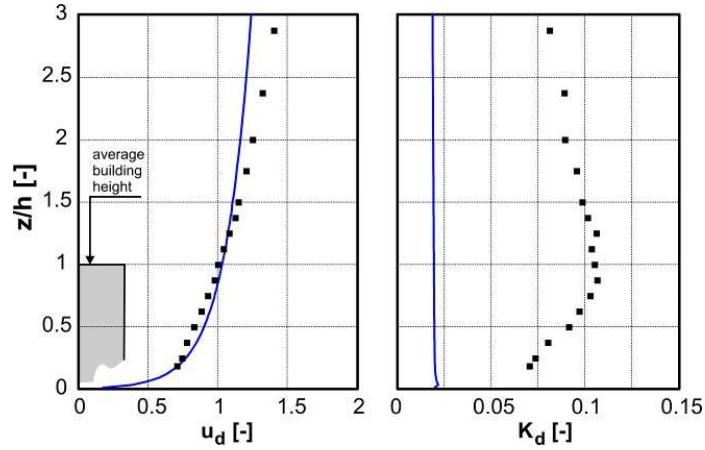


Fig. 4.2: Stream wise dimensionless velocity u_d and dimensionless turbulent kinetic energy K_d profiles.

Simulation: continuous blue line, wind tunnel measurement: dots. h : average building height.

In the following comparison plots, dimensionless turbulent kinetic energy K_d determined by simulations was always multiplied by $2/3$ in order to approximate the contribution of horizontal velocity fluctuations to the turbulent kinetic energy, which was actually measured in the wind tunnel.

4.2 Analysis of vertical profiles

The 23 dimensionless vertical velocity profiles give a first insight into the flow field at the square. Our expectation is that the stream wise velocity component (v in case of northern wind direction) will follow the approaching wind profile (Fig. 4.2) above rooftop level, but around and below rooftop level it will deviate significantly.

Fig. 4.3 shows vertical profiles of mean velocity from both the wind tunnel and CFD simulation, streamlines from CFD and turbulent kinetic energy from the wind tunnel in the mid-plane of the square (cross section A-A in Fig. 4.1). The building located at the northern end of the square generates backflow (marked with A in Fig. 4.3). The presence of this recirculation zone is visible on profiles VP3 and VP4. The streamlines originating from one source point indicate that there is significant inflow from x direction (from the connecting street) into the core of the separation zone.

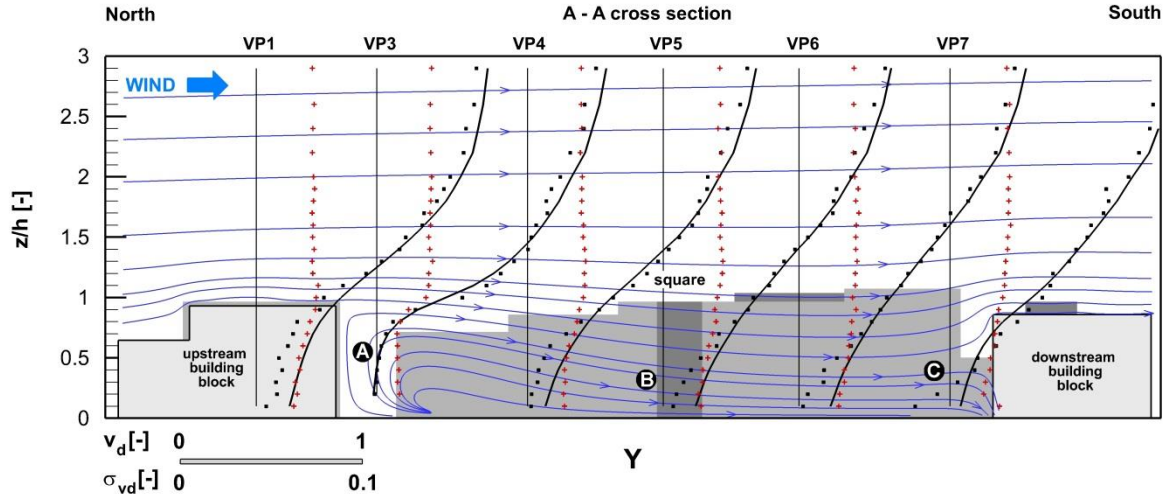


Fig. 4.3: Flow field at northern wind direction along the square (A – A cross section of Fig. 4.1). Black squares and continuous lines: normalised stream wise mean velocity component v_d from measurement and simulation, crosses: normalised velocity standard deviation σ_{vd} from wind tunnel measurement. Streamlines in blue are from the simulation. Note that VP1 lies in a connecting street, not on the square itself.

From the middle of the square (approximately $2.5 h$ distance, B in Fig. 4.3), streamlines reaches the bottom on the square and stagnation point develops in front of the downstream building block. Close to the ground (marked with C in Fig. 4.3), again backflow can be observed in the wind tunnel measurements, showing the presence of a horseshoe vortex, which is unfortunately not resolved by the CFD. Otherwise, CFD follows the measurements quite well, especially above rooftop level, proving the assumption made earlier, that the slight differences in incoming boundary conditions are assimilated, as the flow reaches the square. Near the ground, the stream wise flow velocities are overestimated by CFD.

The flow field in a cross-section of the square at western wind is depicted in Fig. 4.4 (cross section B - B of Fig. 4.1). In this direction, the square is only $2 h$ wide.

- In the range of $1.2 - 3 h$ height the measured velocity values are underestimated by CFD by up to 25% (VP22, VP21 and VP15). As this can be seen in all three profiles of the same cross section, the source of this deviation must lie outside of the depicted domain. Taking a look at Fig. 4.1, the cross section is in line with the 40 m high building marked with C. This is exposed to the incoming wind profile, and while not measured, it is obvious that a separation bubble is generated on its top. However, it is known that CFD models with K- ϵ closure often fail to resolve the separation bubble properly ([17]), and K_d is also overestimated at the leading edge. This will cause underestimated velocities behind the building in question, the

effect of which is still present in Fig. 4.4.

- Measurement shows strong backflow on the square up to rooftop level (VP6); simulation estimates it just until $0.7h$. Streamlines indicate a vortex with horizontal axis dominating the whole square. Similar backflow can be seen behind the downstream building block.
- Building inner yards have despite their small size street-canyon-like horizontal vortices (VP22, VP21).

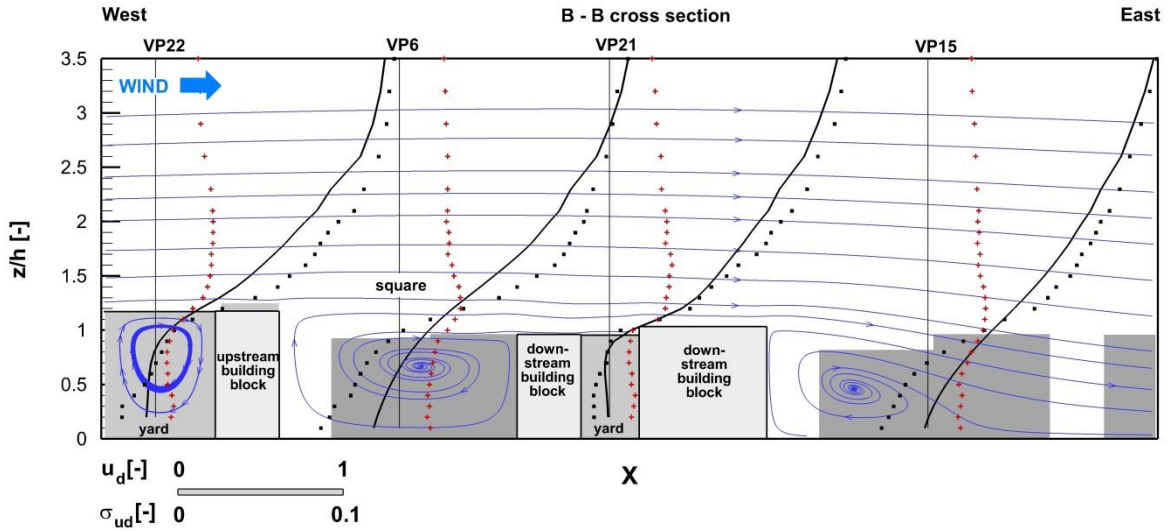


Fig. 4.4: Flow field at western wind direction along the square (B – B cross section of Fig. 4.1). Black squares and continuous lines: normalised stream wise mean velocity u_d from measurement and simulation, crosses: normalised velocity standard deviations σ_{ud} from wind tunnel measurement. Streamlines are from simulation. Please note that profile VP21 is about 30 m off-plane towards south.

At both wind directions, turbulent kinetic energy K_d is almost constant above rooftop level (with an occasional, slight maximum at $1.2 - 1.7 h$ height), and decreases underneath rooftop level towards the ground by about one third. In building inner yards, its value goes down to less than one half.

The vertical velocity profiles in the connecting streets indicate the behaviour already known from previous investigations:

- While above rooftop the wind direction differs not much from the incident one, in the streets the flow is channelled, and wind direction turns parallel with street axis (VP 8, 9, 10, 18, 23 at northern wind, VP9, 18, 19 at western wind). Flow perpendicular or even opposite to the incident wind direction can be observed (Fig. 4.5, left).

- From the 13 profiles measured in the connecting streets, despite the perpendicular above-roof wind direction at many of them, only few show the presence of clear street canyon vortices. This is unsurprising as canyon width to height (w/h) ratio is about 0.5. Rather, according to the results of [18], two smaller vortices above each other can be expected in street canyons.

However, the two effects, channelling and street canyon vortex, give combined helical vortices in several cases like the one observed in VP8 at western wind (Fig. 4.5, right).

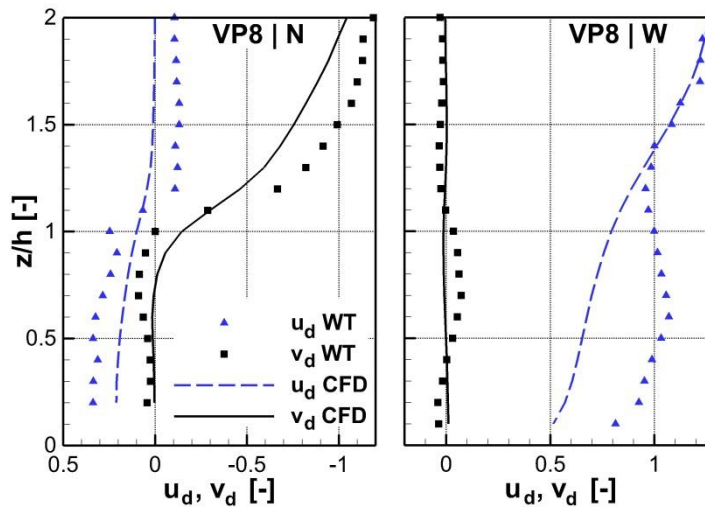


Fig. 4.5: Vertical profiles of both velocity components u_d and v_d in profile VP8 in a connecting street at northern and western wind direction.

4.3 Flow field in horizontal planes

The normalised horizontal velocity magnitude v_{md} at northern wind direction on the three horizontal planes can be seen in Fig. 4.6, with wind tunnel data in the left and CFD data in the right column. Fig. 4.7 shows the normalized turbulent kinetic energy distributions in the same wind direction. Fig. 4.8 and 4.9 show the same variables but in western wind direction. Scalar variables are interpolated from the measurement points onto the planes using inverse-distance interpolation, and streamlines are integrated from the velocity vectors.

CFD simulations only resolve the vortex in the north-eastern corner of the square, although in smaller size, and only visibly at $0.25 h$ height. While the other vortices are suppressed, which gives a velocity field much more in line with the incident wind direction, the magnitude of velocity is about the same as in the measurement.

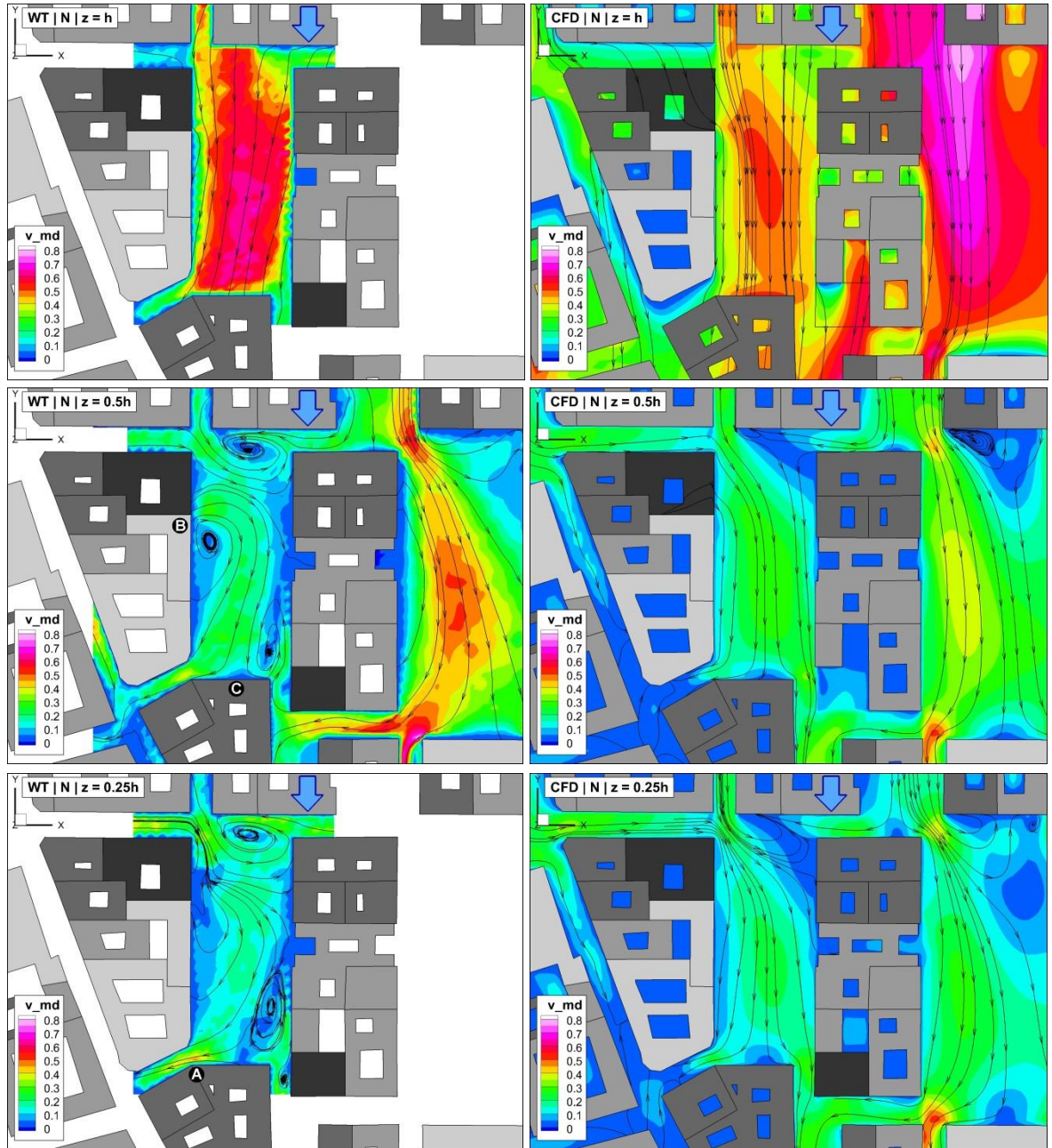


Fig. 4.6: Normalized horizontal velocity magnitude v_{md} distributions on three horizontal planes at northern wind direction. Left column: wind tunnel measurement; right column: CFD simulation.

Turbulent kinetic energy K_d (Fig. 4.7) in the simulation is about 2/3 of that measured in the wind tunnel on average. Due to the stagnation point anomaly ([17]) CFD results for K_d give huge peaks near building leading edges, which are not there in the measurement. Despite these discrepancies, the value of K_d is well predicted in many locations, like building corners.

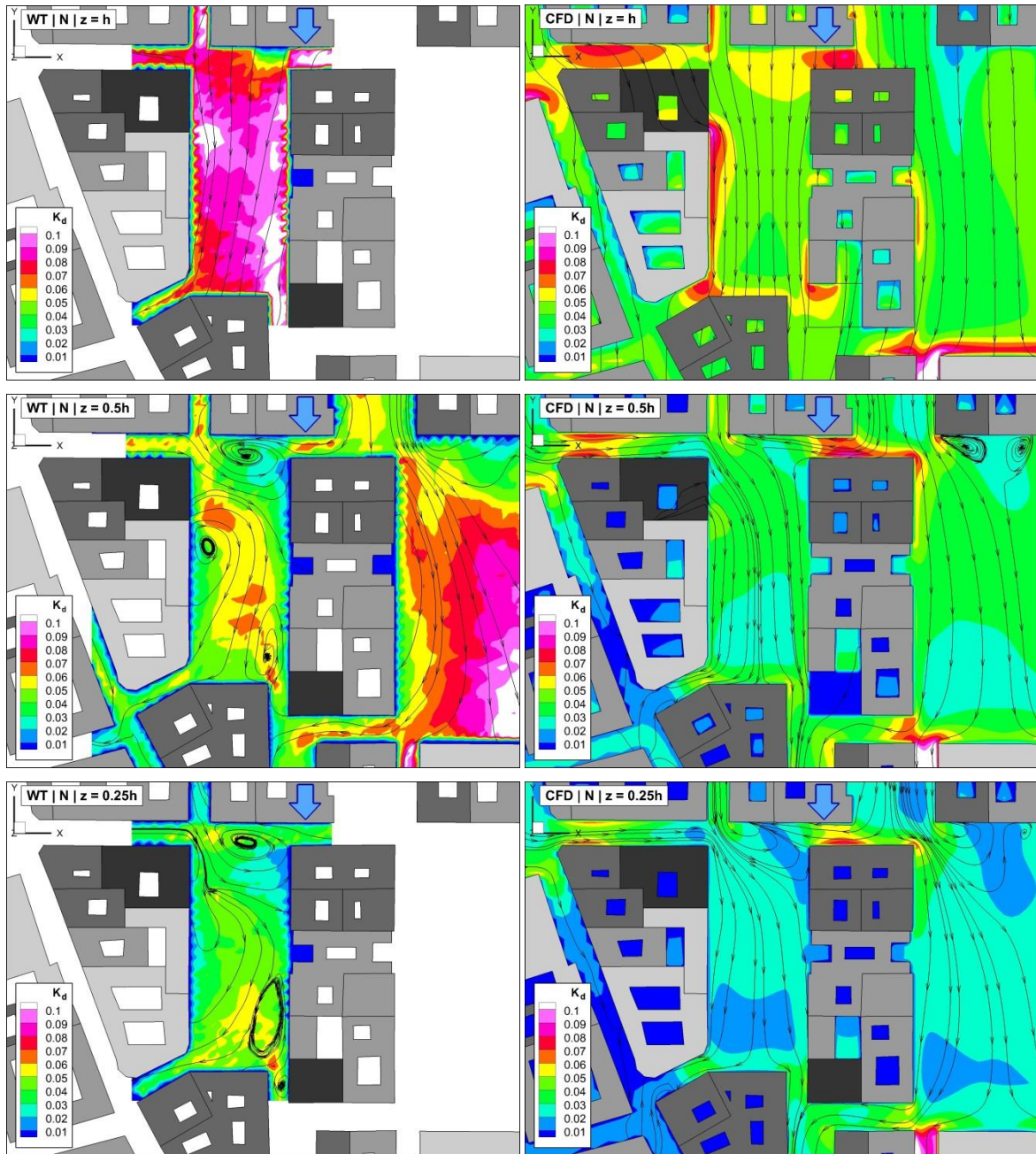


Fig. 4.7: Normalized turbulent kinetic energy K_d distributions on three horizontal planes at northern wind direction. Left column: wind tunnel measurement; right column: CFD simulation.

The velocity and turbulent kinetic energy distributions at western wind direction on two horizontal planes can be seen in Fig. 4.8 and 4.9. The streamlines show that:

- The street marked by D is blocked entirely by a corner vortex.
- Most of the air passes through the square flowing from the street marked by A towards the street marked by E in Fig. 4.8.
- A smaller portion of it enters the separation bubble which is formed behind the

western building block (marked by B in Fig. 4.8). However, this is modified by the high velocity inflow at the NW corner to a helical vortex, which moves air towards the southern part of the square, and pushes air through the southern connecting streets even opposite to the incident wind direction. The high velocity inflow is caused by a conical arrangement of buildings which act as a contractor cone (mark D in Fig. 4.1)

Thus, despite the wind coming from the West, there is a significant north to south convection in the square. It is remarkable that the flow field is very similar to that in a street canyon at slanted wind direction ([19]) with a huge street canyon vortex superposed to a velocity component along the street canyon.

The streamlines from the CFD results shown in the right column of Fig. 4.8 indicate much less air transport towards south and thus, two similar sized contra rotating vortices are evolved in the square. Surely one of the causes for the significantly different flow field in the CFD results is the massive underestimation of the inflow velocity in the mentioned street (A in Fig. 4.8). This can be seen also in the vertical profile VP8 (Fig. 4.5, right). This velocity underestimation is very likely a consequence of stagnation point anomaly and very high simulated K_d in the mentioned street (A in Fig. 4.9). While we were not able to measure the wind field at the western mouth of this street (mark D in Fig. 4.1), it is supposed that the CFD simulation fails to resolve those separation bubbles, which develop on the buildings bordering the Danube River and are thus responsible for the speed-up effect in this street.

The level of turbulent kinetic energy calculated by CFD is similar to that in northern wind direction (thus, underestimating the measurements) and also distorted by stagnation point anomaly, although the low of K_d downstream the western block is properly predicted (see mark B in Fig. 4.9). There is almost no difference in average K_d values at $0.25h$ and at $0.5 h$.

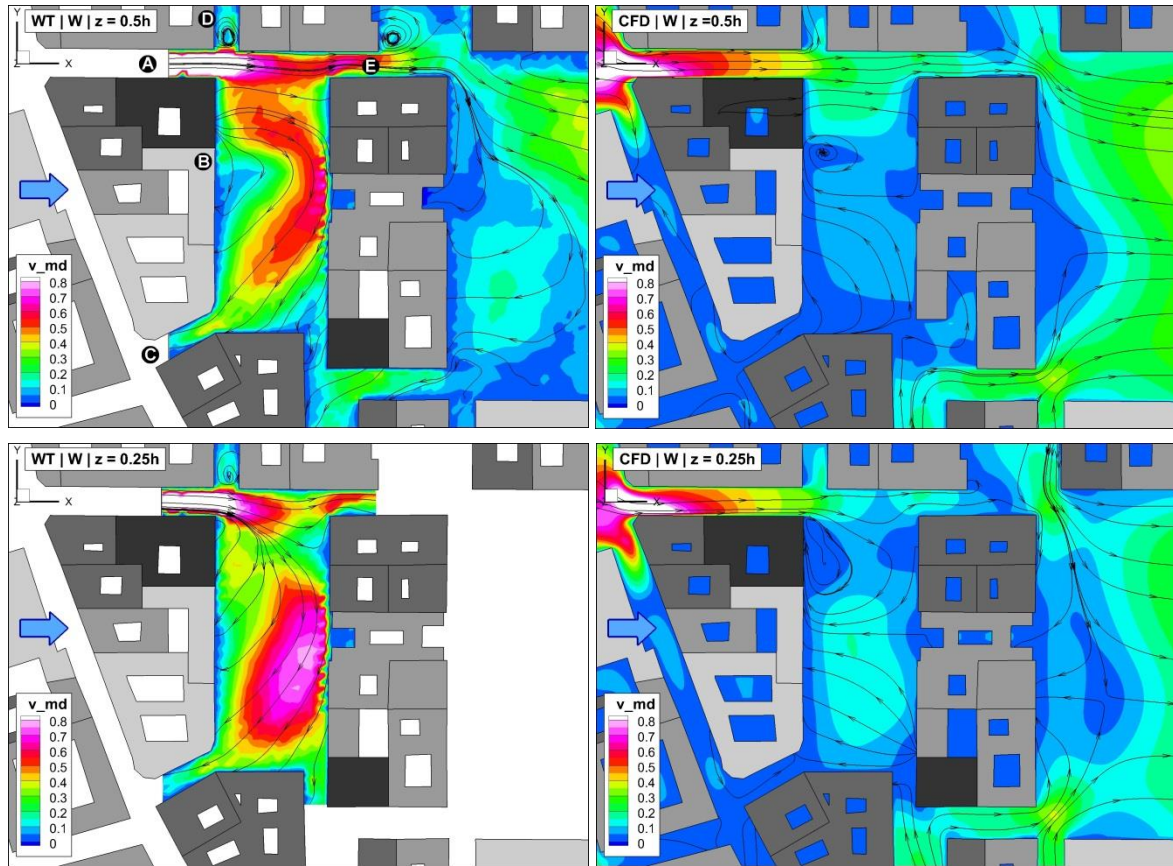


Fig. 4.8: Normalized horizontal velocity magnitude v_{md} distributions on two horizontal planes at western wind direction. Left column: wind tunnel measurement; right column: CFD simulation.

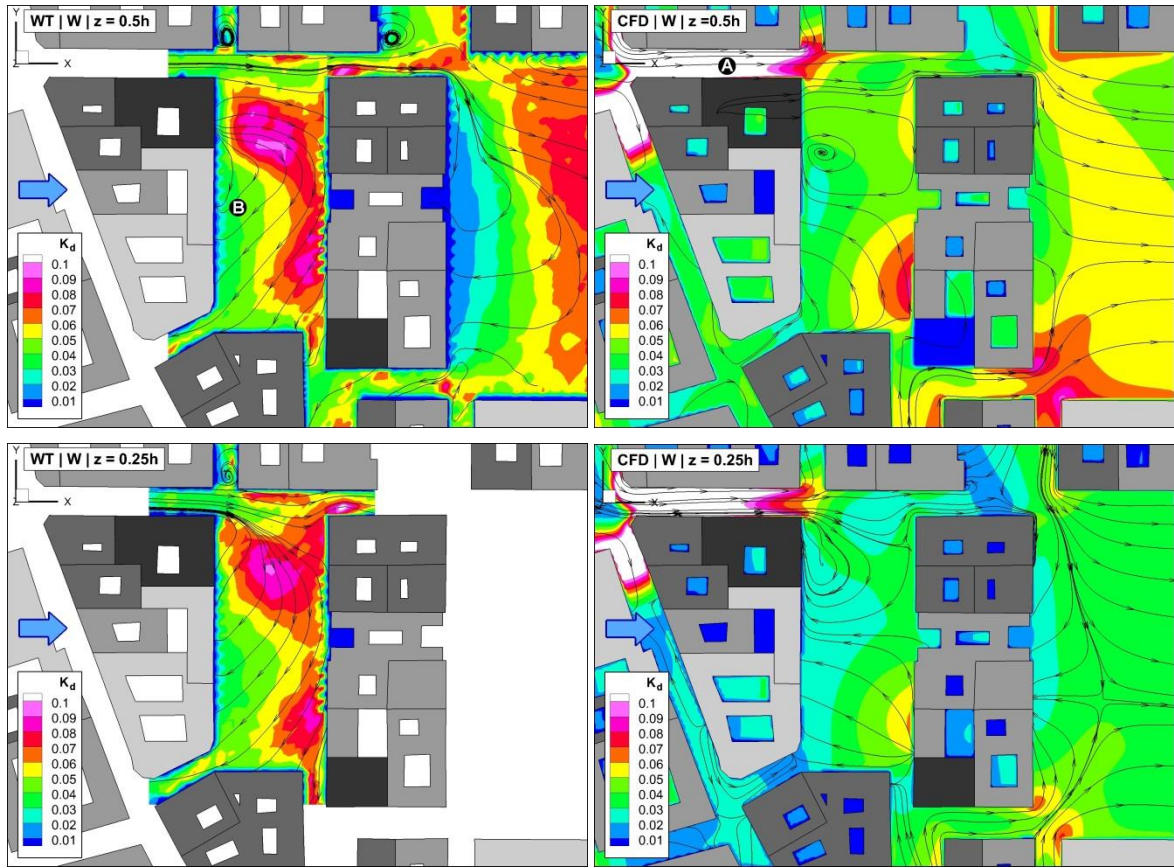


Fig. 4.9: Normalized turbulent kinetic energy K_d distributions on two horizontal planes at western wind direction. Left column: wind tunnel measurement; right column: CFD simulation.

4.4 Three-dimensionality of the flow

Because of the vertical arrangement of the LDV probe under floor, we were not able to measure the vertical velocity component w directly. However, the measured mean horizontal flow field ($\underline{v}_{hor d}$) let us calculate the vertical velocity gradient based on the continuity equation:

$$-\frac{\partial w_d}{\partial z} = \left(\frac{\partial u_d}{\partial x} + \frac{\partial v_d}{\partial y} \right) = \text{div}(\underline{v}_{hor d}). \quad (4.1)$$

On the horizontal ground surface, obviously w must be 0. At a small height, slightly above the ground surface, vertical velocity, if there is any, must decrease towards the surface. Thus we can distinguish three cases for the w velocity component in horizontal planes near the ground:

- a. the flow is horizontal ($w = 0$) thus $\partial w / \partial z = 0$ and $\text{div}(\underline{v}_{hor d}) = 0$

- b. vertical inflow occurs ($w < 0$), flow towards the ground must be decelerated ($\partial w / \partial z < 0$) thus the flow field in horizontal plane will diverge ($\text{div}(v_{\text{hor } d}) > 0$)
- c. vertical outflow occurs ($w > 0$), flow accelerates upwards ($\partial w / \partial z > 0$) and the horizontal flow field will converge ($\text{div}(v_{\text{hor } d}) < 0$).

In conclusion, positive values of the horizontal divergence near the ground are related to updrafts, while negative values indicate downdrafts. The relationship is demonstrated at $0.25h$ height in plot a and b of Fig 4.10 using CFD results at northern wind direction. Divergence calculated from wind tunnel data in northern and western wind direction is shown in plot c and d of Fig 4.10. The results are obviously subject of considerable noise; however, the major spots of vertical air movements are clearly recognizable.

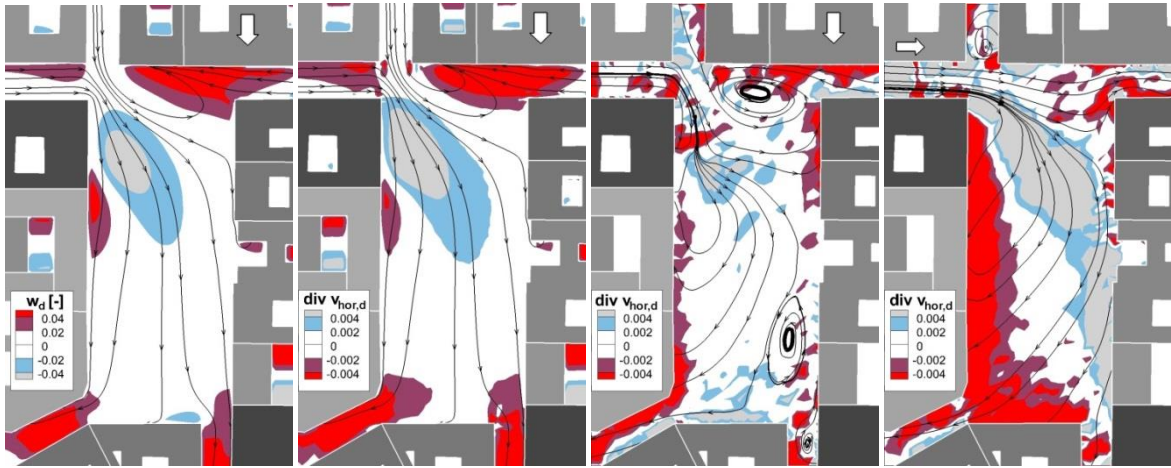


Fig. 4.10: Vertical air movements in the square at $0.25 h$ height. Reddish colours: updraft, light colours: downdrafts. Values close to 0 are blanked. From left to right: (a) CFD simulation: normalized vertical velocity in northern wind direction; (b) CFD simulation: $\text{div}(v_{\text{hor } d})$ in northern wind direction; (c) Wind tunnel measurement: $\text{div}(v_{\text{hor } d})$ in northern wind direction, (d) Wind tunnel measurement: $\text{div}(v_{\text{hor } d})$ in western wind direction.

- In northern wind direction updrafts in the wake of the northern (upstream building block) and at building walls of the north-western corner can be seen, as well as a downdraft in the northern centre of the square caused by the inflow at the northeast corner.
- In western wind direction the magnitude of divergence is significantly larger and shows the single, massive helical vortex dominating the square, causing updrafts on the western and downdrafts on the eastern side.
- Up- and downdrafts can be seen in many of the connecting streets in both wind directions. Considering the direction of streamlines in the streets, these signal weak helical vortices along the street axis.

4.5 Square vs. street canyons

For the generalised, quantitative description of the flow in urban squares, the averaged vertical velocity profiles in the square (VP 3-7) were compared with the averaged profiles measured in the connecting streets (VP 1, 8, 9, 10, 18, 23), to see whether there is any difference. Profiles are also averaged for both measured wind directions.

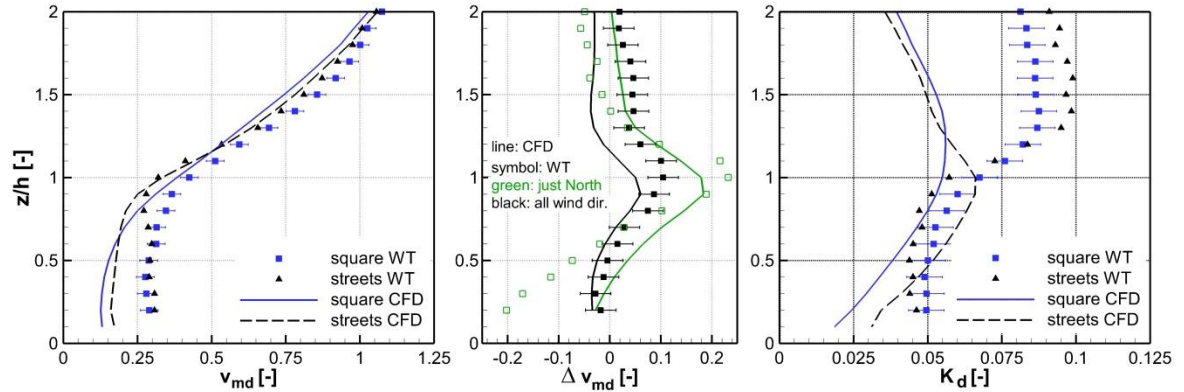


Fig. 4.11: Averaged vertical profiles in the connecting streets (VP 1, 8, 9, 10, 18, 23) vs. profiles VP 3-7 in the square. Left: average velocity magnitude v_{md} ; centre: difference in average velocity magnitude $\Delta v_{md} = v_{md}(\text{square}) - v_{md}(\text{streets})$; right: turbulent kinetic energy K_d

In Fig. 4.11, left, the profiles of mean horizontal velocity magnitude v_{md} profiles are shown.

- CFD and wind tunnel profiles agree very well above rooftop level.
- Below rooftop height h , the average velocity is about 0.3 and almost constant. CFD results under predict this value, and remember the horizontal plane plots in western wind direction (Fig. 4.8)
- v_{md} in the square and in streets differ somewhat between $0.5-1.5 h$. This is caused by a speed-up above $0.5 h$ height in the square. The difference of the two can be seen in the centre plot of Fig. 4.11. Green colours in this plot show that the speed-up is much stronger in northern wind direction, when wind blows along the square's long axis. The explanation for this speedup is that the ABL flow above rooftop level can intrude into the upper layer of the square, and accelerate the flow, while this is not possible in street canyons.

In Fig. 4.11, right, the profiles of turbulent kinetic energy K_d show:

- that K_d in the square is higher below and lower above rooftop level when compared with streets. The explanation for the former is that vicinity of walls damps turbulent

fluctuations in streets much more than in the square. The latter can be explained by the larger distance to walls and edges in the square. Because the highest K_d values are expected in the shear layer above building edge separations, in profiles measured in streets, close to building edges, K_d must be higher above rooftop level.

- CFD predicts K_d in the same magnitude below rooftop level, but the curves are steeper and run below the measured K_d values.

CFD predicts K_d wrongly to be larger in streets than in the square below rooftop level. This is a consequence of the stagnation point over prediction of K_d explained earlier.

5 CONCLUSIONS

A small-scale model of the quarter surrounding József Nádor Square in downtown Budapest was prepared and with this 1:350 scale model flow field measurements were carried out in a Göttingen-type wind tunnel. The measurement data were compared to CFD simulation results. The urban square investigated, although slightly simplified in geometry, can be seen as a test case of high complexity level, similar to real urban areas. Despite this fact, the results allow more generalized conclusions to be made, which can be valid for squares of similar size:

- Average wind speed is growing only at the upper half of the square (near rooftop level), while near ground level it is almost the same, even decreasing slightly, when compared with the neighbouring street canyons. Some building corners with local speed-up form an exception. Turbulence is increased slightly in the square. These differences in both wind speed and turbulence, however, do not exceed 15%.
- The square influences flow in the connecting streets as well. Flow is induced in these by the developing flow structures in the square even in perpendicular or opposite direction to the approach wind. CFD results suggest that wind speed can increase up to 50% in the connecting street compared to a case in which no square is present.
- In both investigated wind direction distinct and complex flow fields were observed, as a result of superposition of advection, corner vortices, separation bubbles, street canyon and horseshoe vortices. These average flow fields are supposed to have major influence on the dispersion of pollutants, an objective of future studies on the square.
- For the study of flow unsteadiness the representation of two-dimensional time-resolved data in the form of wind roses (polar area diagrams) placed over the average flow field proved to be a useful tool. Wind roses could be classified according to their shape to identify the spots, where turbulence is non-isotropic or flow direction is alternating, and thus, pollutant dispersion is influenced.
- MISKAM CFD model was applied to the case geometry in both wind directions. The estimation of the measured flow fields is reasonable, when average velocity magnitude comes into question. Despite the large difference in the incoming

turbulence, K_d is only under predicted by about one third on average.

- However, there are certain non-negligible flaws of the simulation, like smaller or fully suppressed vortices in the mean flow field on the square. These errors can be traced back to the commonly known turbulent kinetic energy over prediction of K- ϵ type closures in stagnation points.
- The flow intermittency effects not resolved by MISKAM are a consequence of the steady RANS approach. As e.g. [20, 21] have shown, Large-Eddy simulation (LES) can give superior results in this regard, although at the cost of much higher computational time and power requirements, which are mostly unavailable at the moment among the users of CFD models in the regulatory / air quality field of application.

BIBLIOGRAPHY

- [1] A. GADILHE, L. JANVIER, G. BARNAUD (1993): Numerical and experimental modelling of the three-dimensional turbulent wind flow through an urban square, *Journal of Wind Engineering and Industrial Aerodynamics*, Vol.46-47, pp.755-763.
- [2] M. PARRA, J. SANTIAGO, F. MARTÍN, A. MARTILLI, J. SANTAMARÍA (2010): A methodology to urban air quality assessment during large time periods of winter using computational fluid dynamic models, *Atmospheric Environment*, Vol.44, Issue 17, pp.2089-2097.
- [3] I. BASTIGKEIT (2011): Erzeugung von Validierungsdaten für wirbelaflösende mikroskalige Strömungs- und Ausbreitungsmodelle, PhD thesis, University of Hamburg
- [4] Á. BUDA (2014): A József Nádor tér és környékének átszellőzési és légszennyettségi vizsgálata MISKAM CFD szoftverrel. BSc thesis, Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Department of Fluid Mechanics
- [5] M. BALCZÓ, T. LAJOS (2012): Active reduction of air pollutant concentrations at an urban square, Proceedings of the ICUC 8 Conference, Dublin, Ireland, August 6-10, 2012
- [6] P. MANNINGER (2011): Experimental investigation of flow in urban squares. Final Project, Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Department of Fluid Mechanics
- [7] M. J. VARGA (2011): Influence of urban squares on air pollutant dispersion. Final Project, Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Department of Fluid Mechanics
- [8] I. GORICSÁN (2005): Atmoszférikus határrétegben lejátszódó áramlási és transzportfolyamatok. PhD Dissertation, Budapest
- [9] ESDU (1972): Characteristics of wind speed in the lower layers of the atmosphere near the ground: strong winds (neutral atmosphere), Engineering Sciences Data Unit 72026.
- [10] VDI 3783 PART 12 (2000): Environmental meteorology, Physical modelling of flow and dispersion processes in the atmospheric boundary layer, Application of wind tunnels, VDI/DIN-Handbuch Reinhaltung der Luft, Band 1b
- [11] 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.

-
- [12] P. KLEIN, B. LEITL, M. SCHATZMANN (2011): Concentration fluctuations in a downtown urban area. Part II: analysis of Joint Urban 2003 wind-tunnel measurements, *Environmental Fluid Mechanics*, Vol.11, Issue 1, pp.43-60.
- [13] J. FRANKE, A. HELLSTEN, H. SCHLÜNZEN, B. CARISSIMO (2007): Best practice guideline for the CFD simulation of flows in the urban environment, COST Office Brussels
- [14] M. BALCZÓ, C. GROMKE, B. RUCK (2009): Numerical modeling of flow and pollutant dispersion in street canyons with tree planting, *Meteorologische Zeitschrift*, Vol.18, Issue 2, pp.197-206.
- [15] J. EICHHORN (2011): MISKAM - Manual for version 6, Giese-Eichhorn, Wackernheim, Germany
- [16] H. OLESEN, A. BAKLANOV, J. BARTZIS, F. BARMAS, R. BERKOWICZ, R. BRZOZOWSKI, R. BUCCOLIERI, B. CARISSIMO, A. COSTA, S. DI SABATINO, G. EFTHIMIOU, J. FRANKE, I. GORICSÁN, A. HELLSTEN, M. KETZEL, B. LEITL, R. NUTERMAN, E. POLREICH, R. TAVARES (2008): The MUST model evaluation exercise: Patterns in model performance, *Croatian Meteorological Journal*, Vol.43, No.43, pp.403-408.
- [17] M. KATO, B. LAUNDER (1993): The modelling of turbulent flow around stationary and vibrating square cylinders, Ninth Symposium on Turbulent Shear Flows, Kyoto, Japan, August 1993, 10.4.1-10.4.6
- [18] A. KOVAR-PANSKUS, P. LOUKA, J. -F. SINI, E. SAVORY, M. CZECH, A. ABDELQARI, P. MESTAYER, N. TOY (2002): Influence of geometry on the mean flow within urban street canyons - A comparison of wind tunnel experiments and numerical simulations, *Water, Air and Soil Pollution: Focus*, Vol.2, Issues 5-6, pp.365-380.
- [19] K. CZÁDER, M. BALCZÓ, J. EICHHORN (2009): Modelling of flow and dispersion in a street canyon with vegetation by means of numerical simulation, Proceedings of the XXIII. MicroCAD International Scientific Conference, Miskolc, Hungary, 19-20 March 2009, 47-52
- [20] M. O. LETZEL, M. KRANE, S. RAASCH (2008): High resolution urban large-eddy simulation studies from street canyon to neighbourhood scale, *Atmospheric Environment*, Vol.42, Issue 38, pp.8770-8784.
- [21] H. NAKAYAMA, B. LEITL, F. HARMS, H. NAGAI (2014): Development of local-scale high-resolution atmospheric dispersion model using large-eddy simulation. Part 4: turbulent flows and plume dispersion in an actual urban area, *Journal of Nuclear Science and Technology*, Vol.51, Issue 5, pp.626-638.