Wind flow modeling in urban areas through experimental and numerical techniques
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Published: 11/04/2017

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Wind flow modeling in urban areas through experimental and numerical techniques

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de rector magnificus prof.dr.ir. F.P.T. Baaijens, voor een commissie aangewezen door het College voor Promoties, in het openbaar te verdedigen op woensdag 11 april 2017 om 16.00 uur

doors

Alessio Ricci

geboren te Atri, Italië
Het onderzoek of ontwerp dat in dit proefschrift wordt beschreven is uitgevoerd in overeenstemming met de TU/e Gedragscode Wetenschapsbeoefening.
Wind flow modeling in urban areas through experimental and numerical techniques

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Eindhoven University of Technology
University of Genoa
April 2017
The research presented in this thesis was performed within the Department of Civil, Chemical and Environmental Engineering (DICCA) of the University of Genoa (Italy), and the unit of Building Physics and Services (BPS) at the Department of Built Environment of the Eindhoven University of Technology (The Netherlands), as part of a double-degree agreement between both universities.

A catalogue record is available from the Eindhoven University of Technology Library

ISBN: 978-90-386-4258-1
Bouwstenen 226
NUR: 955

Cover and interior design by Alessio Ricci
Printed by TU/e print service – DMX print, Eindhoven, The Netherlands

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‘Human behavior flows from three main sources: desire, emotion, and knowledge’.

(Plato)
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Acknowledgments

A journey full of great emotions is drawing to a close. This thesis represents the outcome of a wonderful and fruitful collaboration between two universities, two research groups of professional people and fantastic friends. It was more than a research project, it was a challenge for each person involved. I would like to dedicate this section to all the people that supported me and shared with me this incredible journey.

First of all, I would like to thank my supervisors dr.ir. M.P. Repetto, dr. M. Burlando and prof.dr.ir. B. Blocken, who gave me the opportunity of joining the double PhD program.

I want to express my gratitude to my Italian supervisors, dr.ir. M.P. Repetto and dr. M. Burlando, fantastic mentors and very kind people, who supported me during the entire project. With them I wrote my first ISI journal paper, with them I attended my first international conference; they took care of an aspirant PhD student and they leave today a hopeful researcher. You have the credit to have opened a big door in my career, to have believed in me, to have given me the first big chance.

I am really grateful also to my “Dutch” supervisor, prof.dr.ir. B. Blocken, who gave me the opportunity to work with his outstanding research group. As my Italian supervisors, you bet on me and probably you won. Many thanks for your advice, for sharing your experience and knowledge with me, for giving me the possibility to attend several international conferences around the world, for teaching me the way to write journal papers and for maximizing my potential. I am also really grateful to my daily supervisor dr. Ivo Kalkman for his valuable work, for his comments, suggestions and for supporting me during the two years spent at TU/e.

I would also like to thank all the members of my Committee, prof.dr. Mark Sterling, prof.dr.ir. GertJan van Heijst and dr.ir. Giuseppe Piccardo for carefully reading my thesis and giving me constructive comments.

I am also grateful to the all the members of the Italian Committee of my PhD course at the University of Genoa: prof.dr. R. Massabò, prof.dr. G. Solari, prof.dr. S. Lagomarsino, prof.dr. L. Gambarotta, dr.ir. A. Brencich, dr.ir. L. Carassale, dr. arch. C. Calderini, dr.ir. L. Pagnini, dr.ir. Piccardo, dr.ir. Repetto, dr. M. Burlando,
dr. ir. S. Cattari, dr. ir. F. Tubino, dr. ir. I. Monetto, dr. ir. M. Lepidi. I really appreciated your suggestions which made my research project scientifically more robust. I had hard time with you, but today I can be proud of my work also thanks to your precious help.

During my first three years of PhD career, I had the chance to spend part of my time in teaching and tutoring Bachelor and Master Students of the Civil Engineering course at the University of Genoa. I am grateful to prof. dr. G. Solari, for giving me the opportunity to stay at his side during the Structural Engineering lectures and examinations. It was a honor for me.

I am also grateful to dr. ir. M. Lepidi, who gave me the opportunity to teach the Structural Mechanics course at the Naval Architecture and Electrical Engineering courses of the University of Genova. For the first time, I held a course and I examined 156 students from different backgrounds. It is fantastic to come back in Genoa nowadays, walk inside the university and spend few minutes talking with your former students. I will never forget those great moments.

I also want to express my gratitude to A. Freda, a valuable assistant researcher, a very professional wind tunnel technician, and a sincere friend. It was a dream for me to work in a wind tunnel. Thanks for staying close to me today, this work is also yours, with its own strengths and its weaknesses.

I would like to express my special thanks to the “physicists” of the DICCA: M. Burlando, M. Tizzi, M. Pizzo and P. De Gaetano. Each of you gave a great contribution to this research project.

I am also thankful for the administrative support of the secretaries in Genoa and Eindhoven as well. You made everything easier.

Many thanks to all my former and present PhD colleagues of the University of Genoa, with whom I shared part of my time during my Italian PhD: Mirko, Lorenzo B., Lorenzo S., Daria, Stefy, Davide, Alberto, Chiara, Ilaria, Margherita, Margherita P., Michela M.B., Michela R., Cung, Salvatore, Daniela, Jamil, Hossein, Abdelgalil.

A special thanks also to Lorenzo and Mirko, two outstanding colleagues, two funny guys, my best friends in Genoa, with whom I spent memorable moments.

I would like also to thank all my former and present colleagues of the Urban Physics and Services research group: Rubina, Jorge, Antonio, Xinrong, Alessandro, Hamid, Twan, Wendy, Adelya, Yasin, Katarina Kosutova, Raffaele, Samy, Feiyu, Alex, Olga, Fabio, Nestoras, Rahim, Zahra, Anto, Giacomo, Mattia, Thijs, Xing, Rob, Claudio, Argyrios, Gerson, Paul, Luyang, Qiang, Baifeng, Wei. Special thanks
to my three deskmates, Katarina, Samy and Karin, to stand my daily complaints. You will miss me. None like me will seat down close to you in the future. Special thanks also to Raffaele, my right-hand man - my father - my mother - my brother - in Eindhoven. I could write more and more and more about our days in Eindhoven, but you know, “I don't have time”. Thank you very much for all my friend!

I would also like to thank other former and present colleagues and friends in Eindhoven: Benedetto, Zara, Rick, Katarina Katić, Karin, Basar, Isabella, Emy, Vojta, Ignazio, Rajesh, Sanket, Davide, Veronica, Luca, Chiara, Riccardo, Angela and Christos. With you having a conversation at the coffee machine, playing football or just sharing a cup of coffee was really pleasant.

Many thanks also to my Italian dream team in Eindhoven: Benedetto, Alessandro, Raffaele and Fabio. We made each other our life in Eindhoven wonderful.

Although I have spent the last two years of my life in Netherlands, I have never forgotten my roots. If today I can celebrate this special moment I have to thank above everything my whole family. Nothing would have been possible without the help of my father, my mother, my brother and my special grandmother. You gave me the best present of my life, the ambition.

Last but not least, I would like to thank my special friend, as well as my adviser, my girlfriend Valentina. Someone in the past said “behind every great man there’s a great woman”. In the last months when I was at the edge of breaking, you saved me many times, and now that the sea is smooth I can say that there is no more appropriate quote to define your role in my life. Thank you!

‘...you can't connect the dots looking forward; you can only connect them looking backward. So you have to trust that the dots will somehow connect in your future’. (Steve Jobs)
Summary

Wind flow modeling in urban areas through experimental and numerical techniques

Wind flow in urban areas governs a large number of important issues such as pollutant dispersion, wind-driven rain, pedestrian wind comfort, energy performance of buildings and urban wind energy. However, the complex morphology of cities, which gives rise to a variety of complex flow phenomena such as separation, recirculation and local thermal effects, renders the description of wind flow in urban areas very difficult.

According to the state of the art knowledge of the topic, two different approaches to investigate urban flows are nowadays commonly adopted for wind engineering applications: Computational Fluid Dynamics (CFD) numerical modeling and wind tunnel testing. In the last decades several studies have focused on wind flow numerical modeling over random urban like obstacles, uniform and staggered building arrays, idealized urban surfaces, a semi idealized urban canopy, and actual urban environments. Many uncertainties and errors are related to geometrical model precision, inflow conditions, turbulence models, discretization schemes and numerical approaches (RANS, LES, DNS). However, it is currently not known to which extent the different uncertainties can affect the experimental and numerical results.

The objective of the present thesis is the assessment of the accuracy and suitability of wind tunnel and CFD techniques to predict wind flow in an urban environment. Both experimental tests and numerical simulations can help to quantify the impact of different parameters considered in order to improve the reliability of the results.

For this purpose, a district of Livorno city (Italy) called “Quartiere La Venezia” is chosen as a case study. This district exhibits architectural and urbanistic features typical of many Italian historical centers. The methodology adopted in this work consists of full scale measurements, wind tunnel tests and CFD simulations. Wind speed in selected area is monitored by means of a series of instruments (five ultrasonic anemometers and one LiDAR station), installed in the framework of the European Projects “Wind and Ports” (2009 - 2012) and “Wind, Ports and Sea” (2014 - 2015). Wind tunnel tests are performed on a reduced scale model (1:300) at the University of Genoa. Data measured by the anemometric stations, placed in the
port of Livorno, are used to generate a target for the vertical mean velocity profile employed in the wind tunnel tests. The results, in terms of mean velocity profiles, are used as a benchmark to validate the numerical simulations. A portion of the wind tunnel section is reproduced by the computational domain and 3D steady state RANS simulations are carried out on the same reduced scale model in order to quantify the impact of different numerical parameters: the geometrical simplifications, the inflow conditions, the turbulence models and the aerodynamic roughness lengths.

Experimental and numerical results are compared in terms of mean wind velocity, \( U(z) \), profiles and turbulent kinetic energy, \( k(z) \), profiles at the same measuring positions. Finally, the statistical correspondence between experimental and numerical results for all parameters considered is quantified by means of four validation metrics: fractional bias (FB), normalized mean square error (NMSE), correlation coefficient (R) and a fraction of data within a factor of 1.3 (FAC1.3). Both experimental and numerical results show a strong reduction of wind velocity in the canopy layer, in particular for levels lower than 1.5 times the mean height of the buildings \( (h_b) \). For the case and ranges investigated, geometrical simplifications are shown to have a larger effect on the results than inflow conditions, turbulence modeling approach and aerodynamic roughness height \( (\zeta_0) \).
Chapter 1
Introduction

1.1 Background

Climate change, smart cities development and energy saving are some of the major challenges that humankind will face in the coming years. All these issues are of great relevance for people living in urban areas, and this is also the reason why the interest in the field of urban physics is rapidly growing. Urban physics, in general, encompasses many different research topics like air quality and pollutant dispersion, pedestrian wind comfort, indoor and outdoor ventilation, wind energy in buildings, etc. (Moonen et al., 2012; Blocken 2015a). The factor common to all of these topics is the role that wind flow plays in them. From this consideration follows the importance of being able to model the wind flow in urban areas properly (Murakami, 1997; Stathopoulos, 1997; Baker, 2007; Solari, 2007; Meroney and Derickson, 2014; Blocken, 2014, 2015a; Meroney, 2016; Tominaga and Stathopoulos, 2016; Moonen et al., 2012).

The energy (kinetic and thermal) driving wind flows at the urban scale can be introduced by different sources: the forcing at larger scales (e.g. mid latitude Rossby waves, baroclinic instabilities inside extratropical cyclones), the topography through the formation of gravity waves (when the atmosphere is stable) or convection (when the atmosphere is unstable) because of air topography interaction, the thermal contrast between land and sea that governs the breezes, the surface roughness, the sensible and latent heat fluxes at the ground, etc. This tremendously complicates the problem of modeling urban wind flows as, in principle, atmospheric phenomena occurring at very different spatial and temporal scales, i.e. from the synoptic to the meteorological microscale, can greatly affect the resulting wind field (Orlanski, 1975). In addition, the definition of an urban area is not unambiguous. In fact, research in urban physics spans from the meteorological microscale $\beta$ (0.02 - 0.2 km), which is the scale of single elements (e.g. buildings or trees) in the urban canopy, to the meteorological mesoscale $\beta$ (20 - 200 km), which is comparable to the size of thunderstorms and tropical cyclones in the atmosphere (Orlanski, 1975).
Consequently, the forcing to the urban area also strongly depends on the spatial scale of the area under study.

Wind flow models are well established over flat open terrains, where the wind profile mainly depends on the roughness of the surface and on the thermal stratification. In contrast, wind flow in the urban environment is dominated by a variety of complex factors, such as the heterogeneous geometry of the areas and very local thermal effects. The region amidst and above the buildings in the so called urban boundary layer (UBL) is characterized by continuously changing surface roughness, so that the flow never reaches an equilibrium condition. According to Barlow (2014) the UBL consists of three main parts: the urban canopy layer (UCL), the layer up to the mean roof height where flow channeling occurs along the streets; the urban roughness sublayer (RS) defined as the region including the UCL where the buildings exert significant drag on the flow and the wind is highly spatially dependent; and the inertial sublayer (IS), above the RS, where turbulence is homogenous and fluxes vary little with height (Fig. 1.1). The situation is most complex within the UCL, where the streets give rise to canyoning effects which are strongly dependent on their orientation with respect to the incoming wind.

Although much research was performed on different aspects of urban flows, at present, the UBL is not yet fully understood (Chang and Meroney, 2003; Britter and Hanna, 2003; Baker, 2007; Fernando, 2010; Fernando et al., 2010). Several authors (Murakami, 1997; Baker, 2007; Solari, 2007; Fernando, 2010; Barlow, 2013; Blocken 2014; Meroney 2016) stress that the complexity of the UBL requires studies with multiple approaches, each having particular strengths and weaknesses. Two different approaches exist to investigate urban flows, which are nowadays quite extensively adopted for urban physics and wind engineering applications: numerical methods based on Computational Fluid Dynamics (CFD) and experimental methods based on either field measurements or reduced scale atmospheric boundary layer wind tunnel testing. From a mathematical point of view, both CFD and wind tunnel testing can be thought of as a boundary value problem, where the boundary conditions describe the large scale atmospheric forcing exerted at the outer limits of the urban model, while the model itself accounts for the local forcing,
e.g. due to surface roughness, topography, heat fluxes. Both high resolution numerical models and wind tunnel tests can help to identify basic processes.

1.2 Problem statement

Urban boundary layer development: Different techniques exist to describe the wind flow inside (in the UCL) and above urban canopies (in the RS and IS). Analytical models exist to describe the mean wind velocity profile within a horizontally homogeneous and vertically uniform dense canopy over flat ground (Inoue, 1963) and in sparse canopies (Wang, 2012 and 2014). However, analytical models do not apply to inhomogeneous urban canopies. In contrast, wind tunnel testing and CFD simulations are usually applied to study UCL flows in heterogeneous urban areas with irregularly distributed buildings, cavity type models of a single street canyon or simple building arrays (Kastner-Klein et al., 2001; Allegrini et al., 2013; Stabile et al., 2015), in more complicated arrays of simple obstacles (Ahmad et al., 2005), in a semi idealized urban canopy (Carpentieri and Robins, 2015) or in detailed urban model (Kastner-Klein and Rotach, 2004) (Fig. 1.2). Studies of the real urban atmosphere at full scale or reduced scale, i.e. wind tunnel tests, are extremely important as they can provide benchmark data for numerical modeling (Rotach, 1995; Eliasson et al., 2006; Wood et al., 2009; Niachou et al., 2008), even if they have to be used with care because they also can be affected by uncertainties due to the lack of spatial and time representativeness of single point measurements (Schatzmann and Leitl, 2011). From this point of view, the first goal
of this thesis is to provide a new experimental benchmark of the UCL and UBL in a real urban area, with geometrical and morphometric characteristics typical of many historical districts in Mediterranean cities.

Impact of computational parameters: In the last decades, much work was performed on the reproduction of wind tunnel tests by CFD simulations in order to improve the performance and better understand the strengths and weaknesses of both techniques (Murakami, 1993; Stathopoulos, 1997; Tominaga and Stathopoulos, 2013; Blocken, 2014; Meroney, 2016). As proposed by Moonen et al. (2006) and Calautit et al. (2014) the CFD domain can be constructed by modeling the geometry of the entire wind tunnel including the corner guide vanes, the diffuser and the contraction. However, this choice has a very high computational cost. The more common and less expensive technique that is widely adopted in urban physics and wind engineering aims to reproduce (a portion of) the wind tunnel test section (Fig. 1.3). Nevertheless, the associated computational uncertainties and errors related to geometrical model precision, inflow conditions, turbulence models, discretization schemes and numerical approaches (RANS, LES, DNS) are currently not known in detail (AIAA, 1998; ERCOFTAC, 2000; Oberkampf et al., 2004; AIJ, 2004; Franke, 2006; Versteeg and Malalasekera, 2007; Emory et al., 2013; Gorlé et al., 2015). In this project the deviations caused by four different computational parameters of 3D steady state RANS simulations performed on a selected case study are analyzed: the geometrical simplifications, the inflow conditions, the turbulence model and the roughness height.

Geometrical simplifications: In the last decades several studies have focused on numerical modeling of wind flow over geometrical features with different degrees
Introduction

of precision: random urban like obstacles (Xie et al., 2008), uniform and staggered building arrays (Coceal and Belcher, 2004; Xie and Castro, 2006; An et al., 2013; Razak et al., 2013), idealized urban surfaces (Cheng and Porté Agel, 2015), a semi idealized urban canopy (Hertwig et al., 2012), and actual urban environments (Hanna et al., 2006; Janssen et al., 2013; Montazeri et al., 2013; García Sánchez et al., 2014; Blocken et al., 2016). Geometrical simplifications are applied for three main reasons. The first reason is to reduce the computational cost and manufacturing cost (wind tunnel model) associated with highly detailed geometries. The second is that finest geometries with small details can lead to a deterioration of results in reduced scale wind tunnel testing because the assumption of Reynolds number independence, valid only for high Reynolds numbers (Uehara et al., 2003; Tominaga and Blocken, 2015), may be no longer true. The third is to avoid convergence problems and maximize numerical accuracy when a complicated geometry is reproduced using a comparatively small number of grid cells. It is unclear to what extent the different degrees of precision of urban models (both for CFD simulations and WT tests) affect the quality of results.

**Inflow conditions:** CFD simulation results of urban flow are extremely sensitive to the inflow conditions. As proposed by Moonen et al. (2006) and Calautit et al. (2014), when the entire wind tunnel is modeled by the computational domain, the wind flow can be directly generated by the fan that is explicitly included in the computational domain. In contrast, the commonly used approach is to reproduce

![Figure 1.3 Contours of the dimensionless wind speed (magnitude of the 3D velocity vector) in the empty wind tunnel: (a) in a horizontal plane at a height of 1.75 m above the test section floor; and (b) in a vertical plane along the test section center line; (c) enlarged view of the rectangle in subfigure a (figure by Moonen et al., 2006).](image-url)
only a portion of the test section of the wind tunnel. In this case, the inflow conditions have to be generated either by modeling the fetch of roughness along the test section or by measurement data if available. Mean wind velocity ($U$) and turbulence intensity ($I_u$, $I_v$, $I_w$) profiles are generally only measured along one vertical line placed in the middle of the test section either upstream or on the turntable. The above mentioned experimental data are important in the reproduction of inflow profiles (in terms of mean wind velocity $U$, turbulent kinetic energy $k$, and turbulence dissipation rate $\varepsilon$) corresponding to an atmospheric boundary layer by 3D steady state RANS simulations. Two different options for the description of $k$-$\varepsilon$ type inflow conditions are commonly used in literature, proposed by Richards and Hoxey (1993) and Tominaga et al. (2008), respectively. At present it is unclear how the choice of one of these two options affects the numerical results.

**Turbulence models:** Another interesting question is related to the effect of choice of turbulence model, which provides the closure equations for the RANS approach. The 3D RANS equations and the equations of $k$-$\varepsilon$ and $k$-$\omega$ turbulence models are discussed in Chapter 2. Several types of $k$-$\varepsilon$ and $k$-$\omega$ turbulence models are commonly employed to investigate topics such as pedestrian wind comfort around buildings (Mochida et al., 2002; Janssen et al., 2013; Montazeri et al., 2013), wind flow over complex terrain (Balogh et al., 2012; Blocken et al., 2015b), pollutant dispersion in urban environments (Gousseau et al., 2011a,b; Cui et al., 2014; Blocken et al., 2016), cross ventilation (Ramponi and Blocken, 2012a,b; Perén et al., 2015a,b) and convective heat transfer for external building surfaces (Defraeye et al., 2010; Karava et al., 2011; Montazeri et al., 2015). Therefore, as stated by Blocken (2014), the list of computational studies performed in the last decades in various topics of urban physics and wind engineering is huge. Although in the last decades, researchers have given specific indications and guidance about the use of turbulence models for different urban physics and wind engineering applications, it is still unclear how sensitive the numerical results are to different turbulence models used to simulate the urban environment (Oberkampf et al., 2004). In the present thesis the impact of different turbulence models on 3D steady state RANS simulation results is assessed in terms of deviations in mean velocity, yaw and pitch angles.

**Roughness height:** The surface roughness imposed at the bottom of the computational domain and at the walls of the urban model may be a critical uncertainty for CFD simulations. As stated by Blocken et al. (2007), three different regions of the computational domain with different surface roughness can be
Introduction

...distinguished (Fig. 1.4). In the upstream and downstream regions the obstacles are modeled implicitly. This means that the obstacle geometries are not included in the computational domain with their actual shape and size but that their effect on the wind flow pattern is modeled using either the aerodynamic roughness length ($z_0$) or the equivalent sand grain roughness height ($k_s$) inserted in the wall functions applied to the bottom of the computational domain. In the central region of the domain, the obstacles (buildings, bridges, trees, etc.) are explicitly modeled (i.e. with their actual shape and size) and wall functions are applied to the surface of the obstacles (e.g. the walls and the roofs) and on the ground surface, e.g. on the streets, sidewalks, and grass plains. Two options exist: either a surface roughness height is inserted in these wall functions, representing the roughness of building walls, roofs, streets, etc., or these surfaces are assumed to be smooth (zero roughness).

It is not clear how sensitive the numerical results are to different surface roughness values applied on the urban model surfaces (buildings, streets, etc.). In the present thesis the impact of roughness height in the central part of the computational domain on 3D steady state RANS simulation results is investigated in terms of deviations in mean velocity.

1.3 Objectives and methodology

This thesis focuses on the accuracy and reliability of wind tunnel (WT) and CFD techniques to determine wind flow pattern in an urban environment. For this purpose, a historical district of Livorno city, so called “Quartiere La Venezia”, is chosen as case study. There are two main reasons why this district is selected: first, this urban morphology is representative of historical districts typical of many...
Mediterranean cities, and second the wind flow in the Port of Livorno is monitored by a network of instruments within the framework of the European projects “Wind and Ports” and “Wind, Ports, and Sea” (Solari et al., 2012; Burlando et al., 2015 and 2017), the measurements of which are used in turn to generate the inflow profiles for WT tests and CFD simulations. A full description of the district and the monitoring network of Livorno city is given in Chapter 3. Therefore, the methodology adopted in this work consists of WT tests and CFD simulations. The thesis consists of two main parts described in more detail in the following: “Wind tunnel tests” and “CFD simulations”.

1.3.1 Part I: Wind tunnel tests

The objective of the first part of the thesis is to measure the urban canopy layer (UCL) inside the main curved street canyon of Quartiere La Venezia and the evolution with fetch of the urban boundary layer (UBL) above the model.

Wind tunnel tests are performed on a reduced scale model (1:300) in the closed return circuit wind tunnel of the Department of Civil, Chemical and Environmental Engineering (DICCA) at the University of Genoa. Data measured by the anemometric stations, placed in the port of Livorno, are used to generate a target for the vertical mean velocity profile employed in the wind tunnel tests. The results, in terms of mean velocity profiles and yaw and pitch angles, are used in turn as a benchmark to validate the CFD simulations.

1.3.2 Part II: CFD simulations

The objective of the second part of the thesis is to evaluate the accuracy of the 3D steady state RANS approach in predicting the wind flow pattern for the selected case study. This part of the thesis is organized in three stages, in which the deviations caused by four different parameters are analyzed. In the first stage, the deviations caused by two levels of geometrical simplification of the urban model are investigated. Deviations caused by two different inflow conditions commonly adopted to perform 3D steady state RANS simulations on an urban environment are analyzed in the second stage. Finally, deviations caused by five turbulence models and two different values of surface roughness height are analyzed in the third stage. Mean velocity profiles, turbulent kinetic energy profiles, yaw and pitch angles are compared with the wind tunnel measurements to validate the CFD simulations. Finally, all the deviations are quantified using four validation metrics.
1.4 Structure of the thesis

This thesis is organized as follows:

Chapter 2: contains some basic background on the experimental and numerical techniques adopted: Wind Tunnel (WT) testing and Computational Fluid Dynamics (CFD).

Part I: Wind tunnel tests


Part II: CFD simulations


Chapter 5: the impact of inflow conditions on 3D steady state RANS simulations performed on an urban environment is analyzed.

Chapter 6: the impact of turbulence models and roughness height on 3D steady state RANS simulations performed on an urban environment is analyzed.

Chapter 7: summarizes and discusses the results of the previous chapters and provides recommendations for future work.

1.5 References


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Chapter 2

Experimental and numerical techniques

2.1 The wind tunnel

The wind tunnel technique is used to investigate many topics in urban physics and wind engineering: wind loads on buildings and structures, wind comfort and wind safety for pedestrians, wind energy, etc. Wind tunnel tests are usually based on scale reduction of the geometry of interest and of the related wind flow patterns. Wind tunnel tests and full scale measurements (anemometer and LiDAR data) represent valuable resources for the validation of numerical methods, e.g. CFD simulations.

The first use of a wind tunnel to measure wind forces on buildings was probably in 1893 by Kernot in Melbourne (Australia). He called his device a “blowing machine” (Fig. 2.1). Kernot performed a wide range of tests with this device on various bluff bodies: cubes, cylinders, buildings with different pitched roofs, etc. (Holmes, 2004). At about the same time, Irminger carried out an investigation to study wind pressure on some basic shapes of chimneys in the wind tunnel of Copenhagen (Denmark) (Larose and Franke, 1997). In 1930, Irminger and Nokkentved performed some of the earliest wind tunnel tests to investigate wind pressures on low rise buildings. In the 1930s, Flachsbart carried out studies on wind pressures on a low rise building in smooth and boundary layer flow at the Göttingen Laboratories (Germany). It was probably the first boundary layer wind tunnel study (Simiu and Scanlan, 1996). In 1935, Randers-Pehrson, in a review of the pioneer wind tunnels (Randers-Pehrson, 1935), mentioned a wide range of engineers and physicists who performed wind tunnel tests for various bluff bodies before 1900: Wenham, Phillip, Mach, Renard and Maxim, Vogt, Irminger, La Cour. From 1900 to 1910 several scientists, as Zahm, Wright, Stanton and Prandtl, carried out further experiments which added to the basis of the knowledge in experimental aerodynamics (Larose and Franke, 1997). Jensen provided pioneering contributions in reproducing the atmospheric boundary layer in wind tunnel testing. In 1958, Jensen proposed the use of the inner layer length scale, or the roughness length $z_0$, ...
as the important length scale to accurately reproduce the atmospheric boundary layer flow for neutral conditions (Holmes, 2004). In 1965, Jensen and Franck carried out measurements on a range of building shapes in a small atmospheric boundary layer wind tunnel. This study was a precursor to a series of studies aimed at investigating the wind load on low rise buildings (Holmes, 2004). From the 1960s, atmospheric boundary layer wind tunnel tests were performed around the world for different urban physics and wind engineering studies. An extensive number of tests focused on the generation of atmospheric boundary layer flow in the test section of the wind tunnel (Lloyd, 1966; Davenport and Isyumov, 1967; Armit and Counihan, 1968; Counihan, 1969, 1970; Cermak, 1971, 1975, 1977, 1979, 1981, 1984; Cook, 1973, 1978; Irwin, 1981). At the same time, two types of civil engineering structures (commonly very slender) drew the attention of engineers in North America, Japan and Australia: high rise buildings and bridges. Wind tunnel tests with uniform velocity profiles were performed on reduced scale models (usually sectional models) to investigate the aerodynamics and aerelasticity performance of those structures. The dramatic failure of the first the Tacoma Narrows suspension bridge in 1940, encouraged the study of dynamic actions of the wind on the bridges.

The increasing number of high rise buildings in cities, along narrow streets and inside preexisting neighborhoods, led to a new specific problem: wind effects on pedestrians. A pioneering study about pedestrian wind comfort was published by Isyumov and Davenport (1975), where they presented a comparison between full scale and wind tunnel velocity measurements in the Commerce Court Plaza in

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**Figure 2.1** Sketch of the “blowing machine” of 1893 by Kernot (Aynsley et al., 1977).
Toronto. Wind tunnel studies on this topic were reviewed by Stathopoulos (1997, 2006), Moonen et al. (2012) and Blocken (2014, 2016).

In the past decades, atmospheric boundary layer wind tunnel testing, together with CFD simulations and full scale measurements, has represented one the main assessment techniques applied to many topics in urban physics and wind engineering (e.g. air quality and pollutant dispersion, pedestrian wind comfort, indoor and outdoor ventilation, wind energy in buildings). For these topics, a wide range of building and urban geometries such as cavity type models of a single street canyon, simple building arrays, more complicated arrays of simple obstacles or real urban areas were used to investigate the urban boundary layer (UBL) flows (Fernando, 2010; Barlow, 2013, 2014).

2.1.1 Open and closed circuit wind tunnels

There are two different types of wind tunnels, open and closed circuit wind tunnels, and two basic test section configurations: open and closed test section (Fig. 2.2). The open circuit wind tunnel, also called “Eiffel tunnel”, is normally characterized by a straight patch where the air is coming in by an extractor fan through a contraction to the test section followed by a diffuser (Barlow et al., 1999; Holmes, 2004). In the closed circuit wind tunnel, also called “Prandtl tunnel” or “Göttingen tunnel”, the air is flowing from the fan to the contraction section (passing through to the first series of vanes) and it goes to the test section. Then, the flow returns to the fan through a series of turning vanes, circulating continuously inside the duct. There are advantages and disadvantages to an open circuit wind tunnel compared to a closed circuit:

advantages
- lower construction cost;
- no accumulation of exhaust products in case of smoke visualization;

disadvantages
- sensitive to ambient conditions: the size of the room where it is placed, the quality of the ambient air (e.g. dust), the ambient temperature and pressure gradients between the wind tunnel and room, the objects in the room (e.g. desks and walls);
- higher operating costs;
- more noise during operation.
Also a closed circuit wind tunnel has some advantages and some disadvantages:

**advantages:**
- higher quality flow in the test section: turning vanes in the corner and flow straighteners before the contraction ensure relatively uniform flow in the test section;
- lower operating costs;
- more quiet operation compared to an open circuit tunnel;

**disadvantages:**
- higher costs for the construction;
- if used for smoke flow visualization tests there must be a way to purge tunnel.

According to the classification proposed by Barlow et al. (1999) different types of wind tunnel can be distinguished: aeronautical, smoke, automobile, aeroacoustics, general purpose and environmental wind tunnels. Civil and environmental engineering experiments are usually performed in environmental wind tunnels. These wind tunnels are designed to reproduce the atmospheric boundary layer (ABL).

### 2.1.2 Similarity in reduced scale wind tunnel testing

In order to reproduce the wind flow pattern of full scale at reduced scale (in the wind tunnel), the equality of several dimensionless parameters at both scales is required: the Reynolds number ($Re$), the Mach number ($M$), the Froude number ($Fr$) and the Rossby number ($Ro$) (Barlow et al., 1999). The aforementioned dimensionless numbers are defined as follow:
Experimental and numerical techniques

\[ Re = \frac{U_\infty}{\nu} \]  \hspace{1cm} (2-1)

\[ M = \frac{U_\infty}{c} \]  \hspace{1cm} (2-2)

\[ Fr = \sqrt{\frac{U_\infty^2}{l g}} \]  \hspace{1cm} (2-3)

\[ Ro = \frac{U_\infty}{f l} \]  \hspace{1cm} (2-4)

where \( U_\infty \) is the undisturbed flow velocity, \( \nu \) is the kinematic viscosity of the fluid (i.e. air), \( l \) is a characteristic length scale, \( c \) is the velocity of sound in the fluid, \( g \) is the gravitational acceleration and \( f \) the Coriolis frequency. The Reynolds number describes the ratio between inertial and viscous forces (Eq. 2-1), the Mach number is the ratio between inertial and elasticity forces (Eq. 2-2), the Froude number represents the ratio between inertial and gravity forces (Eq. 2-3) and the Rossby number is the ratio between inertial and Coriolis forces (Eq. 2-4). When thermal effects are of importance, four more dimensionless parameters must be considered: the Richardson number (\( \text{Ri} \)), the Prandtl number (\( \text{Pr} \)), the Eckert number (\( \text{Ec} \)) and the Grashof number (\( \text{Gr} \)). The aforementioned dimensionless numbers are defined as follow:

\[ \text{Ri} = \frac{g \beta \Delta T l}{U^2} \]  \hspace{1cm} (2-5)

\[ \text{Pr} = \frac{\nu}{\alpha} \]  \hspace{1cm} (2-6)

\[ \text{Ec} = \frac{U_\infty^2}{C_p \Delta T} \]  \hspace{1cm} (2-7)

\[ \text{Gr} = \frac{g \beta \Delta T l^3}{\nu^2} \]  \hspace{1cm} (2-8)

In the equations above mentioned, \( \Delta T \) indicates the difference of a certain temperature with respect to the reference temperature, \( \alpha \) is the thermal diffusivity, \( C_p \) is the specific heat and \( \beta \) is the coefficient of thermal expansion. The Richardson number expresses the ratio of buoyancy to flow shear (Eq. 2-5). The Prandtl number
is defined as the ratio of kinematic viscosity to thermal diffusivity. The Prandtl numbers in the experiment and in reality are the same if the air flowing in the wind tunnel has the same environmental temperature and chemical composition (Eq. 2-6). The Eckert number indicates the ratio of kinetic energy at the wall to the specific enthalpy difference between wall and fluid (Gschwendtner, 2004) (Eq. 2-7). The Grashof number indicates the ratio of buoyant forces to viscous forces (Eq. 2-8); it is also equal to the product of Richardson and the square of the Reynolds number.

### 2.1.3 Atmospheric boundary layer wind tunnels

Atmospheric boundary layer wind tunnels are normally used for studies in civil and environmental engineering, such as wind effects on structures, pedestrian wind comfort and pollutant dispersion. The accuracy with which the phenomena of the topics above mentioned can be reproduced in the wind tunnel is strictly dependent on five requirements (Cermak, 1977, 1981; Plate and Cermak, 1963):

- the proper scaling of buildings and topographic features;
- the matching of the Reynolds number (Re);
- the matching of the Rossby number (Ro);
- the atmospheric boundary layer characteristics (i.e. velocity distribution and turbulence profiles, turbulent length scales, spectra);
- the matching of the zero longitudinal pressure gradient found in the real world.

This type of wind tunnel is generally designed to reproduce neutral ABL conditions for various terrain characteristics (Fig. 2.3). For this purpose, devices like spires combined with fence and fetches of roughness elements are usually mounted upstream of the turntable where the wind tunnel model is positioned (Fig. 2.4). A wide range of such devices (e.g. fences, spires, wooden cubes and carpet), with different shapes and made of different materials, was tested in the last 50 years (Bradshaw and Pankhurst, 1964; Armitt and Counihan, 1968; Counihan, 1969; Gartshore, 1973; Cook, 1973, 1978; Metha and Bradshaw, 1979; Irwin, 1981; Farell and Iyengar, 1999; Kozmar, 2011). The role of the fences is to provide an initial momentum deficit; the spires are used to generate turbulence, and they contribute to create momentum deficit as well due to larger dimensions at the base. Finally the fetch of roughness, normally composed of wooden cubes or a carpet placed immediately upstream of the wind tunnel model, is used to reproduce the rough terrain. A sufficient length of the test section is an important requirement to
correctly reproduce the ABL profile in wind tunnels (Stathopoulos, 1984). Moreover, the ABL profile reproduced along the test section is very sensitive to the setup, such as the dimensions of devices and the length of the test section itself (Cermak, 1984). As stated by Counihan (1970) “the downstream section at which one considers the flow to be developed is a function of the maximum allowable spanwise non uniformity for any intended wind tunnel experiments”.

Figure 2.3 Atmospheric boundary layer in the wind tunnel test section: (a) illustration of the mean wind speed profile and the local velocity variations due to turbulence in the flow (image from webpage: http://www.windengineering.byg.dtu.dk/Research/Wind-Tunnel-Testing; Technical University of Denmark - (CEAero) Civil Engineering & Architectural Aerodynamics); (b) picture of the wind tunnel test section with the fetch of roughness at the University of Genoa.

Figure 2.4 Pictures of two different roughness element configurations used to reproduce the atmospheric boundary layer (ABL) at the wind tunnel of the University of Genoa: (a) spires and roughness blocks and (b) spires, fences and roughness blocks.
2.1.4 Measurement equipment

Common instruments used to measure wind velocities in the atmospheric boundary layer wind tunnel are the Pitot static tube and the multihole pressure probe (Fig. 2.5). Both of these devices measure the difference between total and static pressure, which is converted to instantaneous wind velocity. The Pitot static tube is able to provide only the along wind velocity component \( u(x) \) and it is L shaped with the tip oriented towards the incoming wind flow (Fig. 2.5a). Two tip designs for Pitot static tubes can be distinguished: hemispherical and squared off. While a hemispherical tip is able to read the total pressure very accurately for yaw angles up to 3°, the squared off design becomes more accurate for a wider range of angles. However, both square and round tip tubes are not suitable for use with too low Reynolds numbers (Barlow et al., 1999). Unlike the Pitot static tube, the multihole pressure probe measures all three wind velocity components \( (u(x), u(y), u(z)) \) and the static pressure, from which the yaw and pitch angles can be obtained (Fig. 2.5b). The multihole pressure probe has typically an acceptance cone of 90° with respect to the incoming flow, an accuracy of velocity measurements dependent on turbulence levels but generally within +/- 0.3 m/s and an uncertainty (in terms of yaw and pitch angles) given by the supplier equal to +/- 0.5°. However, in regions where high flow gradients occur, for example near building walls, position inaccuracy may locally give rise to a significantly larger uncertainty. For this purpose, another instrument able to improve the angular resolution is also used, the omniprobe (Fig. 2.5c). This device is usually furnished with 12 or 15 pressure ports distributed over the spherical surface of the tip; the advantage of using an omniprobe rather than a traditional multihole probe is the angular resolution. Omniprobes are able to measure velocity vectors with angles of up to 165° with the probe axis (relative to the base to tip direction). This allows the omniprobe to measure flows with very high angularity and even reversed flows.

![Figure 2.5](image-url) Overview of the instruments used for the wind tunnel tests performed at the University of Genoa: (a) Pitot static tube, (b) multihole pressure probe, (c) omniprobe.
2.2 Computational Fluid Dynamics (CFD)

Three main numerical approaches are commonly used for urban wind flow problems: steady Reynolds-averaged Navier-Stokes (RANS), unsteady Reynolds-averaged Navier-Stokes (URANS) and Large Eddy Simulation (LES). Despite the strong increase of computational resources in the last decade which has encouraged the use of more accurate and expensive approaches such as LES, the size of the urban domains to be simulated often represents the main limitation for many CFD users. For this reason, a large number of CFD simulations of urban environments are still performed using the 3D steady state RANS approach. Several CFD best practice guidelines were proposed in the last decades and two main principles for assessing the credibility of modeling and simulation in CFD were defined by many institutes and organizations worldwide: verification and validation (V&V) (Oberkampf et al., 2004). In 2004, Oberkampf et al. published “Verification, validation, and perspective capability in computational engineering and physics”, where, starting from the contents discussed by AIAA (1998), the importance of numerical errors and computational uncertainties were pointed out. More specific advice about CFD simulation of flow in the urban environment were given by many scientists such as Franke (2006, 2007), Tominaga et al. (2008) and Blocken (2015). They underline the importance of the choice of the numerical approach (RANS, URANS or LES), the computational domain and grid, boundary conditions, time step size (in case of unsteady simulations), and discretization schemes of CFD simulations in order to obtain reliable results, and also confirmed the importance of V&V.

2.2.1 Governing equations

The instantaneous motion of an incompressible, viscous, isothermal Newtonian fluid in a three dimensional domain can be described by a set of four partial differential equations: conservation of mass (continuity equation) (Eq. 2-9), and conservation of momentum (Newton’s second law) (Eq. 2-10, 2-11, 2-12). The equations can be expressed in this form (Ferziger and Perić, 1996; Versteeg and Malalasekera, 2007):

\[ \text{div} \bar{u} = 0 \]  
(2-9)

\[ \rho \frac{\partial \bar{u}}{\partial t} + \rho \text{div} (u \bar{v}) = -\rho \frac{\partial p}{\partial x} + \text{div} (\mu \text{grad} u) \]  
(2-10)

\[ \rho \frac{\partial \bar{v}}{\partial t} + \rho \text{div} (v \bar{u}) = -\rho \frac{\partial p}{\partial x} + \text{div} (\mu \text{grad} v) \]  
(2-11)
\[ \rho \frac{\partial w}{\partial t} + \rho \text{div}(w \vec{v}) = -\frac{\partial p}{\partial z} + \text{div}(\mu \text{grad} w) \] (2-12)

where \( \vec{v} \) is the instantaneous velocity vector, \( u, v \) and \( w \) the Cartesian components of the instantaneous velocity vector, \( t \) is the time, \( p \) is the instantaneous pressure, \( \mu \) is the dynamic viscosity of the fluid, \( \rho \) is the density of the fluid. The divergence and gradient operator are respectively indicated by \( \text{div} \) and \( \text{grad} \).

Since directly solving the Navier Stokes equations (referred to as Direct Numerical Simulation, DNS) is extremely expensive, for urban physics and wind engineering problems, an approximated form such as the RANS (Reynolds-averaged Navier-Stokes) equations is commonly solved. As reported in Eq. (2-13) the Reynolds decomposition is used to separate the mean and fluctuating components of every variable:

\[ \phi(x,t) = \bar{\phi}(x) + \phi'(x,t) \] (2-13)

where \( \bar{\phi}(x) \) is the time average and \( \phi'(x,t) \) is the fluctuating component. Replacing the instantaneous variables in Eq. (2-9 - 2-12) by the mean and the fluctuating components, the following set of four equations (Eq. 2-14 - 2-17) is obtained:

\[ \text{div} \vec{V} = 0 \] (2-14)

\[ \rho \frac{\partial U}{\partial t} + \rho \text{div}(U \vec{V}) = -\frac{\partial P}{\partial x} + \text{div}(\mu \text{grad} U) + \left[ -\frac{\partial \rho \mu u'^2}{\partial x} - \frac{\partial \rho \mu v'u'}{\partial y} - \frac{\partial \rho \mu w'w'}{\partial z} \right] \] (2-15)

\[ \rho \frac{\partial V}{\partial t} + \rho \text{div}(V \vec{V}) = -\frac{\partial P}{\partial y} + \text{div}(\mu \text{grad} V) + \left[ -\frac{\partial \rho \mu v'^2}{\partial x} - \frac{\partial \rho \mu v'u'}{\partial y} - \frac{\partial \rho \mu w'w'}{\partial z} \right] \] (2-16)

\[ \rho \frac{\partial W}{\partial t} + \rho \text{div}(W \vec{V}) = -\frac{\partial P}{\partial z} + \text{div}(\mu \text{grad} W) + \left[ -\frac{\partial \rho \mu w'^2}{\partial x} - \frac{\partial \rho \mu v'w'}{\partial y} - \frac{\partial \rho \mu w'w'}{\partial z} \right] \] (2-17)

The vectors \( \vec{V} \) and \( P \) are the mean velocity and the mean pressure and \( U, V \) and \( W \) are the mean wind velocity components in \( x, y \) and \( z \) direction, respectively. The means of the products of two fluctuating components, multiplied by the fluid density, form the elements of the Reynolds stress matrix which represents the influence of the turbulence on the mean flow. The matrix is composed as follows (Eq. 2-18):
However, the previous set of equations does not form a closed set due to the presence of Reynolds stresses. The closure of this set is provided by the turbulence models described in more detail in the next paragraph.

### 2.2.2 Turbulence modeling

Two different categories of turbulence models can be distinguished: first order closure based on the Boussinesq eddy viscosity hypothesis (1877) and second order closure based on Reynolds stress modeling (RSM). The most common turbulence models used to simulate urban physics and wind engineering problems belong to the first category and are based on two transport equations, e.g. \( k-\varepsilon \) or \( k-\omega \) models. The variables of these equations are respectively the turbulent kinetic energy \( (k) \) and the turbulence dissipation rate \( (\varepsilon) \) or the specific dissipation rate \( (\omega) \). The standard \( k-\varepsilon \) model proposed by Jones and Launder (1972) is one of the most widely used and validated turbulence models (Versteeg and Malalasekera, 2007). It is robust and performs particularly well in confined flows where the Reynolds shear stresses are important (Versteeg and Malalasekera, 2007). For this purpose it is commonly adopted for industrial engineering applications (Versteeg and Malalasekera, 2007). In contrast, the model does not perform well in unconfined flows, with large additional strains (e.g. curved boundary layers, swirling flows), rotating flows and complex flows with strong pressure gradients (Versteeg and Malalasekera, 2007). Modified versions of this model are the Renormalization Group (RNG) \( k-\varepsilon \) model proposed by Yakhot and Orszag (1986), and the realizable \( k-\varepsilon \) model proposed by Shih et al. (1995); like the standard \( k-\varepsilon \) model, both of these are subject to important limitations due to the isotropic eddy viscosity assumption. The governing equations of the \( k-\varepsilon \) turbulence models are (Eqs. 2-19 - 2-24):

**Standard \( k-\varepsilon \) model**

\[
\rho \frac{\partial k}{\partial t} + \rho \vec{v} \cdot \nabla (k \vec{V}) = \nabla \cdot \left( \mu + \frac{\mu_t}{\sigma_k} \nabla k \right) + P_k + P_b - \rho \varepsilon - Y_M + S_k
\]  

(2-19)

\[
\rho \frac{\partial \varepsilon}{\partial t} + \rho \vec{v} \cdot \nabla (\varepsilon \vec{V}) = \nabla \cdot \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \nabla \varepsilon \right) + C_{1\varepsilon} \frac{\varepsilon}{k} (P_k + C_{3\varepsilon} P_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon
\]  

(2-20)
Renormalization Group (RNG) $k$-$\varepsilon$ model

$$
\rho \frac{\partial k}{\partial t} + \rho \nabla \cdot (k \mathbf{V}) = \nabla \cdot \left( \mu + \frac{\mu_t}{\sigma_k} \nabla k \right) + P_k - \rho \varepsilon \tag{2-21}
$$

$$
\rho \frac{\partial \varepsilon}{\partial t} + \rho \nabla \cdot (\varepsilon \mathbf{V}) = \nabla \cdot \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \nabla \varepsilon \right) + C_{1\varepsilon} \left( \frac{\varepsilon}{k} \right) P_k - C_{2\varepsilon} \rho \left( \frac{\varepsilon^2}{k} \right) \tag{2-22}
$$

Realizable $k$-$\varepsilon$ model

$$
\rho \frac{\partial k}{\partial t} + \rho \nabla \cdot (k \mathbf{V}) = \nabla \cdot \left( \mu + \frac{\mu_t}{\sigma_k} \nabla k \right) + P_k + P_b - \rho \varepsilon - Y_M + S_k \tag{2-23}
$$

$$
\rho \frac{\partial \varepsilon}{\partial t} + \rho \nabla \cdot (\varepsilon \mathbf{V}) = \nabla \cdot \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \nabla \varepsilon \right) + \rho C_{1\varepsilon} S_k - \rho C_{2\varepsilon} \frac{\varepsilon^2}{k + \sqrt{\varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} P_b + S_\varepsilon \tag{2-24}
$$

where $\mu$ and $\mu_t$ are the molecular dynamic viscosity and the eddy or turbulent dynamic viscosity, respectively. $P_k$ and $P_b$ represent the generation of turbulence kinetic energy due to the mean velocity gradients and the generation of turbulence kinetic energy due to buoyancy, respectively. $S_k$ and $S_\varepsilon$ are the source terms, and $Y_M$ is the dilatation dissipation term. All transport equations above contain some constants, such as $C_\mu$, $\sigma_k$, $\sigma_\varepsilon$, $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ which assume different values for different experiments (Jones and Launder, 1972; Yakhot and Orszag, 1986; Shih et al., 1995). The reader is referred to Versteeg and Malalasekera (2007) for more information about these constants.

The $k$-$\omega$ turbulence models, such as the standard $k$-$\omega$ model proposed by Wilcox (1998) and the shear stress transport (SST) $k$-$\omega$ model proposed by Menter (1997), use the turbulence frequency or the specific dissipation rate ($\omega$) as a second variable instead of turbulence dissipation rate ($\varepsilon$). The standard $k$-$\omega$ model represents a choice of turbulence models for urban wind flows simulations (Franke et al., 2007). It provides a satisfactory performance for swirling flows and in the near wall region (Versteeg and Malalasekera, 2007). However, this turbulence model is prone to over predicting the shear stresses of adverse pressure gradient boundary layers and it has issues with free stream flows (Cebeci, 2004; Versteeg and Malalasekera, 2007). The model is also extremely sensitive to inlet boundary conditions as opposed to the $k$-$\varepsilon$ models (Versteeg and Malalasekera, 2007). The shear stress transport (SST) model represents an enhancement of the standard $k$-$\omega$ model and aims at improving some deficiencies of the latter, as the sensitivity to freestream turbulence levels (Pope,
2000). The main advantage of this turbulence model is that it can be applied to the viscous sublayer without further modification (Versteeg and Malalasekera, 2007); however, it can be deficient in predicting the wake region in the boundary layer (Versteeg and Malalasekera, 2007). The governing equations of the $k$-$\omega$ turbulence models are (Eq. 2-25 - 2-28):

**Standard $k$-$\omega$ model**

$$
\begin{align*}
\rho \frac{\partial k}{\partial t} + \rho \text{div}(k \vec{V}) &= \text{div} \left( \mu + \frac{\mu_t}{\sigma_k} \text{grad } k \right) + P_k - Y_k + S_k \\
\rho \frac{\partial \omega}{\partial t} + \rho \text{div}(\omega \vec{V}) &= \text{div} \left( \mu + \frac{\mu_t}{\sigma_\omega} \text{grad } \omega \right) + P_\omega - Y_\omega + S_\omega
\end{align*}
$$

(Eq. 2-25)

(Eq. 2-26)

**Shear stress transport (SST) $k$-$\omega$ model**

$$
\begin{align*}
\rho \frac{\partial k}{\partial t} + \rho \text{div}(k \vec{V}) &= \text{div} \left( \mu + \frac{\mu_t}{\sigma_k} \text{grad } k \right) + P_k - Y_k + S_k \\
\rho \frac{\partial \omega}{\partial t} + \rho \text{div}(\omega \vec{V}) &= \text{div} \left( \mu + \frac{\mu_t}{\sigma_\omega} \text{grad } \omega \right) + P_\omega - Y_\omega + D_\omega + S_\omega
\end{align*}
$$

(Eq. 2-27)

(Eq. 2-28)

where $\mu$ and $\mu_t$ are respectively the molecular dynamic viscosity and the eddy or turbulent dynamic viscosity. $P_k$ and $P_\omega$ represent the rate of production of turbulent kinetic energy and the generation of $\omega$, respectively. $Y_k$ and $Y_\omega$ represent the dissipation of $k$ and $\omega$ due to the turbulence; $D_\omega$ is the cross diffusion term. The reader is referred to Versteeg and Malalasekera (2007) for information about the constants.

In the last decades several authors published reviews of turbulence models (Ferziger and Perić, 1996, Wilcox, 1998, Pope, 2000, Cebeci, 2004, Hirsch, 2007, Versteeg and Malalasekera, 2007). However, it is worth to note that none of the available turbulence models gives a totally accurate description of turbulence flows (Hirsch, 2007), and the best choice can be problem specific (Franke et al., 2007).
2.3 References


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Part I

WIND TUNNEL TESTS
Chapter 3

Wind tunnel tests on Livorno district

This chapter has been published as:


This paper presents the results of an experimental study aimed at investigating the urban boundary layer (UBL) in a district of Livorno city, in Tuscany (Italy). The wind flow over this area was measured in the wind tunnel (WT) of the University of Genova using a model in scale 1:300. Two sets of measurements were carried out, aimed at measuring the urban canopy layer (UCL) inside the main curved street canyon and the evolution with fetch of the UBL above the urban model. The development of the UBL and its variability with fetch was analyzed in terms of spatial evolution of friction velocity, roughness length and zero plane displacement of the vertical velocity profiles. It is shown that, at the transition from sea to urban area, friction velocity and roughness length grow quite rapidly to higher values. After the transition, the skin friction coefficient and the roughness length decrease, while the zero plane displacement slightly increases with the same order of magnitude of the height of the buildings. The results are also intended to become a benchmark for further WT and numerical investigations of a real neighborhood with architectural characteristics typical of historical cities.
3.1 Introduction

Wind flow is a driving force for many phenomena affecting the urban environment, such as indoor and outdoor ventilation, heat transfer, pedestrian wind comfort and safety, pollutions dispersion and air quality (Fernando et al., 2010; Cui et al., 2016; Blocken and Stathopoulos, 2013). Despite its importance for human life in cities, however, urban flows are still far from being completely understood. This is due to the fact that they depend on many variables of the urban environment, such as the geometric complexity of buildings and local thermal effects, that are difficult to be properly determined and extremely variable from case to case, thus inducing high uncertainties in the flow description. According to Barlow (Barlow, 2014), who reviews the urban boundary layer (UBL), i.e. the boundary layer (BL) that develops over urban areas, in terms of its structure and evolution, the UBL consists of three main parts. The urban canopy layer (UCL) is the layer approximately up to the mean roof height where flow channeling occurs along the streets; the urban roughness sublayer (RS) defined as the region above the UCL where the roughness elements, i.e. the buildings, exert significant drag on the flow and the wind is highly spatially dependent. The inertial sublayer (IS), above the RS, is where turbulence is homogeneous and fluxes vary little with height.

Different techniques exist to describe the wind flow inside (in the UCL) and above canopies (in the RS and IS). As far as the UCL is concerned, for example, some analytical models exist that span from the heuristic model described by Inoue (Inoue, 1963) for the mean wind profile within a horizontally homogeneous and vertically uniform dense canopy over flat ground, to more recent models like the one proposed by Wang (Wang, 2012 and 2014), which is valid also in sparse canopies. These models, however, are based on the assumption of homogeneous canopies (Coceal and Belcher, 2004; Segalini et al., 2013; Cheng and Porté-Agel, 2015). Conversely, analytical models do not apply to inhomogeneous urban canopies. In heterogeneous urban areas, site specific CFD numerical or experimental tests are usually carried out to study UCL flows in areas with irregularly distributed buildings (Tominaga and Stathopoulos, 2013; Carpentieri and Robins, 2015; Blocken et al., 2016). High resolution numerical models can help to identify basic processes (Razak et al., 2013; Lin et al., 2014; Ramponi et al., 2015), but the results must be validated carefully, as they are strongly dependent on the model conditions (Blocken, 2015). Wind tunnel (WT) tests were also adopted to study wind flows in standard UCL reference cases, using cavity type models of a
single street canyon or simple building arrays (Allegrini et al., 2013; Stabile et al., 2015; Kastner-Klein et al., 2001), as well as in more complicated arrays of simple (i.e. usually cubic, rectangular or cylindrical) obstacles (Ahmad et al., 2005). Conversely, WT tests of real urban areas are rather uncommon (Carpentieri and Robins, 2015; Kastner-Klein and Rotach, 2004). Field studies in real urban atmosphere at full scale or reduced scale, i.e. WT tests, are extremely important as they can provide benchmark data for modelling (Niachou et al., 2008; Rotach, 1995; Eliasson et al., 2006; Wood et al., 2009), even if they have to be used with care because they also can be affected by uncertainties due to the lack of spatial and time representativeness of single point measurements (Schatzmann and Leitl, 2011). From this point of view, the first goal of this paper is to provide a new experimental benchmark of the UCL in a real urban area, with the geometrical and morphometric characteristics typical of many historical districts in European cities.

Above the UCL, the classical logarithmic law of the wall valid under neutral conditions (Stull, 1988), which depends on the three parameters friction velocity, $u^*$, aerodynamic roughness length, $z_0$, and zero plane displacement, $d$, is usually adopted to describe the mean profiles in both numerical and experimental studies (Kastner-Klein and Rotach, 2004; Macdonald et al., 1998; Cheng and Castro, 2002; Liu et al., 2003). Many different techniques exist to estimate these parameters from the mean profiles, as reported for example by (Kastner-Klein and Rotach, 2004). Some are based on morphometric assumptions to estimate $d$ (Liu et al., 2003; Grimmond and Oke, 1999) or $z_0$ (Macdonald et al., 1998) in terms of plan area density and frontal area density, respectively, while the other parameters can be inferred through a best fit procedure of the wind profiles. In real urban areas, these parameters change according to the aerodynamic response to surface heterogeneities (Barlow, 2014), which is usually taken into account through the development of a new internal boundary layer (Fisher et al., 2006). Despite the importance of determining the inner boundary layer (IBL) for understanding the mean profiles evolution, this topic is poorly considered in the literature. Cheng and Castro (Cheng and Castro, 2002) have recently dealt with the issue of UBL growth with fetch over a simplified array of cubes in the WT, but it is not clear whether their findings are a special case or can be generalized to other, possibly more realistic, conditions. Following this consideration, the second main scope of the present paper consists of studying the wind flow evolution with fetch in a real urban case, in order to provide a confirmation of the case specific behavior reported by (Cheng and Castro, 2002).
As stated above, a wide literature exists concerning numerical simulations and WT tests in simplified conditions that provide some analytical parameterizations of mean flow and fluxes in the UCL. These formulas are extremely useful for applications that require the knowledge of the mean flow properties. Conversely, only few papers deal with full or reduced scale measurements in real cases, which could be used for calibration and validation of other models, as strongly supported by several authors (Fernando et al., 2010; Barlow, 2014; Fernando, 2010; Barlow, 2013). From this point of view, the present study is intended to be part of a wider research project aimed at investigating the wind flow in the UBL of a real urban district in the City of Livorno, placed in Tuscany along the Tyrrhenian coast of central Italy.

There are many reasons why this district was selected: first, it is representative, in terms of geometrical and morphological characteristics, of a typical historical district of many Mediterranean cities; second, it is placed along the coastline, so that it represents an ideal case to study the transition between two contiguous areas of different aerodynamic roughness; third, to the western part of the district an anemometric monitoring network exists that can be used to provide useful information about the wind climatology of this area, both in terms of most frequent and extreme values, as well as about the actual wind flow entering the district from the sea; finally, the monitoring network is expected to grow in the future to include instruments to measure the wind flow within the UCL, which could be directly related to the actual wind flow blowing from the sea. In the long term, therefore, this district is supposed to become an important cross validated benchmark that will provide the scientific community with direct full scale measurements, WT tests and CFD simulations of a real urban area.

The first part of the paper presents the WT measurements of the reduced scale district, discussing the results on the basis of similar experiences and analytical models reported in literature: the selected urban area and its wind climatology obtained from the local monitoring network data are described (Section 3.2); the WT tests performed on the area under study for three directions of the wind blowing from the sea ($\alpha = 240^\circ$, $\alpha = 270^\circ$, and $\alpha = 300^\circ$) under neutral stability conditions are reported in detail (Section 3.3). In particular, two sets of measurements are presented, aimed at evaluating, respectively, the wind profiles along a street canyon and above the irregular building pattern of the district.

In the second part of the paper (Section 3.4) an attempt is made to analyze quantitatively the vertical wind velocity profiles and their evolution over the urban
fetch, with reference to simple analytical models reported in literature. In the UBL, the Monin-Obukhov similarity does not necessarily hold as this theory is strictly valid over flat and homogeneous terrain, whereas fully developed conditions do not occur here because of the limited fetch of the test section as well as the strong inhomogeneity, i.e. caused by the high buildings’ geometrical variability, of the WT model. Nevertheless, the logarithmic law of the wall is shown to work properly, even if the parameters show a considerable variability over the urban area, which is consistent with the transition that is expected to occur to the mean velocity profiles when the urban area is approached from the sea. The spatial evolution of the fitting parameters with fetch over the urban model is then discussed critically comparing our results with other analyses in literature, in particular with the ones reported by Cheng and Castro (Cheng and Castro, 2002). Our results seem to confirm that the evolution of the profiles parameters observed by (Cheng and Castro, 2002) are not a special case, but rather a general behavior consistent with morphometric models (Macdonald et al., 1998), at least in qualitative terms.

Finally, in Section 3.5 the discussion of the results and the future perspectives of this research project are summarized.

### 3.2 Urban area and wind flow characterization

Livorno is a coastal Italian city placed in Tuscany, in flat terrain (Fig. 3.1a). For the present study, a historical district on the sea side was selected, so called “Quartiere La Venezia”, with a plan extension of about 36,000 m² (Fig. 3.1). The district comprehends an industrial area, in the north western part, which is part of the Livorno Port facilities, and a residential area (delimited by the blue dashed line in Fig. 3.1c), distributed along a linear narrow street and canal (Viale Caprera), a curved street and canal (Canale Rosciano) and a square (Piazza del Luogo Pio). The industrial area is characterized by low and regular buildings (blocks C and P in Fig. 3.1c). The residential urban fabric shows architectural and urbanistic features typical of many Italian and Mediterranean historical centers, characterized by quite complex layout, with blocks of different shaped buildings and internal courts. The skyline is quite regular, with buildings of similar height. Table 3.1 summarizes the main geometrical features of the blocks, reporting the volume, the plan area, and the average height above the terrain level, evaluated as the ratio between volume and area. The last two lines report the summary values, considering the whole area (complete) and only the residential area (residential). Table 3.2 summarizes the plan area density of
the selected district, evaluated as the ratio between the blocks’ area and the district’s area.

The wind flow in the selected area was monitored by means of a series of instruments, installed in the framework of the European Projects ‘Wind and Ports’ (2009 - 2012) (Solari et al., 2012) and ‘Wind, Ports and Sea’ (2014 - 2015) (Burlando et al., 2015), handling the problem of the wind safe management and risk assessment of the main North Tyrrhenian commercial ports. In particular, five sonic anemometers were placed in the Port of Livorno and were measuring data since 2011. Moreover, a wind profiler (LiDAR) on the seaside and two additional anemometric station were recently added to the port’s monitoring network, measuring data from October 2015. Table 3.3 summarizes the main characteristics of the described instruments: its code, kind of instrument, height above the terrain of the measured data, location, sampling rate, and year of installation. Data measured from anemometric stations installed in 2011 were used to characterize the statistical feature of the 10 min averaged wind velocity in the selected area. Data measured from more recent instruments, together with a series of anemometric stations that are being installed in the urban canopy (along Canale Rosciano) will be adopted in future analyses for comparison with real data. Fig. 3.1a shows the instruments nearby the selected area (white dotted rectangle). Fig. 3.2 shows the wind roses obtained from the measurements of the anemometers LI03 and LI04: the prevailing wind directions are from east and west. The maximum registered value of wind speed is 25 m/s. A more extensive statistical characterization of the wind flow in the area can be found in (Solari et al., 2012; Burlando et al., 2014a, 2015).

The following analyses were performed assuming the wind blowing from West because the wind profiles coming from the sea are expected to be more representative of a flat and homogeneous surface upwind to the area under study. Moreover, the following analyses take into account only neutral conditions, which are associated with high wind velocities, thus West sectors are assumed as more relevant, corresponding to the strongest wind velocities.
Figure 3.1 Pictures of Livorno city (Italy): (a) location of the district Quartiere La Venezia with the anemometric stations (LI03, LI04, LI06, LI07) and LiDAR station, (b) zoom on the selected district Quartiere la Venezia, (c) and sketch of the modeled area.
Table 3.1
Main characteristics of the building blocks of the selected district. Symbols are related to Fig. 3.1c.

<table>
<thead>
<tr>
<th>Blocks</th>
<th>Vol. [m³]</th>
<th>Area [m²]</th>
<th>Weigh. mean height [m]</th>
<th>Std. dev. height [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.48e04</td>
<td>2.75e03</td>
<td>12.65</td>
<td>11.65</td>
</tr>
<tr>
<td>B</td>
<td>4.40e03</td>
<td>3.84e02</td>
<td>11.45</td>
<td>3.30</td>
</tr>
<tr>
<td>C</td>
<td>3.61e04</td>
<td>3.36e03</td>
<td>10.74</td>
<td>5.91</td>
</tr>
<tr>
<td>D</td>
<td>3.37e04</td>
<td>3.35e03</td>
<td>10.06</td>
<td>3.40</td>
</tr>
<tr>
<td>E</td>
<td>2.96e04</td>
<td>1577</td>
<td>18.78</td>
<td>2.66</td>
</tr>
<tr>
<td>F</td>
<td>5.19e04</td>
<td>2.26e03</td>
<td>22.90</td>
<td>8.36</td>
</tr>
<tr>
<td>G</td>
<td>1.20e05</td>
<td>7.44e03</td>
<td>16.09</td>
<td>6.07</td>
</tr>
<tr>
<td>H</td>
<td>1.15e04</td>
<td>684</td>
<td>16.88</td>
<td>-</td>
</tr>
<tr>
<td>I</td>
<td>7.35e04</td>
<td>5.32e03</td>
<td>13.82</td>
<td>6.87</td>
</tr>
<tr>
<td>L</td>
<td>1.56e04</td>
<td>2.03e03</td>
<td>7.67</td>
<td>3.43</td>
</tr>
<tr>
<td>M</td>
<td>5.74e04</td>
<td>3.08e03</td>
<td>18.65</td>
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</tr>
<tr>
<td>N</td>
<td>5.09e04</td>
<td>2.81e03</td>
<td>18.12</td>
<td>5.46</td>
</tr>
<tr>
<td>O</td>
<td>3.27e04</td>
<td>2.28e03</td>
<td>14.30</td>
<td>4.30</td>
</tr>
<tr>
<td>P</td>
<td>3.54e04</td>
<td>5.87e03</td>
<td>6.031</td>
<td>2.77</td>
</tr>
<tr>
<td>Q*</td>
<td>5.94e04</td>
<td>8.59e03</td>
<td>6.91</td>
<td>-</td>
</tr>
<tr>
<td>Complete</td>
<td>6.45e05</td>
<td>5.18e04</td>
<td>12.49</td>
<td>7.42</td>
</tr>
<tr>
<td>Residential</td>
<td>5.16e05</td>
<td>3.40e04</td>
<td>15.18</td>
<td>7.27</td>
</tr>
</tbody>
</table>

* The tower of this block has not been considered to calculate the main parameters.
Table 3.2
Plan area density of the selected district. Symbols are related to Fig. 3.1c.

<table>
<thead>
<tr>
<th>Database</th>
<th>Blocks’ area [m^2]</th>
<th>District’s area [m^2]</th>
<th>Plan area density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete</td>
<td>5.18e04</td>
<td>1.70e05</td>
<td>0.30</td>
</tr>
<tr>
<td>Residential</td>
<td>3.40e04</td>
<td>9.91e04</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Table 3.3
Main characteristics of the wind monitoring network in the Port of Livorno as reported in Fig. 3.1a. Height refers to the altitude above ground level (AGL) where measurements are taken. 3D and 2D sonic anemometers are indicated in the Table by 2D and 3D s.a. respectively.

<table>
<thead>
<tr>
<th>Code</th>
<th>Sensor</th>
<th>Height AGL [m]</th>
<th>Location</th>
<th>Sampling rate [Hz]</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>LI01*</td>
<td>3D s.a.</td>
<td>20</td>
<td>Light tower ‘Colmata’</td>
<td>10</td>
<td>2011</td>
</tr>
<tr>
<td>LI02*</td>
<td>3D s.a.</td>
<td>20</td>
<td>Light tower ‘Terminal’</td>
<td>10</td>
<td>2011</td>
</tr>
<tr>
<td>LI03</td>
<td>3D s.a.</td>
<td>20</td>
<td>Light tower ‘Vestrini’</td>
<td>10</td>
<td>2011</td>
</tr>
<tr>
<td>LI04</td>
<td>3D s.a.</td>
<td>20</td>
<td>Light tower ‘Benetti’</td>
<td>10</td>
<td>2011</td>
</tr>
<tr>
<td>LI05*</td>
<td>3D s.a.</td>
<td>75</td>
<td>Silo roof ‘Grandi Molini’</td>
<td>10</td>
<td>2011</td>
</tr>
<tr>
<td>LI06</td>
<td>2D s.a.</td>
<td>12</td>
<td>Dock ‘Molo Mediceo’</td>
<td>10</td>
<td>2015</td>
</tr>
<tr>
<td>LI07</td>
<td>2D s.a.</td>
<td>23.8</td>
<td>Building ‘Palazzo Rosciano’</td>
<td>10</td>
<td>2015</td>
</tr>
<tr>
<td>LiDAR</td>
<td>LiDAR</td>
<td>40 - 250</td>
<td>Dock ‘Molo Mediceo’</td>
<td>1</td>
<td>2015</td>
</tr>
</tbody>
</table>

* The anemometric stations LI01, LI02, L0I5 have not been reported in Fig. 3.1a.

Figure 3.2 Directional distribution of the wind measurements in Livorno recorded by (a) LI03 and (b) LI04 anemometers, placed at 20 m above the ground surface.
The vertical wind profile to be used as inflow condition during the WT tests was chosen according to the numerical simulations developed in the framework of the *Wind and Ports* project (Solari et al., 2012; Burlando et al., 2014a, 2014b). The adopted numerical model, WINDS (Wind Interpolation by Non-Divergent Schemes) (Burlando et al., 2007a, 2007b), is a mass consistent model that determines the 3D mean wind velocity field over the computational domain, starting from one (or possibly more) input value of the mean wind velocity and direction, by means of a twostep procedure. Firstly, wind data are interpolated over the computational domain, transforming the initial wind data in a three dimensional “first guess” wind field. Then the interpolated field is iteratively adjusted in order to satisfy the mass conservation constraint. In the “final” 3D wind field, mass is conserved over the entire domain, both accounting for flow through the boundaries and imposing mass conservation locally everywhere. Moreover, the IBL concept is applied, so that, when the air flow encounters steep changes of surface roughness, an IBL develops within which the lower part of the wind profile is in balance with respect to the new surface, while the upper part is still in balance with respect to the old surface.

In the present project, two computational domains were realized over the urban area, with increasing resolution. A macro area with a horizontal grid resolution of about 270 m was simulated, including the docks and the main topographical features that affect the wind climatology of the area itself. Furthermore, a micro area was nested inside the macro area to simulate the wind fields with a horizontal grid resolution of 80 m. Each domain has 30 vertical levels, ranging from 5 to 5,000 m above ground level. Each computational domain was characterized by a Digital Terrain Model of the topography, supplied by the Italian Geographic Institute, and by a digital map of the roughness length of the terrain, derived from the digital land cover maps of the CORINE project (Bossard et al., 2000) by associating a suitable terrain roughness length to each coverage type. Fig. 3.3 (grey square symbols) shows the mean wind profile obtained numerically by means of WINDS in the grid point correspondent to the LI03 anemometer’s position (see also Fig. 3.1a), for the incoming wind direction 270° and an input wind velocity of 30 m/s imposed at the top of the atmospheric boundary layer (ABL). The axes show the ratio $U/U_{top}$ (abscissa) and the height $z$ (ordinate), with the wind velocity value $U_{top}$ computed by WINDS at height $z = 135$ m, considered to normalize the wind profile. This profile was used as the target input profile for the WT tests, as explained in Section 3.3.
3.3 Wind tunnel tests

3.3.1 Model building and test setup

The WT tests were performed in the wind tunnel of the Department of Civil, Chemical and Environmental Engineering (DICCA) of the University of Genoa, which is a closed loop subsonic circuit for aerodynamic and civil experiments. The WT has two different test sections, with cross section of 1.7 x 1.35 m² (width x height). The selected area was reproduced in a very detailed 1:300 scale model, using medium density fiberboard of different thickness for plates and buildings, and 3 mm thick closed cell PVC foamboard panels for roofs and bridges. Fig. 3.4 shows some pictures of the urban model in the WT tests. The blockage ratio in the cross section was below 3.5%.

The experimental session was aimed at measuring the wind velocity profile in different positions of the UCL. One set of measurements consisted of 10 points fixed on the urban model and placed along the street canyon Canale Rosciano (Fig. 3.5a). The positions correspond to the top of the building where the anemometric station LI07 is installed, A1₁, and to the position where four anemometric stations
are supposed to be installed in the near future along the canal, A2\textsubscript{2} - A5\textsubscript{2}, for comparison with real data, and by their sides, A2\textsubscript{1} - A5\textsubscript{1} and A3\textsubscript{3}. Another set of measurements consisted of a grid of 15 points, L1\textsubscript{1-5}, L2\textsubscript{1-5}, L3\textsubscript{1-5}, whose coordinates were kept fixed with respect to the wind tunnel local reference system (Fig. 3.5b,c,d). For this reason, in Fig. 3.5 their position changes with respect to the WT model, which is instead rotated inside the WT test section according to three different incoming wind directions (\(\alpha\)). For sake of completeness, Fig. 3.6 shows the corresponding skylines for different lines L and different angles (\(\alpha\)).

WT tests were performed for three wind directions (\(\alpha = 240^\circ, 270^\circ, 300^\circ\)) corresponding to the prevalent directions of the extreme winds in this area (see Fig. 3.2). All the measurements were performed by means of a fast response multi hole pressure probe (Fig. 3.4b). The probe was placed at different locations and heights using a triaxial traversing system installed over the roof of the test section. Measurements were acquired at a sampling frequency of 2 kHz and for 30 seconds at each point. The used fast response probe provides the three components of velocity, the flow probe relative angularity and the static pressure.

**Figure 3.4** Pictures of the WT model in the wind tunnel: (a) complete WT model and (b) detail along the street canyon *Canale Rosciano.*
As stated in Section 3.2, the inflow condition in the WT, i.e. the mean velocity profile upstream of the WT model, was calibrated on the basis of numerical simulations (see Fig. 3.3). The ABL was developed by a rough surface on the WT floor, obtained with a symmetric pattern of spires and rectangular wood blocks of variable dimensions. This is a common procedure to generate an ABL in wind tunnels. However, an unexpected effect of the roughness arrangement was the nonuniformity mean wind profile in the spanwise direction, such as along the WT cross section, which is shown in Fig. 3.3. Fig. 3.7 shows the mean wind velocity measured in the spanwise direction along the WT section approximately 1 m upstream of the first building of the urban model. The lateral coordinate $y$ is set to zero in the middle of the cross section. It is worth note that such a nonperfect symmetry with respect to $y = 0$ is subsequent to the creation of the boundary layer (i.e. the flow is symmetric and homogeneous in the test section when the working
WT section is empty). Based on authors’ knowledge, the reason why a symmetric roughness fetch configuration leads to nonsymmetric mean wind profile along the WT section is not well documented in the literature, and it will be investigated in the future. It is worth pointing out, however, that wind speed differences across the section were quite limited at every height (i.e. roughly in the range ± 5%). This drawback can cause limited bias in the present work, whereas can lead to larger errors for other purposes, e.g. pressure coefficients estimations.

Figure 3.6 Vertical sections made along the lines L1-5, L2-5 and L3-5 for the wind directions $\alpha = 240^\circ$, $\alpha = 270^\circ$ and $\alpha = 300^\circ$.
3.3.2 Wind flow in the urban canyon

Fig. 3.8 shows the mean wind velocity profiles measured at four positions A2 - A5 in the central line of Canale Rosciano, for the incoming wind direction $\alpha = 270^\circ$ (Fig. 3.5, red symbols and labels) in logarithmic scale. The left panel of each picture reports, on the abscissa, the measured longitudinal $u(z)$ (blue circles), lateral $v(z)$ (orange squares), vertical $w(z)$ (light blue diamonds) components and mean value $U(z)$ (red dashed line) at height $z$, normalized with respect to the reference undisturbed incoming velocity ($U_{ref}$), corresponding to freestream conditions above the boundary layer. To reduce uncertainties, at every point the wind profile are nondimensionalized with respect to the value assumed at the same $y$. For each measured $z$ level, the yaw angle $\phi(z)$ and the pitch angle $\theta(z)$ are displayed, showing the horizontal and vertical deviation from the incoming along wind direction, respectively. The inflow wind profile (grey continuous line) is also reported. The right panel shows the longitudinal $I_u(z)$ (blue circles), lateral $I_v(z)$ (orange squares) and vertical $I_w$ (light blue diamonds) turbulence intensity. At level higher than $z = 60$ m, corresponding to $3 h_b$, the mean wind velocity was almost constant in the four positions, with small deviations from the input profile, yaw $\phi(z)$ and pitch $\theta(z)$ tending to zero and regular turbulence intensities. In between 30 and 60 m, corresponding to the layer from 1.5 $h_b$ to 3 $h_b$, the wind velocity in the horizontal plane was almost aligned with the incoming direction (yaw tending to zero), whereas some noticeable vertical deviations were observed. The wind velocity was also progressively less intense from A2 to A5. At levels lower that 1.5 $h_b$, the canyoning
effect was emphasized for positions from A3\textsubscript{2} to A5\textsubscript{2} along the canal, where the wind velocity largely decreased, the lateral $v(z)$ and vertical $w(z)$ components assumed significant values, the yaw $\phi(z)$ and pitch $\theta(z)$ angles strongly increased and the turbulence intensities grew up to more than 50%. Fig. 3.9 shows the wind profiles measured in all the ten positions along the street canyon *Canale Rosciano*, normalized with respect to the reference undisturbed incoming velocity aloft ($U_{ref}$), considering the inflow direction $\alpha = 240^\circ$ (Fig. 3.9a), $\alpha = 270^\circ$ (Fig. 3.9b) and $\alpha = 300^\circ$ (Fig. 3.9c), in semi logarithmic scale. The normalized mean wind profiles showed different behaviors in three layers: in the upper layer, greater than 3 $h_b$, the profiles had a linear tendency in the log diagram, confirming a logarithmic shape in equilibrium with the inflow roughness value; in the layer between 1.5 $h_b$ and 3 $h_b$, the pure logarithmic law seemed not to hold anymore, even if the profiles maintain a quite regular tendency; in the UCL, lower than 1.5 $h_b$, the profiles showed strong local effects. The velocity reduction due to the UCL was much more evident for the wind direction $\alpha = 270^\circ$ and $\alpha = 300^\circ$, especially at the positions A3 and A4, where the canal is almost orthogonal with respect to the inflow. In such points, the wind velocity at low levels reduces almost to zero, as the flow tends to move over the building roofs, as shown in the Fig. 3.10.
Figure 3.8 Comparison of the vertical profiles in terms of mean wind velocity ($U$), velocity components ($u$, $v$, $w$), and turbulence intensity ($I_u$, $I_v$, $I_w$) for the wind inflow direction $\alpha = 270^\circ$ at the positions (a) A2, (b) A3, (c) A4 and (d) A5. As an example the values of yaw ($\phi$) and pitch ($\theta$) angles are reported at the levels $z = 6, 10, 20, 30$ and $40$ m.
Figure 3.9 Comparison of the vertical mean wind velocity profiles ($U$) at all the measured positions (A1 - A5) along Canale Rosciano, for the incoming wind directions (a) $\alpha = 240^\circ$, (b) $\alpha = 270^\circ$ and (c) $\alpha = 300^\circ$. The velocity values were normalized with respect to the reference wind velocity value ($U_{ref}$) at $z = 180$ m (full scale equivalent).

Figure 3.10 Mean wind velocity ($U$) maps at $z = 10$ m (full scale equivalent) above ground surface at the measured positions (A1 - A5) along Canale Rosciano, for the wind inflow directions (a) $\alpha = 240^\circ$, (b) $\alpha = 270^\circ$ and (c) $\alpha = 300^\circ$. 
3.3.3 Wind flow above the roofs

Similarly to Fig. 3.8, Fig. 3.11 shows the wind velocity profiles measured at five positions (L2_1 - L2_5) in the central line of the grid, with incoming wind direction $\alpha = 270^\circ$ (see Fig. 3.5, blue symbols and labels). Note that, in some points, the measurements are limited in height for the presence of buildings. Compared to the measurements detected along Canale Rosciano, the present results showed a more regular trend in the layer greater than 1.5 $h_b$. The wind velocity was almost constant at four positions showing small deviations from the inlet profile especially in the lower part of the profiles, where the yaw and pitch angles were tending to zero according to the regular trend of turbulence intensities. At levels lower than 1.5 $h_b$, the canopy effect was emphasized mostly at the positions L2_3 (Fig. 3.11c) and L2_5 (Fig. 3.11e). Fig. 3.12 shows the wind profiles measured at the grid points L1_1-5, L2_1-5, and L3_1-5, normalized with respect to the reference undisturbed incoming velocity aloft ($U_{ref}$), considering the inflow direction $\alpha = 240^\circ$ (Fig. 3.12a), $\alpha = 270^\circ$ (Fig. 3.12b) and $\alpha = 300^\circ$ (Fig. 3.12c), in semi logarithmic scale. Compared with the measurements along Canale Rosciano (Fig. 3.8), the wind flow behavior in the upper layer (greater than 3 $h_b$) and in the UCL (lower than 1.5 $h_b$) was qualitatively reiterated with a general lower dispersion of the wind profiles in the canopy. More relevant differences were found in the layer between 1.5 $h_b$ and 3 $h_b$, in which the deviation from the logarithmic profile was shown only for the grid points corresponding to the densest urban pattern, for each wind direction.
Figure 3.11 Comparison of the vertical profiles in terms of mean wind velocity \((U)\), velocity components \((u, v, w)\), and turbulence intensity \((I_u, I_v, I_w)\) for the wind inflow direction \(\alpha = 270^\circ\) at the positions (a) L2_1, (b) L2_2, (c) L2_3, (d) L2_4 and (e) L2_5. As an example the values of yaw \((\phi)\) and pitch \((\theta)\) angles are reported at the levels \(z = 6, 10, 20, 30\) and \(40\) m.
3.4 Evolution of the wind profiles with fetch

In the previous sections, it is shown that the wind velocity in the UCL is very complex and locally affected by the surrounding buildings, which have different characteristics, in terms of shape and horizontal and vertical dimensions, all along the Canale Rosciano. The flow inside the UCL is difficult to be modeled and predicted precisely, as analytical models do not apply to inhomogeneous urban canopies and site specific high resolution WT or numerical models are required to study UCL flows in areas with irregularly distributed buildings.

Above the UCL, however, the experimental results can be compared to analytical solutions. For neutrally stratified boundary layers, in particular, the vertical profile of the mean horizontal velocity, $U$, can be modelled according to the logarithmic law of the wall (Stull, 1988):

Figure 3.12 Comparison of the vertical mean wind velocity profiles ($U$) at the measured grid points (L1, L2, L3) for the incoming wind directions (a) $\alpha = 240^\circ$, (b) $\alpha = 270^\circ$ and (c) $\alpha = 300^\circ$. The velocity values were normalized with respect to the reference wind velocity value ($U_{ref}$) at $z = 180$ m (full scale equivalent).
where $z_0$ is the aerodynamic roughness length, $d$ the zero plane displacement, $u^*$ the friction velocity, and $\kappa$ the von Karman constant. This law is strictly valid in the IS, above the top of the RS, where turbulent fluxes are constant. In the present case, however, both IS and RS were expected to vary unevenly depending on the height of the buildings, but quite regularly along the model according to the increase of fetch, as confirmed by the following analysis. Eq. (3-1) was used to regress the measured wind velocity profiles at positions A and L through a nonlinear least squares curve fitting method (Marquardt, 1963). As an example, Fig. 3.13 shows the fit obtained for profiles A1 and A2, for the wind direction $\alpha = 240^\circ$. Note that the number of measurements available, $N$, varied with the profile considered, as profiles over buildings has less measurement points than the other ones, e.g. 10 measures for A1 against 14 for A2 (see the position of A1 and A2 in Fig. 3.5). For each wind profile, the corresponding parameters $u^*$, $z_0$, and $d$ were estimated through the following iterative process: firstly, the fit was performed using all the measurements available, $M$, e.g. $M = 14$ for profile A2 (black squares in Fig. 5.13); then the same parameters were estimated discarding the measurements closer to the ground one by one, e.g. discarding the measurement taken at 6 m ($M-1$), then the one at 10 m ($M-2$), etc. repeating iteratively the fit until only the uppermost three measurements were retained. The reason of this approach is twofold. On the one hand, the robustness of the fitting procedure can be checked and the sensitivity of the parameters with respect to the adopted number of measurements per profile can be evaluated. On the other hand, for some profiles it may happen that either the fitting procedure does not converge using all the measurements, or it leads to unphysical values of the parameters. This problem arises when a certain number of measurements, $N$, laying in the UCL, i.e. below the RS, are used in the fitting procedure, inducing a distortion of the profile with respect to the log-law-of-the-wall, Eq. (3-1). For instance, this happened for the case of position A2 when measurements at 6 and 10 m were not discarded.

Unfortunately, the boundary between UCL and RS is not known a priori. In the literature, some definitions of $h_{RS}$ are available, but there is not a unique formulation considered universally valid. Rotach (Rotach, 1999), for example, reported several definitions of the RS height according to various criteria, derived from WT tests of different homogeneous distributions of the roughness elements. He stated, however, that “the average spacing of buildings in real cities is less well defined than that of roughness elements in a wind tunnel experiment”.
In fact, the limit of the RS was not expected to vary regularly over an urban model as in this region the flow was strongly influenced by the individual roughness elements, i.e. the buildings, which were not regularly spaced one another, like in the present layout.

Despite the impossibility to state in advance which measurements had to be discarded for each wind profile, a rough estimate of the UCL - RS boundary can be possibly obtained through the fitting procedure itself. In principle, when the fitting procedure works properly, eventually after that \( N \) measurements were removed (\( N = 2 \) for \( A2_1 \)), it means that all the retained measurement points, \( M - N \) (\( M - N = 12 \) for \( A2_1 \)), laid within the RS or above. Therefore, the last measure retained closer to the ground (at 20 m for \( A2_1 \)) still belongs to the RS, while the one below (at 10 m for \( A2_1 \)) was in the UCL, which means that the UCL - RS boundary for \( A2_1 \) was somewhere in between 10 and 20 m above the ground. A more precise evaluation of the UCL and RS limit is beyond the scope of the present paper and won’t be reported in the following discussion.

This procedure was applied systematically and the final values of the parameters were chosen, for each wind profile, retaining the maximum number of measurements, \( M \leq N \), whose fit showed \( R^2 \geq 0.995 \), which ensured the goodness of the inference procedure. Table 3.4 summarizes the obtained values for the
considered points and for the incoming flow directions $\alpha = 240^\circ$, $270^\circ$, and $300^\circ$. The obtained estimates were checked carefully and evaluated critically in order to prevent defective values due to the above mentioned criteria that we adopted in the automatic fitting procedure. For instance, concerning the wind direction $\alpha = 240^\circ$, all the fitted parameters turned out to be coherent one another without any correction, with the exception of points L1$_1$, L1$_2$ and L2$_2$. In these particular positions the flow distortion was limited to the lower levels of the profiles, because of the presence of very low elements around them or upstream, and the best fits performed through the analytical profile in Eq. (3-1) presented slightly negative values of $d$, which were clearly unphysical. Therefore, the zero plane displacement value was forced to be equal to 0 only for these particular measuring positions. Note that this is equivalent to assuming a logarithmic profile that does not depend on the zero plane displacement anymore, which is reasonable because all these measuring positions were the closest to the inflow, where the profiles were not influenced by the presence of the buildings yet. The same considerations hold for points A2$_2$, L2$_1$, and L3$_1$ when the wind direction is $\alpha = 270^\circ$ and for positions L1$_1$ and L3$_1$ when the wind direction is $\alpha = 300^\circ$. Fig. 3.14 shows the results of the fitting procedure applied to the $\alpha = 240^\circ$, $270^\circ$, and $300^\circ$ case, respectively, corresponding to the values reported in Table 3.4. In this figure, all parameters showed qualitatively quite a regular pattern with fetch, which can be assumed to correspond approximately to the distance from the inlet: $u^*$ (a) and $z_0$ (b) decreased with fetch, whereas $d$ (c) increased with fetch. Note that all the values in Fig. 3.14(a-c) are normalized with respect to the corresponding maxima.

The general behavior of the three parameters is reported in Fig. 3.15, which shows the variation of $u^*$, $z_0$, and $d$ as a function of fetch for all the wind directions. As an example, the friction velocity, $u^*$, for case $\alpha = 240^\circ$ decreased roughly linearly from its maximum value 1.33 to the minimum 0.76 m/s (Table 3.4), which correspond to $u^*/U_{\infty}$ ranging from 0.079 to 0.045. This is fully consistent with the results reported by Cheng and Castro (2002), who found a similar behavior both in terms of trend and $u^*/U_{\infty}$ values, suggesting that in the transition from flat terrain to the UCL the skin friction coefficient, $C_f = 2 \left( \frac{u^*}{U_{\infty}} \right)^2$, changes accordingly to $u^*$. 
Table 3.4
Parameters of the analytical logarithmic law of the wall (Eq. 3.1).

<table>
<thead>
<tr>
<th>positions</th>
<th>$\alpha = 240^\circ$</th>
<th>$\alpha = 270^\circ$</th>
<th>$\alpha = 300^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$u^*$ [m/s]</td>
<td>$z_0$ [m]</td>
<td>$d$ [m]</td>
</tr>
<tr>
<td>A1_1</td>
<td>0.89</td>
<td>0.07</td>
<td>25.4</td>
</tr>
<tr>
<td>A2_1</td>
<td>1.22</td>
<td>0.67</td>
<td>6.2</td>
</tr>
<tr>
<td>A2_2</td>
<td>1.20</td>
<td>0.60</td>
<td>7.8</td>
</tr>
<tr>
<td>A3_1</td>
<td>1.24</td>
<td>0.65</td>
<td>11.2</td>
</tr>
<tr>
<td>A3_2</td>
<td>1.17</td>
<td>0.46</td>
<td>14.2</td>
</tr>
<tr>
<td>A3_3</td>
<td>1.18</td>
<td>0.43</td>
<td>21.5</td>
</tr>
<tr>
<td>A4_1</td>
<td>0.93</td>
<td>0.09</td>
<td>26.5</td>
</tr>
<tr>
<td>A4_2</td>
<td>0.89</td>
<td>0.07</td>
<td>27.4</td>
</tr>
<tr>
<td>A5_1</td>
<td>0.83</td>
<td>0.04</td>
<td>26.9</td>
</tr>
<tr>
<td>A5_2</td>
<td>0.76</td>
<td>0.02</td>
<td>27.6</td>
</tr>
<tr>
<td>L1_1</td>
<td>1.11</td>
<td>0.37</td>
<td>-</td>
</tr>
<tr>
<td>L1_2</td>
<td>1.12</td>
<td>0.40</td>
<td>-</td>
</tr>
<tr>
<td>L1_3</td>
<td>0.96</td>
<td>0.14</td>
<td>3.7</td>
</tr>
<tr>
<td>L1_4</td>
<td>1.03</td>
<td>0.17</td>
<td>16.8</td>
</tr>
<tr>
<td>L1_5</td>
<td>0.85</td>
<td>0.04</td>
<td>22.8</td>
</tr>
<tr>
<td>L2_1</td>
<td>1.16</td>
<td>0.56</td>
<td>0.5</td>
</tr>
<tr>
<td>L2_2</td>
<td>1.21</td>
<td>0.68</td>
<td>-</td>
</tr>
<tr>
<td>L2_3</td>
<td>1.15</td>
<td>0.49</td>
<td>0.8</td>
</tr>
<tr>
<td>L2_4</td>
<td>0.91</td>
<td>0.10</td>
<td>19.5</td>
</tr>
<tr>
<td>L2_5</td>
<td>0.82</td>
<td>0.04</td>
<td>26.7</td>
</tr>
<tr>
<td>L3_1</td>
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<td>1.07</td>
<td>2.7</td>
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<td>L3_3</td>
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<td>0.36</td>
<td>9.6</td>
</tr>
<tr>
<td>L3_4</td>
<td>0.96</td>
<td>0.13</td>
<td>21.3</td>
</tr>
<tr>
<td>L3_5</td>
<td>0.88</td>
<td>0.06</td>
<td>25.9</td>
</tr>
</tbody>
</table>
The roughness length, $z_0$, for case $\alpha = 240^\circ$ showed a decreasing trend as well, up to a value about 0.02 m. This was just the opposite from Cheng and Castro (2002) who measured an increasing followed by a constant trend, but it might be due to the difference between their and our experimental setup. In fact, the Cheng and Castro’s (2002) experiments presented quite a sparse UCL with a very regular spatial structure: their canopies consist of arrays of cubes spaced 1 cube’s edge each other and had a constant value of frontal area density as well as plan area density equal to 0.25, so that quite a large distance occurred from the roughness elements, which corresponded to a relatively low zero plane displacement and high roughness length values. The presented urban model, instead, was characterized by denser blocks irregularly spaced with an overall plan area density of 0.30, which increased to 0.34 within the residential area. According to (Barlow, 2013), the latter value corresponds

Figure 3.14 Maps of the spatial variability of the fitting parameters of Eq. (3-1) over the urban model calculated at the positions A (along Canale Rosciano) and L (regular grid) for the incoming wind directions $\alpha = 240^\circ$, $\alpha = 270^\circ$, $\alpha = 300^\circ$: (a) friction velocity $u^*$, (b) roughness length $z_0$, (c) zero plane displacement $d$. Dashed line in panels (a) represent approximately the corresponding fetch.
to the transition from a wake interference flow to purely skimming conditions, which correspond to relatively higher zero plane displacement and lower roughness length values. Moreover, decreasing values of $z_0$ with increasing values of frontal area density are consistent with the morphometric models for the roughness length (Coceal and Belcher, 2004). The zero plane displacement, $d$, for case $\alpha = 240^\circ$ increased from about 0 to 27.6 m. This was comparable to the mean height of the blocks in the WT model, which increased from about 8 - 10 m of the south western blocks to about 20-25 m of the north eastern ones.

The scenario depicted by these results corresponds to the transition from the inflow velocity profile, which is logarithmic with $u^* = 0.9 \text{ m/s}$, $z_0 = 0.1 \text{ m}$, and $d = 0 \text{ m}$, to an UBL where a zero plane displacement exists of the order of magnitude of the mean blocks’ height. The sharp increase of $u^*$ and $z_0$ from their inflow values (0.9 m/s and 0.1 m, respectively) to the urban area (1.33 m/s and 1.45 m, for case $\alpha = 240^\circ$) at $x = 0 \text{ m}$ in Fig. 3.15 is also consistent with the much larger roughness elements that the wind flow suddenly encountered when it faced the blocks. In Fig. 3.15, the linear trends of $u^*$, $z_0$, and $d$ are also shown. For $u^*$ and $z_0$ a linear function depending on two parameters, i.e. slope and intercept, was adopted, while for $d$ the intercept was assumed equal to 0 at $x = 0 \text{ m}$. The mean value of slope and intercept of $u^*$, considering all the three wind directions, are -0.0011 $(\text{m s}^{-1})/\text{m}$ and 1.17 m/s, respectively, which means that the friction velocity decreased approximately 0.1 m/s every 100 m. The mean value of slope and intercept for $\ln(z_0)$, considering all the three wind directions, are -0.0095 m/m and 0.019 m, respectively. In terms of roughness length, $z_0$, the mean value at $Lx_1 = 0$ is 0.99 m, which decreased to 0.40, 0.15, and 0.06 m after 100, 200, and 300 m, respectively, reducing of 2 orders of magnitude in a few hundred meters. Conversely, the mean value of $d$ increased about 10 m every 100 meters of fetch, from 0 at $Lx_1 = 0$ to about 30 m when the distance from $Lx_1$ was 300 m. It is not easy to find in the literature wind tunnel high resolution measurements performed in realistic urban canopies with geometric characteristics similar to the present case, to compare our results with. For instance, Kastner-Klein and Rotach (2004) studied the flow in the central part of Nantes (France). From the morphological point of view, this area was not really identical to Quartiere La Venezia in that the plan area density reached values up to 0.6 or more, whereas the height of the buildings was around 20-25 m. Moreover, the measurements were mostly concentrated in the central part of the urban model, only few of them were aligned along the direction of fetch, and the fetch was about half of the fetch in Livorno, i.e. around 150 m. Despite these differences, they
found an increasing trend of the displacement height of about 13 m (morphometric method) or 30 m (shear stress parameterization) every 100 m, depending on the method adopted to evaluate $d$. As for $u^*$ and $z_0$, they did not vary appreciably with fetch and a regular trend of these parameters was not clearly discernible from their data.

**Figure 3.15** Spatial evolution of the fitting parameters of Eq. (3-1) with fetch over the urban model calculated at positions A (along Canale Rosciano, circles) and L (regular grid, triangles): friction velocity $u^*$ (top), roughness length $z_0$ (center), zero plane displacement $d$ (bottom). The linear regressions for $u^*$, $z_0$, and $d$ are also shown. The dotted lines in the top and central panels correspond to the inlet profile’s values of $u^*$ and $z_0$. 
3.5 Conclusions and perspectives

The present paper described an experimental research project aimed at investigating the wind flow pattern in a historical district of Livorno city (Italy), so called Quartiere La Venezia. A set of WT measurements was carried out over the district by means of a detailed WT model in scale 1:300. The first set of tests focused on the mean wind profiles measured at different measuring positions (A1 - A5) placed inside Canale Rosciano, for three different inflow directions (\( \alpha = 240^\circ \), \( \alpha = 270^\circ \), \( \alpha = 300^\circ \)). The obtained values showed a strong reduction of the wind velocity in the UCL, in particular for levels lower than 1.5 \( h_b \), which is the mean height of the buildings.

The second set of tests was carried out on a regular grid of positions (L1-5, L2-5, L3-5), in order to systematically observe the wind flow pattern in the UBL. In particular, the development of the boundary layer with fetch was analyzed. It turned out that, after the discontinuity between the inflow condition and the WT model, the wind profile’s parameters follow quite a regular evolution along the measuring positions, according to a linear decreasing (increasing) trend for friction velocity and roughness length (zero plane displacement). The discontinuity between inlet boundary layer and UBL was rather abrupt, i.e. \( u^* \) increased from 0.9 to about 1.2-1.3 m/s and \( z_0 \) from 0.1 to about 1.0-1.1 m, depending on the wind direction considered; however, dedicated measurements should be performed to get a more accurate description of this behaviour along the transition, which have not been performed yet.

These results were critically compared with other similar tests available in the literature (Kastner-Klein and Rotach, 2004; Cheng and Castro, 2002). The comparison with (Cheng and Castro, 2002), in particular, showed satisfactory agreement as far as the variability of the friction velocity is concerned, providing further confirmation that in the transition between surfaces with lower to higher aerodynamic roughness the skin friction coefficient did not remain unchanged, which is also relevant in the context of the blending height concept for velocity (Barlow, 2014). Conversely, the evolution of the roughness length was different from the one reported by (Cheng and Castro, 2002), so that this parameter was more case specific than \( u^* \) and further investigations deserve. Note that, however, both results were consistent with the morphometric models for \( z_0 \) in (Cheng and Castro, 2002) the frontal area density did not change in the canopy and the roughness length, immediately after the transition, which unavoidably cause a more or less sharp discontinuity, was approximately constant; in the present case the
frontal area density increased with fetch and the roughness length decreased accordingly. Similar considerations hold for the zero plane displacement, which increased in the present case as well as in (Kastner-Klein and Rotach, 2004) according to the increase of plane area density of both wind tunnel models.

Finally, at present it is not clear whether the wind profile parameters converge towards some asymptotical values for longer fetches, as one might expect, and how long the fetch should be to get stable values. In our model the parameters vary along the whole district, which is approximately 300 m (full scale equivalent), without reaching any steady condition.

3.6 References


Cui, P.Y., Li, Z., Tao, W.Q., 2016. Wind-tunnel measurements for thermal effects on the air flow and pollutant dispersion through different scale urban areas. Building and Environment 97, 137-151.


Part II

CFD SIMULATIONS
Chapter 4

The impact of geometrical simplifications

This chapter has been submitted for publication as:


Wind flow in urban areas is strongly affected by the urban geometry. In the last decades most of the geometries used to reproduce urban areas, both in wind tunnel (WT) tests and Computational Fluid Dynamics (CFD) simulations, were simplified compared to reality in order to limit experimental effort and computational costs. However, it is unclear to which extent these geometrical simplifications can affect the reliability of the numerical and experimental results. The goal of this paper is to quantify the modeling errors caused by geometrical simplifications. WT tests were firstly performed at scale 1:300 for three wind directions for the “Quartiere La Venezia” district of Livorno city (Italy). Next, wind flow in two CFD models with different levels of geometric detail has been simulated at the same reduced scale using the 3D steady Reynolds-averaged Navier-Stokes (RANS) approach. Finally, a comparison in terms of mean wind velocity profiles between WT test results and CFD simulations was made, and the agreement was quantified using four validation metrics (FB, NMSE, R and FAC1.3). The results show that the more detailed geometry provided significantly improved performance, especially for the wind direction $\alpha = 240^\circ$ (22% difference in terms of FAC1.3).
4.1 Introduction

The fabric of cities and the complexity of their morphology make the analytical description of wind flow in urban areas very difficult. Analytical wind flow models are generally well established over flat open terrain, where the wind profiles mainly depend on the aerodynamic roughness of the surface and on thermal stratification. In contrast, wind flow in urban environments is dominated by a variety of complex factors, such as the heterogeneous geometry of buildings, separation, recirculation and local thermal effects.

The region above the buildings, usually defined as urban boundary layer (UBL), is influenced by continuously changing surface roughness, so that the wind flow never reaches an equilibrium condition. The situation is even more complex within the canopy layer, where streets give rise to complex canyoning effects that are strongly dependent on the canyon orientation with respect to the incoming wind. Many researchers have investigated different aspects of urban flows (see e.g. reviews by Britter and Hanna, 2003; Fernando, 2010; Fernando et al., 2010), but at present the UBL is not yet completely understood although WT tests and CFD simulations are frequently used in engineering applications.

In the last decades several studies have focused on wind flow numerical modeling over random urban like obstacles (e.g. Xie et al., 2008), uniform and staggered building arrays (e.g. Coceal and Belcher 2003; Xie and Castro, 2006; An et al., 2013; Razak et al., 2013), idealized urban surfaces (e.g. Cheng and Porté-Agel, 2015) a semi idealized urban canopy (e.g. Hertwig et al., 2012) and actual urban environments (Janssen et al., 2013; Montazeri et al., 2013; García Sánchez et al., 2014). In general, there are many uncertainties and errors related to geometrical model precision, inflow conditions, turbulence model, discretization schemes and numerical approaches (RANS, LES, DNS) - (Emory et al., 2013; Gorlé et al., 2015). Carpentieri and Robins (2015) have recently analyzed the impact of morphological parameters on flow in the urban canopy layer (UCL). Their results show how the building height variability, the angles between street canyon orientations and incoming wind and other local geometrical features can heavily influence the characteristics of the urban flow.

Several authors (Chang and Meroney, 2003; Fernando, 2010; Barlow, 2013) underline that the complexity of the UBL requires studies with multiple approaches with complementary strengths and weaknesses. WT tests and CFD numerical simulations are used by many researchers. The joint use of these two techniques has
enabled a better understanding of urban aerodynamics and has enhanced the performance of both (Murakami, 1990; Stathopoulos, 1997; Baker, 2007; Tominaga and Stathopoulos 2013; Blocken, 2014, 2015; Meroney, 2016). However, results of both techniques are strongly dependent on geometrical model details (AIAA, 1998; ERCOFTAC, 2000; AIJ, 2004; Franke, 2006; Blocken, 2014). Nevertheless, geometrical simplifications are often required in both techniques, and the question therefore arises how different levels of simplification affect the results.

The aim of this study is to quantify the so called computational uncertainty (AIAA, 1998; Oberkampf et al., 2004; Versteeg and Malalasekera, 2007) caused by geometrical simplifications of the urban model, both intentionally imposed (e.g. to limit experimental manufacturing cost or computational cost) and arising from a limited knowledge of the system to be analyzed (e.g. the epistemic uncertainty). For this purpose, a historical district so called “Quartiere La Venezia” in Livorno city (Italy) was selected as case study. This area was chosen because the nearby port was monitored by several different measurement instruments in several locations, which will provided input data and validation data for the present study. They consist of anemometric stations and a LiDAR wind profiler installed in the framework of the European projects “Wind and Ports” (Solari et al., 2012) and “Wind, Ports, and Sea” (Burlando et al., 2015a). The location is particularly interesting since the highest wind velocity observations generally occur for Western winds, in which case the incoming velocity profile in the district can be measured through the aforementioned LiDAR station (Fig. 4.1). Moreover, the transition from sea to land is expected to strongly influence the vertical wind profile in this area.

The study was carried out in two steps. In the first step WT tests on a WT model (at scale 1:300) were performed and the mean profiles of velocity and turbulence intensity were measured at several positions: in the street canyon “Canale Rosciano” and in specific positions of a local reference system. The results were reported in a previous publication (Ricci et al., 2017). In the second step, reported in the present paper, 3D steady state RANS simulations using the realizable k-ε turbulence model were performed at the same scale as the WT tests. Two geometries with different levels of precision were tested, i.e. a simplified and an approximated model.

The remainder of this chapter is organized as follows. Section 4.2 contains a short description of the WT test data used to validate the numerical simulations. Section 4.3 describes the CFD models (simplified and approximated), the boundary conditions and the computational setup. Section 4.4 shows the comparison of the
WT and CFD results in terms of mean wind velocity profiles. In Section 4.5, the level of agreement between WT and CFD results is quantified using validation metrics. Finally, Section 4.6 (discussion and limitations) and Section 4.7 (summary and conclusions) conclude the paper.

4.2 Description of the experimental setup

Only the most important aspects of the experimental tests are discussed in this section; the reader is referred to Ricci et al. (2017) for more details. Experimental tests on the WT model were performed in the atmospheric boundary layer (ABL) wind tunnel of the Department of Civil, Chemical and Environmental Engineering (DICCA) of the University of Genoa, Italy. The wind tunnel at DICCA is a closed subsonic circuit with a test section of 8.8 m long and a cross section of 1.70 m (width) × 1.35 m (height). A WT model of the case study - Quartiere la Venezia in Livorno city - was created at a scale of 1:300 using medium density fiberboard (MDF) of different thicknesses for the ground plates and buildings, and 3 mm closed cell PVC foamboard panels for roofs and bridges (Fig. 4.2a). In order to minimize interactions between the WT model and the WT walls, the blockage ratio in the cross section was kept below 3.5% for all wind directions. Three western wind directions were tested (α = 240°, 270° and 300°), corresponding to the prevalent wind directions for the strongest winds (Fig. 4.2). The mean wind velocity

Figure 4.1 Pictures of Livorno city (Italy): (a) location of the test district (yellow circle), anemometric stations (A_{vp} 3, A_{vp} 4 and A_{vp} 6) and LiDAR station, (b-c) test district Quartiere La Venezia, (d) Canale Rosciano (West - East), (e) Canale Rosciano (East - West), (f) a small canal inside Quartiere La Venezia.
scenarios obtained during the European project ‘Wind and Ports’ (Solari et al., 2012) by means of the WINDS model (Wind Interpolation by Non-Divergent Schemes), anemometric data, and the digital land cover maps of the CORINE project (Bossard et al., 2000) were used as reference for the choice of the incoming flow profiles in the WT tests (Fig. 4.3). Based on this an ABL profile with aerodynamic roughness length $z_0 = 0.1$ m and friction velocity $u^* = 0.89$ m/s was used for the WT tests.

Mean wind velocity values were measured in two sets of positions (Fig. 4.4). In the first set 10 positions inside Canale Rosciano (A1 - A5) were monitored at 15 heights in the range from 0.02 to 0.6 m above the bottom (i.e. from 6 to 180 m above sea level - full scale equivalent). The anemometric station at point A1 is placed on the building roof of the Livorno Port Authority at 30 m above sea level. Since these positions are fixed to the model geometry, their position in the tunnel is dependent on wind direction. The second set was distributed along a Cartesian grid laid out according to the WT local reference system, consisting of 15 measurement positions at 15 heights, from 0.02 to 0.6 m above the bottom, aligned on three lines of five measurement positions each (L1, L2, L3). Since these positions are fixed to the WT section, their location with respect to the WT model is dependent on wind direction. The first set was used to obtain information related to the flow pattern in the UCL while the second set was used to investigate the wind flow pattern in the UBL. Both sets of measurements will be used to validate the CFD simulations performed for the two models described in Section 4.3.

**Figure 4.2** Wind tunnel setup: (a) digital model used to build the WT model, (b) WT schematic, (c) pictures of the WT model. Only the extruded buildings (a) were built in the WT model.
Figure 4.3 Relationship between the WT test section and the CFD computational domain. Top: top view. Bottom: side view. Symbols: \((W)\) width and \((H)\) height of the WT and computational domain; \((L_{WT})\) length of the test section; \((L)\) distance between the measured wind profile and the end boundary; \((L_{CFD})\) length of the computational domain; \((15h_{max})\) distance between the last building of the urban model and the outlet face of the computational domain, where \(h_{max}\) is the maximum height of buildings.

Figure 4.4 Location of measurement positions \((L_{1,5}, L_{2,5}, L_{3,5})\) (a) and \((A_{1-5})\) (b) in the investigated district of Livorno city.
4.3 CFD simulations: computational settings and parameters

4.3.1 Computational geometry, domain and grid

CFD simulations were performed at WT scale (1:300) for the same wind directions of the WT tests ($\alpha = 240^\circ, 270^\circ, 300^\circ$). As shown in Fig. 4.3, in order to facilitate the comparison between WT and CFD results a portion of the WT test section was reproduced by the computational domain (Moonen et al., 2006; Yoshie et al., 2007; Juretić and Kozmar, 2013; Calautit et al., 2014). In particular, the size adopted for the domain was $L \times W \times H = 5.5 \times 1.70 \times 1.35 \text{ m}^3$, where the width ($W$) and height ($H$) were coincident with the WT cross section while the length ($L$) represents the downstream part of the test section. As recommended by Blocken (2015) three different blockage ratios were calculated: the vertical blockage ratio $BR_H$, the transversal blockage ratio $BR_L$ and the frontal area blockage ratio $BR$. Ideally these ratios should be below 17% for the first two and 3% for the last one. The values given in Eq. (4-1) below show that this criterion was met for $BR_H$ but not for $BR$ and $BR_L$: especially the value for $BR_L$ is quite high. However, the projected frontal area gives an overly pessimistic estimate of the importance of blockage effects due to the existence of streets in the model through which air can flow. Furthermore, since all measurement positions were located in the central part of the urban model, the effect of possible artefacts near the edges of the model on observations in these measurement positions is expected to be limited. Regardless, most important for the validation study is that the cross section of the computational domain matches the WT cross section.

$$BR = \frac{A_{\text{building}}}{A_{\text{domain}}} = 3.5\% \quad BR_H = \frac{H_{\text{building}}}{H_{\text{domain}}} = 5.8\% \quad BR_L = \frac{L_{\text{building}}}{L_{\text{domain}}} = 58.8\%$$ (4-1)

Two CFD models with different levels of precision were constructed using Gambit 2.4.6. The first model, referred to as simplified model, was obtained by representing groups of buildings as single bluff bodies with a height equal to the arithmetic average height of that building group. The second model, so called the approximated model, was obtained by including buildings with their real ground plan and heights, but replacing pitched roofs with flat ones. The computational grids were constructed using the grid generation technique presented by van Hooff and Blocken (2010) in order to achieve a high level of control over the grid layout. This is especially important close to the ground, near the walls of the buildings and inside the narrow canals and streets. The grids were constructed using best practice
The impact of geometrical simplifications (Franke et al., 2007; Tominaga et al., 2008; Blocken et al., 2015). At least ten cells were used along every building edge and street width. The grids for both models are displayed in Fig. 4.5 for the wind direction $\alpha = 240^\circ$. In order to avoid convergence problems and maximize numerical accuracy, only hexahedral and prismatic cells were used. Three grids were generated for each of the geometries, one for each wind direction. Key statistics for each grid are shown in Tables 4.1 and 4.2. It can be seen that the approximated models required roughly twice the effort than the simplified ones, both in terms of the mesh procedure and the required runtime. A comparison between the real urban area, the WT model and both CFD models is presented in Fig. 4.6.

Table 4.1
Comparison of computational grids for the simplified and approximated models.

<table>
<thead>
<tr>
<th>Wind direction</th>
<th>Simplified model (No. of cells)</th>
<th>Approximated model (No. of cells)</th>
<th>App/Sim</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha = 240^\circ$</td>
<td>13,205,730</td>
<td>23,275,935</td>
<td>1.76</td>
</tr>
<tr>
<td>$\alpha = 270^\circ$</td>
<td>11,283,586</td>
<td>20,817,834</td>
<td>1.84</td>
</tr>
<tr>
<td>$\alpha = 300^\circ$</td>
<td>11,394,163</td>
<td>19,915,959</td>
<td>1.75</td>
</tr>
</tbody>
</table>

Figure 4.5 Pictures of computational grid for simplified (left), and approximated (right) CFD models of Livorno city for the wind direction $\alpha = 240^\circ$. 

Table 4.1
Comparison of computational grids for the simplified and approximated models.
Table 4.2  
Comparison of effort required for the simplified and approximated models.

<table>
<thead>
<tr>
<th>Computational time</th>
<th>Simplified model</th>
<th>Approximated model</th>
<th>App/Sim</th>
</tr>
</thead>
<tbody>
<tr>
<td>total time for grid generation (h)</td>
<td>432</td>
<td>687</td>
<td>1.59</td>
</tr>
<tr>
<td>total runtime (h)</td>
<td>234</td>
<td>402</td>
<td>1.72</td>
</tr>
</tbody>
</table>

Figure 4.6 Quartiere La Venezia: view from wind direction $\alpha = 240^\circ$. (a) Photo of the actual area, (b) photo of the WT model, (c) computational grid of the simplified CFD model, (d) computational grid of the approximated CFD model.

4.3.2. Boundary conditions

At the domain inlet the experimental inflow conditions were reproduced by prescribing the mean wind velocity profile $U(z)$ detected approximately 1 m upstream of the urban model in the WT. The turbulent kinetic energy $k(z)$ and the turbulence dissipation rate $\varepsilon(z)$ were calculated using the equations below (Tominaga et al., 2008):

$$k(z) = \frac{1}{2}(\sigma_u^2(z) + \sigma_r^2(z) + \sigma_w^2(z))$$  \hspace{1cm} (4-2)

$$\varepsilon(z) = C_\mu k(z) \frac{dU}{dz}$$  \hspace{1cm} (4-3)
For Eq. (4-2) the velocity standard deviations $\sigma_u(z)$, $\sigma_v(z)$ and $\sigma_w(z)$ obtained in the WT tests were employed. In Eq. (4-3) the model constant $C_\mu$ is 0.09 and a smoothing function was used to remove excessive numerical noise introduced by the gradient calculation. Since the WT equipment does not allow measurements to be made over the entire height of the WT, mean wind velocities and velocity standard deviations were directly measured only from 0 to 0.6 m and from 1.20 and 1.35 m. In the central part, between 0.6 and 1.20 m, these quantities were linearly interpolated in order to link both measured parts (Fig. 4.7). It should be noted that the height of the tallest building is 0.15 m, and as a result the particular shape of the vertical profiles above 0.6 m is expected to be of minor or no importance for the resulting flow patterns below the 0.15 m threshold. At the outlet mean zero static pressure was imposed. At the sides and top of the domain as well as on the building and bridge surfaces standard wall functions were employed using a roughness height $k_s$ equal to zero. At the bottom of the domain, the same wall functions were used with a roughness length $\zeta_0$ equal to 0.0033 m. An overview of these boundary conditions is given in Fig. 4.8. From the friction velocity $u^*$, derived from the measured mean wind profile $U(z)$ by a fit with a log law, the size of the first near wall cell was chosen in order to obtain dimensionless wall unit values $y^+$ in the logarithmic layer range (30-300; Blocken et al., 2007a,b).

![Figure 4.7 Inflow profiles: mean wind velocity ($U$), turbulent kinetic energy ($k$) and turbulence dissipation rate ($\varepsilon$). Also indicated are measured values (black circles) and assumed values (orange dots). The height of the tallest building ($h_{max}$), as indicated by the blue rectangle in the figure, is equal to 0.15 m.](image)


The equivalent sand grain roughness \( k_s \) was calculated \((k_s = 0.0013 \text{ m})\) in accordance with Blocken et al. (2007a) as \( k_s = 9.793 z_0 / C_s \), where \( C_s \) (the roughness constant) was taken equal to 2.5 in order to comply with the necessary condition \( y_p > k_s \), where \( y_p \) is the distance of the centroid of the first cell from the wall.

### 4.3.3. Solver settings

The CFD simulations were performed using the open source CFD package OpenFOAM 2.3.0 using the 3D steady state RANS approach. The realizable \( k-\varepsilon \) turbulence model was adopted for closure (Shih et al., 1995). Second order discretization schemes were used for the convective and viscous terms of the governing equations. The SIMPLE algorithm was adopted to couple pressure and velocity fields (Patankar, 1980; Ferziger and Perić, 2002). Numerical convergence was achieved when the residuals showed no discernible fluctuation and further decrease during the iterative process. All CFD simulations were performed on a High Performance Computing (HPC) system at DICCA, using a computer node with 32 cores running in parallel at 1.4 GHz.

### 4.4 Comparison of WT and CFD results

#### 4.4.1 Contours of amplification factor

Wind velocity contours were analyzed through various horizontal and vertical sections made at different heights and widths of the computational domain. Fig. 4.9 shows - at 0.02 m above the bottom - the wind amplification factors, defined as the local wind velocity magnitude divided by the inlet wind velocity magnitude at the same height, \( U_{in,0.02m} \), for both CFD models and for three wind directions.
In Figs. 4.9a-b ($\alpha = 240^\circ$), the Canale Rosciano is almost aligned with the incoming wind direction and, as a result, the wind flow is funneled through the canal. Separation and reversal zones are not observed along the canal for this wind direction. Inside the canal, the wind velocity in the simplified model is substantially higher than in the approximated one.

In Figs. 4.9c-d ($\alpha = 270^\circ$), the Canale Rosciano is more sheltered from the wind compared with the previous direction. The simplified model shows higher wind velocities in the central part of the domain (to the North of the Canale Rosciano) with respect to the approximated one.

From Figs. 4.9e-f ($\alpha = 300^\circ$), the Canale Rosciano is about perpendicular to the approach flow, and it is therefore to a large degree sheltered by the upstream buildings. The approximated model shows higher wind velocities and more extensive leeward zones at the beginning and the end of the canal, respectively. Overall, for this wind direction, the CFD simulations seem to be quite sensitive to the geometric detailing (Fig. 4.10). Important differences between the two levels of detail employed in this study are found inside the narrow street and canal.

Fig. 4.11 shows wind velocity contours of both CFD models at the centerline of the computational domain for the wind direction $\alpha = 240^\circ$. The velocity values are normalized with respect to the maximum inflow wind velocity measured at 0.6 m above the bottom $U_{in,0.6m}$. Despite the fact that model detail can heavily modify the wind flow behavior inside the urban context, overall, the thickness of the UBL is described similarly by both CFD models. Indeed, Fig. 4.11 showed almost the same horizontal development of stratification for the simplified and approximated models, although the maximum height of the buildings was different for both models (0.10 and 0.15 m). This is useful information in our understanding of the physical interpretation of displacement height.
Figure 4.9 Contours of wind amplification factor: comparison between simplified and approximated models for wind directions (a, b) $\alpha = 240^\circ$, (c, d) $\alpha = 270^\circ$ and (e, f) $\alpha = 300^\circ$ - horizontal sections (left) and axonometric view (right) made at 0.02 m above the bottom. Canale Rosciano is indicated by “CR” in the figures.
4.4.2 Vertical wind profiles

Fig. 4.12 shows mean wind velocity profiles obtained from the WT and CFD models for three wind directions at four positions. The set of measuring positions placed at the central line of the Canale Rosciano (A2 - A5) were chosen in order to understand the canyoning effects inside the urban area. The axes show the ratio $U/U_{in,0.6m}$ (abscissa) vs. normalized reference height $z/z_{ref}$ (ordinate), with the incoming wind velocity $U_{in,0.6m}$ measured at a reference height of $z_{ref} = 0.6$ m as
normalization factor. Overall, above roughly 0.17 m, corresponding to $z/z_{ref} \approx 0.28$, the mean wind profiles are undisturbed for all models (WT, simplified CFD, approximated CFD) and approximately coincident with the incoming profiles, especially for the wind direction $\alpha = 240^\circ$. In the latter case ($\alpha = 240^\circ$) the wind is approximately aligned with the Canale Rosciano and can flow through the city blocks rather freely. It is also evident that, when the orientation of the Canale Rosciano is more inclined with respect to the incoming wind (from $\alpha = 240^\circ$ to $\alpha = 300^\circ$), the CFD profiles show the same velocity up as the WT tests in the higher part of the profiles. At lower heights, the wind velocity profiles are strongly modified by the buildings and the different degrees of precision with which they are represented turn out to have a large effect on the flow, especially inside the narrow street and canal.

Fig. 4.12a ($\alpha = 240^\circ$): at point A2, where the incoming flow is aligned with the canal, the agreement between CFD and WT results is satisfactory. At point A3 the CFD model predictions are less accurate. Intentionally chosen, this point is located directly leeward of the important bridge near the city center and in the middle of a crossroads. At point A4 the level of detail of the CFD model plays a key role. In this part of the canal the incoming flow is no longer perfectly aligned with it, and the wake effects due to the presence of the buildings can be extremely dependent on their shape. Whereas the velocity profile of the approximated model shows a very similar trend compared with the WT profile, the simplified model displays a larger gap to the WT results between the 0.06 and 0.16 m levels. In the last position A5, which is located in the middle of a canal curve, the approximated model again leads to a better prediction than the simplified one. Overall, for this wind direction, the approximated model shows better agreement with WT measurements than the simplified one. This is also true for the measuring positions which are not reported here.

Fig. 4.12b ($\alpha = 270^\circ$): at point A2, the agreement between the CFD models and the WT data is almost the same as for the wind direction $\alpha = 240^\circ$, and the profiles show a perfect match in the higher part of the domain down to $z/z_{ref} = 0.1$ (0.06 m above the bottom). The discrepancy between WT and CFD results becomes significant close to the ground, though, at positions A3 and A4 important differences are found between 0 and 0.2 $z/z_{ref}$. As previously stated, these positions are located directly leeward of some buildings (see also Figs. 4.9c-d), where the results are affected by the underestimation of the turbulent kinetic energy $k$ due to
the 3D steady state RANS approach here adopted. As an example, Fig. 4.13 shows the underestimation of turbulent kinetic energy for all wind directions at position A3. The quantitative agreement between WT and CFD results is unsatisfactory for this wind direction, although the qualitative wind profile development of the models inside the Canale Rosciano (from point A2 to A5) is somewhat similar. This is probably due to the canyoning effects along the water canal. The worst agreement between CFD and WT results occurs at point A2 below $z/z_{ref} = 0.15$, at point A3 below $z/z_{ref} = 0.3$, at point A4 below $z/z_{ref} = 0.35$ and at point A5 below $z/z_{ref} = 0.45$.

Fig. 4.12c ($\alpha = 300^\circ$): The worst performance of the CFD models is obtained for this wind direction. The buildings located at the edge of the Canale Rosciano represent a barrier for the wind flow. Only for point A2, located windward of the canal, the comparison is satisfactory. For the rest of the positions (A3, A4 and A5) the CFD profiles are quite different from the WT ones. The wind flow is not channeled along the Canale Rosciano and canyoning effects occur in the simulations behind the buildings placed at the edge of the channel: see Figs. 4.9e-f. This aspect explains the trend of the profiles at different positions. The worst agreement between CFD and WT results is observed at position A2 below $z/z_{ref} = 0.1$, and at positions A3, A4 and A5 below $z/z_{ref} = 0.45$. 
Figure 4.12 Comparison of the vertical mean wind velocity profiles at the positions A2 to A5 for the inflow directions (a) $\alpha = 240^\circ$, (b) $\alpha = 270^\circ$ and (c) $\alpha = 300^\circ$, for the simplified model (CFD sim), approximated model (CFD app), and WT model (WT). The inlet profile (black dashed line) is also shown for comparison.
4.4.3. Error analysis along vertical lines

A comparison between the CFD and WT test results was made along vertical lines at the positions A2₁ and A4₁ (see also Fig. 4.4) for 15 heights and three wind directions. Normalized mean wind velocities in the CFD results and WT data are plotted against each other in Fig. 4.14. The abscissa reports the ratio between the mean wind velocity measured at height $z$ and the reference mean wind velocity measured at $z = 0.6$ m above the bottom ($U_{ref}$) in the WT tests; the ordinate axis shows the same ratio for the CFD results. The same wind flow behavior already described in Section 4.4.2 for the positions at the center of the canal (A2₂, A3₂, A4₂ and A5₂) is also observed for the positions located close to buildings at the border of the canal (A2₁, A3₁, A4₁ and A5₁). Fig. 4.14a shows better agreement between the approximated model and the WT model than the simplified one. In the latter case the velocity ratio is overestimated compared to the WT data. In contrast, the approximated model shows a slight underestimation of the velocity values close to the ground. For the inflow direction $\alpha = 270^\circ$, shown in Fig. 4.14b, remarkable discrepancies are observed between the CFD and WT velocity ratios, especially at point A4₁ near the ground. This is found for both models, probably due to the flow reversal zones close to the walls (see Fig. 9c-d). The results shown in Fig. 4.14c are consistent with those for the central line of the Canale Rosciano (Fig 4.12c). The large deviations between CFD and WT results highlighted at point A2₁ for this inflow direction are more pronounced for the simplified model than for the approximated one.
direction ($\alpha = 300^\circ$) can be due to the zone of flow separation present at the beginning of the canal (see Figs. 4.9e-f). Underestimation and overestimation of the velocity ratios occur at point A4i, in the lower and higher part of the profiles, respectively. Fig. 4.14 clearly shows one of the limitations of this study. As a matter of facts, the accuracy that can be achieved is most likely limited by the deficiencies of the 3D steady state RANS approach. The use of a more accurate geometry may therefore not lead to improved predictions within the areas where nonstationary flow patterns occur. This limitation was already pointed out, for instance, by Murakami (1993) and Tominaga et al. (2008b), who have discussed this for building aerodynamics and by Burlando et al. (2015b), who have discussed this point using an analogous CFD model to simulate the flow around a vertical axis wind turbine.

Figure 4.14 Comparison of normalized mean wind velocity values along the vertical profiles A2i - A4i for inflow directions (a) $\alpha = 240^\circ$, (b) $\alpha = 270^\circ$ and (c) $\alpha = 300^\circ$ for the WT model (WT), simplified and approximated models. Dashed lines correspond to 10% errors.
4.5 Deviations caused by geometrical simplifications

4.5.1 Validation metrics

The statistical performance of both CFD models was evaluated (Chang and Hanna, 2004; Gousseau et al., 2013) in order to quantify the agreement in the mean velocity \( U \) between WT and CFD results. Based on the study by Schatzmann et al. (2010), four different validation metrics were used:

\[
FB = 2 \frac{(\overline{U_{WT}} - \overline{U_{CFD}})}{\overline{U_{WT}} + \overline{U_{CFD}}}
\]

\[
NMSE = \frac{(\overline{U_{WT}} - \overline{U_{CFD}})^2}{\overline{U_{WT}} \cdot \overline{U_{CFD}}}
\]

\[
R = \frac{\overline{(U_{WT} - \overline{U_{WT}})(U_{CFD} - \overline{U_{CFD}})}}{\sigma_{U_{WT}} \cdot \sigma_{U_{CFD}}}
\]

\[
1/1.3 \approx 0.77 \leq \frac{\overline{U_{CFD}}}{\overline{U_{WT}}} \leq 1.3
\]

Here \( \overline{U_{WT}} \) is the mean wind velocity magnitude (m/s) from the WT experiments, \( \overline{U_{CFD}} \) is the mean wind velocity magnitude from the CFD simulations (m/s) using the simplified or approximated model, and \( \sigma \) is the standard deviation over a specific dataset. The ideal values corresponding to complete agreement between CFD and WT results are \( FB = 0, \ NMSE = 0, \ R = 1 \) and \( FAC1.3 = 1 \).

4.5.2 Statistical performance: wind velocities in horizontal planes

The validation metrics were calculated on horizontal planes at 15 heights (\( z \)) (from 0.02 m to 0.6 m above the bottom) for all measuring positions A and L (overall 25 positions) and for all inflow wind directions (\( \alpha = 240^\circ, \alpha = 270^\circ, \alpha = 300^\circ \)). Results for a height of \( z = 0.02 \) m above the bottom are given in Table 4.3 for each considered wind direction. Results of Table 4.3 are based on data which are graphically displayed in Fig. 4.15. On the abscissa the mean wind velocity value \( U_{WT} \) measured at all available positions is displayed, normalized with respect to the mean inlet wind velocity magnitude taken at reference height \( U_{in,0.02} \) (0.02 m above the bottom). The equivalent ratio \( \overline{U_{CFD}}/U_{in,0.02} \) of the WT data is reported on the ordinate.
For a wind direction of $\alpha = 240^\circ$ the $FB$ values of the *approximated* model clearly show a tighter distribution around the diagonal compared to the *simplified* model, indicating better agreement. For $\alpha = 270^\circ$ the same $FB$ value is obtained for both models while for $\alpha = 300^\circ$ the *simplified* model performs slightly better than the *approximated* one. A similar trend is observed for the $NMSE$ which shows better performance of the *approximated* model for $\alpha = 240^\circ$. Its performance becomes comparable to that of the *simplified* model for $\alpha = 270^\circ$ while it is slightly outperformed by the *simplified* model for $\alpha = 300^\circ$. The correlation coefficient $R$ of the approximated models is in general fairly good. For $\alpha = 240^\circ$ and $\alpha = 300^\circ$ the *approximated* model clearly performs better than the *simplified* model while they show similar performance for $\alpha = 270^\circ$. Finally, the metric $FAC1.3$ has been used to understand how many data positions fall within 30% of experimental data. No difference in the performance of both models is observed in this metric for $\alpha = 270^\circ$ and $\alpha = 300^\circ$, while the *approximated* model performs much better for $\alpha = 240^\circ$.

**Table 4.3**
Validation metrics ($FB$ = Fractional Bias, $NMSE$ = Normalized Mean Square Error, $R$ = correlation coefficient, $FAC1.3$ = Fraction of data within a factor of 1.3) for both models, three inflow directions ($\alpha = 240^\circ$, $\alpha = 270^\circ$, $\alpha = 300^\circ$), and 25 measurement positions (A and L) at $z = 0.02$ m above the bottom. Also indicated are the number of measurement positions that were not occupied by the urban model and were therefore available for statistical analysis (note that this depends on the wind direction as positions L are fixed with respect to the WT).

<table>
<thead>
<tr>
<th>$\alpha = 240^\circ$, $z = 0.02$ m</th>
<th>CFD sim vs WT</th>
<th>CFD app vs WT</th>
<th>ideal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$FB$</td>
<td>-0.15</td>
<td>-0.04</td>
<td>0</td>
</tr>
<tr>
<td>$NMSE$</td>
<td>0.07</td>
<td>0.04</td>
<td>0</td>
</tr>
<tr>
<td>$R$</td>
<td>0.64</td>
<td>0.77</td>
<td>1</td>
</tr>
<tr>
<td>$FAC1.3$</td>
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<td>0.89</td>
<td>1</td>
</tr>
<tr>
<td>Samples</td>
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<td>18</td>
<td>25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\alpha = 270^\circ$, $z = 0.02$ m</th>
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<th>CFD app vs WT</th>
<th>ideal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$FB$</td>
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<tr>
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<td>0.12</td>
<td>0</td>
</tr>
<tr>
<td>$R$</td>
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<td>1</td>
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<tr>
<td>$FAC1.3$</td>
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<td>1</td>
</tr>
<tr>
<td>samples</td>
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<td>25</td>
</tr>
</tbody>
</table>
The impact of geometrical simplifications

<table>
<thead>
<tr>
<th>$\alpha = 300^\circ$, $z = 0.02$ m</th>
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<th>CFD app vs WT</th>
<th>ideal value</th>
</tr>
</thead>
<tbody>
<tr>
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<td>$FACI.3$</td>
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</tr>
</tbody>
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| Figure 4.15 | Comparison of CFD and WT data at the monitored positions (A and L) for inflow directions: (left) $\alpha = 240^\circ$, (center) $\alpha = 270^\circ$, (right) $\alpha = 300^\circ$ at a height $z = 0.02$ m above the bottom. Dashed black lines correspond to 10% and 30% errors. |

4.6 Discussion and limitations

In this case study, 3D steady state RANS with the realizable $k$-$\varepsilon$ turbulence model is applied to simulate mean wind velocity patterns in an urban environment reproduced at reduced scale (1:300). According to Moonen et al. (2006), a portion of the WT section was reproduced by the computational domain in order to facilitate the comparison between WT and CFD results. This study is based on several assumptions:

- The study was performed for only a single city district. Nevertheless, the selected area may be considered representative of many historic towns including different types of buildings and narrow and curved streets.

- WT tests and CFD simulations were performed only for a neutrally stratified ABL flow, which typically occurs at the highest wind velocities.

- Only two geometries with different degrees of precision were constructed, referred to as the simplified and the approximated ones. Although the latter is similar to the urban model used for WT testing, some simplifications were
still made (e.g. flat roofs instead the pitched roofs) in order to simplify the meshing procedure.

- CFD simulations were performed using the 3D steady state RANS approach, which is known to be deficient especially in separation zones. Large Eddy Simulation (LES) are currently planned in order to investigate the impact of this limitation.

- Only a limited number of measuring positions (25 positions in the horizontal plane) was taken into account during the WT tests and subsequently used to validate the CFD results. For each point, however, 15 different heights were monitored in the vertical direction, so that the overall number of positions is actually equal to 375. These positions, in turn, were measured for three wind directions, which means 1125 independent measurements.

In spite of these limitations, the numerical simulations showed a satisfactory agreement with the WT tests for wind direction $\alpha = 240^\circ$ when the finer geometry (approximated model) was used.

4.7 Summary and conclusions

In this paper the local scale forcing effects on wind flows in an urban environment were evaluated. 3D steady state RANS simulations were performed on a selected case study, the Quartiere la Venezia in Livorno city (Italy), for three wind directions ($\alpha = 240^\circ, 270^\circ, 300^\circ$) at the same reduced scale (1:300) of previously performed WT tests. In order to investigate to which extent geometrical model details can affect CFD and WT results, two geometries with different degrees of precision were constructed: the simplified (coarser) and the approximated (finer) model. The mean wind velocity profiles in both CFD models at 25 positions for 15 heights each and three different wind directions were compared with the WT test results. In order to quantify the agreement between WT and CFD results, the statistical performance was evaluated using four different validation metrics: $FB$, $NMSE$, $R$ and $FAC1.3$.

From this study, the following observations can be made:

- The velocity contours have shown the sensitivity of the simulations to the different degrees of model precision. The largest differences between flow fields in the approximated and simplified models were found in the narrow streets and canal, especially for a $240^\circ$ wind direction.
The impact of geometrical simplifications

- Although the geometric detail can heavily affect the wind flow behavior inside the urban context, the thickness of the UBL is similar for both CFD models.
- For the wind directions $\alpha = 270^\circ$ and $\alpha = 300^\circ$, corresponding to a decrease of the flow alignment with respect to the Canale Rosciano, the agreement between CFD and WT results decreases.
- The CFD results confirm that poor correspondence between CFD and WT test results is found in locations where nonstationary phenomena occur. It is likely that here the 3D steady state RANS approach becomes the main source of error, in which case a more detailed geometry may not improve the flow prediction.
- The validation metrics ($FB$, $NMSE$, $R$ and $FAC1.3$) confirm that the finer geometry on average assures notably better performance than the coarse one.

Overall, wind flow modelling in urban areas is affected by many errors and uncertainties related to the inflow conditions, boundary conditions, numerical approach (RANS, LES, DNS), turbulence models, etc. A discussion of all these errors and uncertainties is beyond the scope of the present paper, but the future intention is to quantify their relative importance for the urban area investigated in this paper. In particular, numerical investigations on the same urban model (at scale 1:300) are in progress to quantify the uncertainties concerning inflow conditions as well as the modelling approach.

4.8 References


Chapter 5

The impact of inflow conditions

Wind flow modeling in urban areas is usually performed by means of wind tunnel testing (WT) or Computational Fluid Dynamics (CFD) simulations. Results obtained with both techniques can be affected by many uncertainties. This study aims at investigating how the different inflow conditions commonly adopted to simulate urban wind flows may affect the accuracy of the results.

CFD simulations were performed for a selected urban area - “Quartiere La Venezia” in Livorno (Italy) - using the 3D steady Reynolds-averaged Navier-Stokes (RANS) approach. WT tests performed on the same urban model were used to validate the CFD simulations. In particular, two types of inflow profiles were considered: the first, corresponding to the real profiles measured upstream of the urban model during the WT tests, and the second a logarithmic fit to the real profiles. Mean wind profiles at 25 measuring positions in the urban area were compared, and the statistical performance in terms of four metrics was quantified for both inflow conditions. A better performance in terms of mean wind velocity of the CFD case employing the real profiles as inflow conditions was found for the wind directions WSW and WNW. For these wind directions, both CFD cases showed respectively a gap of 6% and 7% in terms of correlation coefficient (R). In contrast, the validation metrics (R and FAC2.0) highlighted an unsatisfactory agreement between both CFD cases and WT case in terms of yaw and pitch angles for all wind directions considered.
5.1 Introduction

Many factors affect the accuracy of wind flow modeling in an urban environment: reviews on this topic were made by e.g. Britter and Hanna (2003), Fernando (2010), Fernando et al. (2010) and Barlow et al. (2013). The proper representation of large scale forcing through the inlet boundary conditions and local scale forcing due to urban obstacles (e.g. buildings and trees) represent only a few of many challenges. Several studies focused on numerical wind flow modeling over random urban like obstacles (e.g. Xie et al., 2008), uniform and staggered building arrays (e.g. Coceal and Belcher 2004; Xie and Castro, 2006; An et al., 2013; Razak et al., 2013; Blocken et al. 2016), idealized urban surfaces (e.g. Cheng and Porté-Agel, 2015), a semi idealized urban canopy (e.g. Hertwig et al., 2012; Carpentieri and Robins, 2015) and actual urban environments (Hanna et al., 2006; Janssen et al., 2013; Montazeri et al., 2013; García Sánchez et al., 2014; Blocken et al. 2012, 2016). While best practice guidelines contain a maximum blockage ratio which ensures that interaction effects between the sides of the domain (or test section) and the model are sufficiently small (ASCE 2003; Franke et al., 2007; Tominaga et al., 2008; Blocken, 2015), the choice of inflow conditions is not as straightforward. Extensive literature exists on the representation of the atmospheric boundary layer (ABL) in WT tests employing different types of spires, fences and sets of roughness elements (Counihan, 1969; Irwin, 1980; Kozmar, 2011a,b). Measurements of mean wind velocity, turbulence intensity, spectra and turbulent length scales of different boundary layer WT setups were compared extensively with actual atmospheric data (Lloyd, 1966; Armitt and Counihan, 1969, 1970; Cermak, 1972; Plate, 1982, 1999; Farell and Iyengar, 1999; Balendra et al., 2002; Kozmar, 2010). As stressed by Counihan (1969,1970), who tried to simulate a neutral ABL in a boundary layer WT, spanwise uniformity of ABL flow, upstream of the turntable (where the WT model is usually placed), is an important requirement. However, nonuniformity in the spanwise direction, in terms mean wind velocity \( U(z) \) and turbulence intensity \( I(z) \) profiles, often occurs during WT tests (Counihan, 1970). This is likely caused by the limited length of the WT test section combined with the roughness element configurations employed to generate the ABL profile (Counihan, 1970). However, the related uncertainties in the WT results (e.g. velocity, turbulence intensity, pressure coefficient values) are unknown.

In the past decades, much work has been performed on the reproduction of WT tests by CFD simulations (Moonen et al., 2006; Yoshie et al., 2007; Calautit et
al., 2014) in order to improve the performance and better understand the strengths and weaknesses of both techniques (Murakami, 1990; Stathopoulos, 1997; Baker, 2007; Tominaga and Stathopoulos 2013; Blocken, 2014, 2015; Meroney, 2016). As proposed by Moonen et al. (2006) and Calautit et al. (2014), the inflow conditions can be directly reproduced by modeling the entire WT including the corner guide vanes, the diffuser and the contraction as part of the computational domain. However, this approach entails a very high computational cost. The more common and less expensive technique that is widely adopted in urban physics and wind engineering applications consists of reproducing (only a portion of) the WT section. In this technique, for 3D steady state RANS simulations, the mean wind velocity ($U$), turbulent kinetic energy ($k$) and the turbulence dissipation rate ($\varepsilon$) or specific dissipation rate ($\omega$) profiles are imposed at the inlet face of the computational domain, which most often coincides with a measuring position located upstream of the turntable in the WT section. At this point two options can be chosen: to reproduce the real profiles (detected somewhere in the WT section upstream of the turntable) or to employ well known analytical profiles fitted to the WT measurements acquired upstream of the WT model. While the velocity profile is well defined in both options, the turbulence quantities ($k$, $\varepsilon$ and $\omega$) are commonly calculated using two different sets of equations. The first, proposed by Richards and Hoxey (1993), only considers two parameters derived from the fit of the mean wind velocity profile detected somewhere upstream of the WT model: $u^*$ and $z_0$. The second set, proposed by Tominaga et al. (2008), permits the use of the real turbulence quantities, e.g. $\sigma_u(z)$, $\sigma_v(z)$ and $\sigma_w(z)$, measured during the WT tests. Both sets of equations are reported and described in Section 5.3.2. At present it is not clear how the choice of one these two options affects the CFD results. This is the topic of this paper.

The present study is part of a larger research project aimed at quantifying the impact of CFD parameters (geometrical simplifications, inflow conditions, turbulence models, numerical approach, etc.) on RANS simulation results of wind flow over a historical urban area. For this purpose a neighborhood of Livorno city (Italy), so called Quartiere La Venezia, is selected as a case study. There are two reasons for choosing this area: first, this urban morphology is representative of many historical districts of Mediterranean cities, and second the wind flow in the Port of Livorno is monitored by a network of instruments within the framework of the European projects “Wind and Ports” and “Wind, Ports, and Sea” (Solari et al., 2012; Burlando et al., 2015, 2017). In a preliminary step, atmospheric boundary layer wind
tunnel (ABLWT) tests were performed on a reduced scale model (1:300). The present paper presents 3D steady state RANS simulations employing the realizable \( k-\varepsilon \) turbulence model and two types of inflow profiles applied to the reduced scale urban model (corresponding to that of the WT tests) by reproducing a portion of WT section. Mean wind velocity and turbulent kinetic energy profiles, and yaw angles and pitch angles are compared with the WT results. Finally, four validation metrics are used to quantify the deviations, in terms of mean velocity and yaw and pitch angles, caused by the inflow profiles.

The paper is organized as follows. Section 5.2 contains a short description of the urban model and the experimental setup. In Section 5.3 the computational settings and parameters are described: the computational geometry, domain and grid, the inflow conditions, the boundary conditions and the solver settings. Section 5.4 shows the comparison of the WT and CFD results in terms of mean wind velocity and turbulent kinetic energy profiles, yaw and pitch angles. In Section 5.5 the agreement between WT and CFD results is quantified using validation metrics. Finally, Section 5.6 concludes the paper with discussions and conclusions.

### 5.2 Description of experimental setup

The studied urban district *Quartiere La Venezia* was reproduced at a reduced scale of 1:300 (Fig. 5.1). ABLWT tests of wind flow over this urban area were performed at the Department of Civil, Chemical and Environmental Engineering (DICCA) of the University of Genoa. The ABLWT, a closed circuit wind tunnel for aerodynamics and civil experiments, has two different test sections, both with a cross section of \( 1.70 \times 1.35 \) m\(^2\) (width \( \times \) height). WT tests were performed for three incoming wind directions (\( \alpha = 240^\circ, 270^\circ, 300^\circ \)) corresponding to the prevalent ones for the strongest winds (Ricci et al., 2017a). The blockage ratio was kept below 3.5% for all wind directions considered. The wind flow pattern inside the urban area was monitored at 25 measuring positions and 15 heights (from 0.02 to 0.6 m above the bottom) as shown in Fig. 5.2(a-b). In particular, two sets of positions were used: the positions (L1\(_1\)-L1\(_5\), L2\(_1\)-L2\(_5\), L3\(_1\)-L3\(_5\)) consisting of a grid of 15 positions with the same local reference system as the WT section (Fig. 5.2a), and ten positions (A1\(_1\) - A5\(_2\)) fixed to the urban model and placed along “Canale Rosciano” (Fig. 5.2b). In order to reproduce the neutral ABL profile in the WT section, spires, fences and roughness cubes of various dimensions (i.e. 6 \( \times \) 6, 3 \( \times \) 3 and 2 \( \times \) 2 cm\(^2\)) were used. For more details the reader is referred to Ricci et al. (2017a).
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5.3 CFD simulations: computational settings and parameters

5.3.1 Computational geometry, domain and grid

CFD simulations were performed on the reduced scale model (1:300) of Quartiere La Venezia for the same incoming wind directions as the WT tests. The size of the domain was $L \times W \times H = 5.5 \times 1.70 \times 1.35 \text{ m}^3$, where the width ($W$) and the height ($H$) were consistent with the cross section of the WT, and the length ($L$) was the downstream end of the WT test section. Three different blockage ratios were considered as recommended by Blocken (2015): the vertical blockage ratio $BR_H$ (ideally $\leq 17\%$), the lateral blockage ratio $BR_L$ (ideally $\leq 17\%$) and the frontal area blockage ratio $BR$ (ideal value $\leq 3\%$). While the vertical blockage ratio $BR_H = 5.8\%$ was well below the recommended threshold, the frontal ($BR$) and lateral ($BR_L$) blockage ratio values...
(equal to 3.5% and 58.8% respectively) were higher than recommended. Nevertheless, the projected frontal area does not take into account that the urban model also consists of streets, canals and open squares through which the wind can flow. For this reason the frontal blockage ratio could be considered a rather pessimistic indicator for the present geometry. Moreover, it is worth to note that, since all the measuring positions (A and L) were located in the central part of the district, the effect of the side walls on the measurements can be expected to be quite limited. Finally, it is important to underline that all the blockage ratios were the same as in the WT tests.

In an earlier publication, in order to quantify the impact of geometrical simplifications, two geometries of Quartiere La Venezia with different degrees of precision were generated using Gambit 2.4.6: the simplified model and the approximated model (Ricci et al., 2017b). According to the results obtained in the first stage of this research project the best performing geometry (the approximated model) was chosen for further analysis. In order to correctly reproduce the inflow conditions of the WT tests the inlet face of the computational domain was placed where the incoming profile was measured in the WT (approximately 1 m upstream of the first building of the urban model). For each considered wind direction, a separate grid was constructed using the technique proposed by van Hooff and Blocken (2010) according to best practice guidelines (Franke et al., 2007; Tominaga et al., 2008; Blocken, 2015). Fig. 5.3 shows the grids generated for each wind direction. The resulting grids counted 23.2 million cells for $\alpha = 240^\circ$, 20.8 million cells for $\alpha = 270^\circ$, and 19.9 million cells for $\alpha = 300^\circ$. Fully hexahedral meshes with increased resolution close to the walls (buildings, bridges and ground level) were used in order to maximize the numerical accuracy and to avoid convergence problems (Blocken et al. 2012).
5.3.2 Inflow conditions

Two commonly adopted sets of inflow conditions were used in the present study. The first set, so called the *real profiles*, consisted of the mean wind velocity profiles $U(z)$ and the velocity standard deviations $\sigma_u(z)$, $\sigma_v(z)$, $\sigma_w(z)$ as measured in the WT. The profiles were measured along three vertical lines (L1, L2, L3) (Fig. 5.4). Line L2 was located at the central axis of the cross section and equally spaced with respect to L1 and L3 of 0.25 m ($a$). The height of the WT cross section ($H = 1.35$ m) was assumed as reference height ($z_{ref}$) (Fig. 5.4). Lines L1 and L3 are placed at

![Figure 5.3 Perspective view of the computational grids: (a) wind direction $\alpha = 240^\circ$, (b) wind direction $\alpha = 270^\circ$, (c) wind direction $\alpha = 300^\circ$.](image)
0.6 m (b) from the side walls of the WT (Fig. 5.4). The lines were chosen approximately 1 m (d) upstream of the first building of the urban model, and perfectly aligned with the lines L1_{1.5} L2_{1.5} and L3_{1.5} previously introduced in Fig. 5.2a. Due to the limitations of the WT equipment, mean velocities and standard deviations of the velocity fluctuations were directly measured from 0 to 0.44 \( z/z_{ref} \) above the tunnel floor - by means of 15 measuring positions, by a multihole pressure probe supported by a robotic hand, and from 0.9 and 1.0 \( z/z_{ref} \) (near the top wall - by means of 8 measuring positions), using a boundary layer rake (Barlow et al., 1999). In the range 0.44 - 0.9 \( z/z_{ref} \) mean velocity values and velocity standard deviations were linearly interpolated (between two positions: A1 - B1, A2 - B2, and A3 - B3) in order to link both measured parts (Fig. 5.4 and 5.5). Different mean wind velocity profiles were found along the three lines (L1, L2, L3), stressing a nonuniformity of the ABL flow in the spanwise direction upstream of the turntable (Fig. 5.5a). This nonuniformity was also found in the turbulent kinetic \( k(z) \) and turbulence dissipation rate \( \varepsilon(z) \) profiles, since they were calculated using the same WT measurements \( U, \sigma_u(z), \sigma_v(z), \sigma_w(z) \) mentioned above (Fig. 5.5b-c). The equations (Eqs. 5-1 and 5-2) proposed by Tominaga et al. (2008) were used:

\[
k(z) = \frac{1}{2}(\sigma_u^2(z) + \sigma_v^2(z) + \sigma_w^2(z))
\]

\[
\varepsilon(z) = C_{\mu}^{1/2} k(z) \frac{dU}{d\kappa}
\]

where \( C_{\mu} \) is a model constant equal to 0.09. Mean wind velocity, turbulent kinetic energy and turbulence dissipation rate profiles were imposed (as inflow conditions) at the inlet face of the computational domain (Fig. 5.5). At the inlet face, the values of \( U, k \) and \( \varepsilon \) were linearly interpolated using the known values of the three lines (L1, L2, L3, Lw) and kept constant in the range Lx - L1 and L3 - Lx, where Lx corresponds to the centroid of second cell starting from the lateral edges (Fig. 5.4). The linear interpolation was performed between the centroid of two contiguous cells of the entire inlet face using the function of the open source program used to perform the CFD simulations (OpenFOAM 2.3.0). The nonuniformity of profiles in the spanwise direction (\( W \)) is further clarified by Figs. 5.5(d,e,f), where the horizontal profiles of \( U, k \) and \( \varepsilon \) at for different heights (at 0.015, 0.024, 0.050 and 0.074 \( z/z_{ref} \) above the WT floor) were plotted as an example. Profiles of Fig. 5.5, were nondimensionalized with the friction velocity \( (\nu^*) \) obtained by the fit (0.89 m/s), the square of the friction velocity \( (\nu^*)^2 \), and the fraction \( \nu^*/\lambda \), respectively, where \( \lambda \) represents a characteristic length scale which was taken equal to the height \( (H = 1.35 \text{ m}) \) of the computational domain.
Figure 5.4 The computational domain with size $L \times W \times H = 5.5 \times 1.70 \times 1.35$ m$^3$. The black dots along the three vertical lines (L1, L2 and L3) are the positions chosen for the WT tests to measure the mean velocity and standard deviations of the velocity fluctuations. The lines indicated by $L_c$ correspond to the positions of the centroid of second cells (of the inlet face) starting from the lateral edges in turn indicated by $L_w$. The distances indicated by “a”, “b” and “d” are equal to 0.25 m, 0.60 m and approximately 1 m, respectively.

Figure 5.5 Nondimensionalized real profiles. Vertical and horizontal profiles are plotted along the three lines (L1, L2 and L3) and in the spanwise direction ($y$) at four different heights (0.015, 0.024, 0.05 and 0.074 of $z/z_{ref}$ above the bottom). The figures show the following vertical and horizontal profiles: (a) mean wind velocity, (b) turbulent kinetic energy and (c) turbulence dissipation rate. The height of the tallest building ($h_{max} = 0.15$ m) is indicated by the gray rectangle in the subfigures (a,b,c).
In the second set of inflow conditions, so called the fitted profiles, the velocity inflow profile was calculated by fitting the profile obtained by spanwise averaging of the three real velocity profiles (L1, L2, L3) previously described (see Fig. 5.5a) to a logarithmic law (Eq. 5-3). The fit was realized only in the range $0 - 0.44 \frac{z}{z_{ref}}$ (above the WT floor) (Fig. 5.6a). In the range $0.9$ and $1.0 \frac{z}{z_{ref}}$ the profile was obtained by averaging the three real velocity profiles (L1, L2, L3) measured by a boundary layer rake (as above described) (Fig. 5.6a). In the range $0.44 - 0.9 \frac{z}{z_{ref}}$ the mean velocity and the standard deviations of the turbulent fluctuations were linearly interpolated in order to link both parts, as done for the first set of inflow profiles (Fig. 5.6a). In Eq. 3, $\kappa$ indicates the von Karman constant which was taken equal to 0.41. Eqs. (5-4) and (5-5) proposed by Richards and Hoxey (1993) were used to calculate the turbulent kinetic energy $k$ and the turbulence dissipation rate $\epsilon(z)$ (Fig. 5.6b-c):

$$U(z) = \frac{u^*}{\kappa} \ln \left( \frac{z}{z_0} \right)$$

(5-3)

$$k = \frac{u^{*2}}{\sqrt{C_{\mu}}}$$

(5-4)

$$\epsilon(z) = \frac{u^{*3}}{\kappa(z + z_0)}$$

(5-5)

**Figure 5.6** Nondimensionalized fitted profiles: (a) mean wind velocity, (b) turbulent kinetic energy and (c) turbulence dissipation rate. The height of the tallest building ($h_{max} = 0.15$ m) is indicated by the gray rectangle in the subfigures (a,b,c).
Mean velocity $U(z)$, turbulent kinetic energy $k(z)$ and turbulence dissipation rate $\varepsilon(z)$ profiles shown in Fig. 5.6 were nondimensionalized with respect to the same values used for the first set of inflow profiles. The profiles of $U$, $k$ and $\varepsilon$ were imposed on the inlet face of the computational domain using the same procedure adopted for the first set as well.

The relative difference found between the real (considering the mean value obtained among the three values at lines L1, L2 and L3) and fitted velocity values at 0.02 m above the bottom was equal to 4.42%.

### 3.3 Other boundary conditions and solver settings

Other boundary conditions were also defined in order to reproduce the WT experimental conditions. The size of the first near wall cell was chosen in order to obtain dimensionless wall unit values $y^+$ in the logarithmic layer range (30-300; Blocken et al., 2007a,b). The equivalent sand grain roughness height $k_s$ was calculated according to Blocken et al. (2007a) as $k_s = 9.793 \frac{z_0}{C_s}$. In this equation $C_s$ (the roughness constant) was taken equal to 2.5 in order to comply with the necessary condition $y_p > k_s$, where $y_p$ is the distance of the centroid of the first near wall cell from the wall. At the bottom of the domain a rough wall function was used with a roughness height $k_s$ equal to 0.0013 m. At the sides and top of the computational domain as well as on the obstacles modeled explicitly (e.g. building and bridge surfaces), standard wall functions were employed using a roughness height $k_s$ equal to zero. Finally, a zero absolute static pressure boundary condition was applied at the outlet face (Fig. 5.7). The 3D steady state RANS approach and the realizable $k$-$\varepsilon$ turbulence model (Shih et al., 1995) were adopted. Second order discretization schemes for the governing equations and the SIMPLE algorithm for pressure velocity coupling were used (Versteeg and Malalasekera, 2007). Convergence was reached when the residuals showed negligible fluctuations during the iterative process. The following minimum values of residuals were found for all CFD simulations performed: $10^{-8}$ for the three components of momentum, $10^{-7}$ for the three mean velocity components and $10^{-6}$ for the turbulent kinetic energy and turbulence dissipation rate. All CFD simulations were carried out using the open source CFD package OpenFOAM 2.3.0 and the cluster of the Department of Civil, Chemical and Environmental Engineering of the University of Genoa (Italy) using 32 cores of AMD Opteron™ processors running at 1.4 GHz. Each simulation required approximately 190 - 200 wall clock hours.
5.4 CFD simulations: results

5.4.1 Wind velocity contours

Contours of dimensionless wind velocity obtained for the real profile and the fitted profile cases for the three incoming wind directions, made at 0.02 m above the bottom and corresponding with the lowest measuring height in the WT tests, are presented in Fig. 5.8(a-f). All the contours were nondimensionalized with respect to the friction velocity value at the inlet, $u^* = 0.89$ m/s. In general, the contours showed only small differences between the real profile and the fitted profile cases for the three wind directions analyzed.

For the wind direction $\alpha = 240^\circ$ the real profile case showed a higher wind velocity values than the fitted profile case upstream of the model; in contrast a comparable wind flow pattern of both CFD cases was found along Canale Rosciano (Figs. 5.8a,b). In this configuration the incoming wind direction was almost aligned with the entrance of Canale Rosciano and the wind velocity at this height was reduced by the ancient fortress of Livorno called “Fortezza Antica” and the bridge of “Viale della Cinta Esterna” (indicated in the figures by “F” and “bridge” respectively).

For the wind direction $\alpha = 270^\circ$ approximately the same velocity fields both
outside the urban area and along Canale Rosciano were observed for both CFD cases. (Fig. 5.8c-d).

For the wind direction $\alpha = 300^\circ$ two areas with high wind velocity were found for both CFD cases: the first at the entrance of Canale Rosciano and the second close to the right side wall of the computational domain. The latter was probably caused by the proximity of WT side and urban model edges. A higher wind velocity for the fitted profile case compared with the real profile case was found in those zones (Figs. 5.8e-f).

![Figure 5.8](image)

**Figure 5.8** Velocity contours of the real profile case (a, c, e) and fitted profile case (b, d, f) for three wind directions ($\alpha = 240^\circ$, $270^\circ$, $300^\circ$). The contours were made at 0.02 m above the bottom and nondimensionalized by the friction velocity value of the inlet profile. The ancient fortress of Livorno called “Fortezza Antica”, Canale Rosciano and the bridge on “Viale della Cinta Esterna” are respectively indicated by “F”, “CR” and “bridge” in the figures.
5.4.2 Vertical profiles of mean velocity

The horizontal homogeneity of the velocity profiles between the inlet face and the position of the first building of the urban model was analyzed in an empty domain with the same dimensions \((L \times W \times H = 5.5 \times 1.70 \times 1.35 \text{ m}^3)\) of the one used for the simulations for the urban model. The mean velocity profiles, for both sets of inflow conditions, were monitored along the line \(L2\), between inlet of the domain and the position where the urban model started (point \(P_c\) in Fig. 5.4) at 0.02 m above the bottom. Relative differences of 0.91\% and 1.62\% (with an increasing of the velocity) were found at point \(P_c\) between real and fitted velocity values, respectively, and their respective inflow values at the inlet face (at 0.02 m above the bottom).

In order to better understand the wind flow pattern inside Canale Rosciano the mean wind velocity profiles obtained from WT and CFD simulations were compared at the positions A2 - A5 (see Fig. 5.2). The first position of the ordinate \(z/\z_{ref} = 0.03\) corresponds to 0.02 m above the bottom.

In general, both CFD results showed a satisfactory agreement with WT results for \(\alpha = 240^\circ\). In contrast, for \(\alpha = 270^\circ\) and \(\alpha = 300^\circ\), where more extensive leeward zones were present over Canale Rosciano, the agreement between WT and CFD results deteriorated. Inlet velocity profiles of both CFD models are also reported in Fig. 5.9 and are indicated by orange and blue dashed lines for real and fitted profiles, respectively. A progressive reduction in mean wind velocity values compared with inlet wind velocities was observed along the water canal from point A2 to A5 between 0.03 and 0.25 \(z/\z_{ref}\). This aspect will be further discussed in Section 5.4.3.

For \(\alpha = 240^\circ\) (Fig. 5.9a) the difference between both CFD cases was approximately constant for the four positions (from A2 to A5). At positions A2 and A3 the fitted profile case showed an overestimation in terms of wind velocity values between 0 and 0.75 \(z/\z_{ref}\) compared to the real profile and WT cases. At positions A4 and A5 the gap previously observed between the two CFD cases was reduced, especially in the lower part of the profiles. However, an overestimation of CFD results compared to WT results was still present at point A5.

For \(\alpha = 270^\circ\) (Fig. 5.9b) the two CFD cases showed almost the same performance in the lower part of the profiles but not in the higher part, where the real and fitted profile cases displayed the same discrepancies already observed for the inflow profiles in Fig. 5.5a. Both CFD cases showed an unsatisfactory agreement with WT results below \(z/\z_{ref} = 0.15\). Since the alignment of the incoming wind flow with Canale Rosciano was decreasing with increasing \(\alpha\) over the range of wind
directions considered (see also Figs. 5.8c-d) the recirculation zones along the water canal were larger compared to $\alpha = 240^\circ$.

For $\alpha = 300^\circ$ (Fig. 5.9c) the agreement between CFD and WT results was unsatisfactory at all the positions considered except point A3. At this position some differences were found between both CFD cases below $z/z_{ref} = 0.1$. In contrast, at positions A2, A4 and A5 the same performance of the real profile and fitted profile cases was observed.

5.4.3 Vertical profiles of turbulent kinetic energy

Turbulent kinetic energy profiles, calculated using the velocity standard deviations $\sigma_u(z)$, $\sigma_v(z)$ and $\sigma_w(z)$ obtained in the WT tests and CFD simulations were compared for the three wind directions at positions A2 - A5 (Fig. 5.10). Turbulent kinetic energy profiles confirmed that canyoning effects likely occurred along Canale Rosciano, in agreement with the findings of Section 5.4.2. Whereas for all wind directions mean velocities were decreasing from point A2 to A5 (Fig. 5.9) due to separation zones, turbulent kinetic energy was progressively increasing (Fig. 5.10). In general, although at some of the positions (e.g. A3, A4, and A5) CFD and WT profiles showed a similar trend, an unsatisfactory agreement between CFD and WT results was found. An underestimation of turbulent kinetic energy for the CFD cases compared to the WT case was observed for all wind directions considered, especially in the lower part of the profiles (from 0 to 0.30 $z/z_{ref}$).

For the wind directions $\alpha = 240^\circ$ and $270^\circ$ the real profile case showed better agreement with the WT case than the fitted profile case from 0.4 to 1.0 $z/z_{ref}$. In the lower part, from 0 to 0.2 $z/z_{ref}$, the profiles of both CFD cases were almost coincident.

For the wind direction $\alpha = 300^\circ$ the real profile case performed substantially better than the fitted profile case. Nevertheless, vertical oscillations of the real profiles were found at all the measuring positions below $z/z_{ref} \approx 0.6$, possibly caused by the large leeward zones present along Canale Rosciano.
Figure 5.9 Comparison of mean wind velocity profiles inside Canale Rosciano at positions A21 - A52 for the inflow directions (a) $\alpha = 240^\circ$, (b) $\alpha = 270^\circ$ and (c) $\alpha = 300^\circ$, for the real profile case (orange line), fitted profile case (blue line), and WT data (black dots). Also indicated are inlet profiles for both cases (dotted lines).
Figure 5.10 Comparison of turbulent kinetic energy profiles inside Canale Rosciano at positions A21 - A52 for the inflow directions (a) $\alpha = 240^\circ$, (b) $\alpha = 270^\circ$ and (c) $\alpha = 300^\circ$, for the real profile case (orange line), fitted profile case - (blue line), and WT data (black dots). Also indicated are inlet profiles for both cases (dotted lines).
5.4.4 Yaw and pitch angles

In order to better understand the wind flow patterns inside Canale Rosciano, yaw ($\phi$) and pitch ($\theta$) angles at positions A21 - A52, at 0.02 m above the bottom, for WT tests and CFD simulations were compared for all wind directions (Tables 5.1, 5.2, 5.3). The yaw and pitch angles were respectively calculated as (Eqs. 5-6 and 5-7):

$$\phi(z) = \tan^{-1}\left(\frac{v}{u}\right)$$

(5-6)

$$\theta(z) = \tan^{-1}\left(\frac{w}{u}\right)$$

(5-7)

where $u$, $v$ and $w$ indicate the mean wind velocity values in the streamwise ($x$), spanwise ($y$) and vertical ($z$) directions respectively.

In general, while a satisfactory agreement was found in terms of $\phi$ between the real profile and fitted profile cases, discrepancies between CFD and WT results were observed for all wind directions considered. This is particularly clear in Fig. 5.11, where the velocity magnitude $U$ and yaw angle $\phi$ of WT and CFD cases were superimposed on velocity contours of the fitted profile case. Reasonable agreement in terms of $\phi$ between WT and CFD cases (for both CFD cases) was found where the highest velocities were observed:

- for $\alpha = 240^\circ$: positions A21, A22, A42 and A51 (Table 5.1 and Fig. 5.11a-b);
- for $\alpha = 270^\circ$: positions A33 and A52 (Table 5.2 and Fig. 5.11c-d);
- for $\alpha = 300^\circ$: positions A21, A22, A33 and A42 (Table 5.3 and Fig. 5.11e-f).

In contrast, the measuring positions placed in the leeward zones over Canale Rosciano showed a large discrepancy between WT and CFD results in terms of $\phi$, confirming the limitations of the RANS approach in the accurate prediction of separation zones. This limitation was further confirmed by comparing $\theta$; while the real profile and fitted profile cases compared well with each other the comparison with WT results was unsatisfactory.
The impact of inflow conditions

Table 5.1
Comparison of yaw $\phi(z)$ and pitch $\theta(z)$ angles for wind tunnel (WT), CFD real profile (CFD r.p.) and CFD fitted profile (CFD f.p.) cases at positions A2; - A5; for the inflow direction $\alpha = 240^\circ$ at 0.02 m above the bottom. Positive values of $\phi(z)$ and $\theta(z)$ represent counterclockwise rotation around the $z$ axis and clockwise rotation around the $y$ axis, respectively.

<table>
<thead>
<tr>
<th>point</th>
<th>WT $\phi(z)$</th>
<th>CFD r.p. $\phi(z)$</th>
<th>CFD f.p. $\phi(z)$</th>
<th>WT $\theta(z)$</th>
<th>CFD r.p. $\theta(z)$</th>
<th>CFD f.p. $\theta(z)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2</td>
<td>-21.87°</td>
<td>-23.44°</td>
<td>-23.28°</td>
<td>15.0°</td>
<td>-1.24°</td>
<td>-1.56°</td>
</tr>
<tr>
<td>A3</td>
<td>24.79°</td>
<td>13.87°</td>
<td>13.10°</td>
<td>-3.88°</td>
<td>-1.53°</td>
<td>-1.70°</td>
</tr>
<tr>
<td>A3</td>
<td>23.18°</td>
<td>14.61°</td>
<td>14.35°</td>
<td>-3.64°</td>
<td>-3.34°</td>
<td>-3.55°</td>
</tr>
<tr>
<td>A3</td>
<td>-19.20°</td>
<td>-30.11°</td>
<td>-29.79°</td>
<td>13.56°</td>
<td>1.27°</td>
<td>1.45°</td>
</tr>
<tr>
<td>A4</td>
<td>38.51°</td>
<td>34.40°</td>
<td>34.32°</td>
<td>-5.68°</td>
<td>-2.37°</td>
<td>-2.24°</td>
</tr>
<tr>
<td>A4</td>
<td>38.49°</td>
<td>38.64°</td>
<td>38.52°</td>
<td>-8.38°</td>
<td>0.79°</td>
<td>0.71°</td>
</tr>
<tr>
<td>A5</td>
<td>25.01°</td>
<td>23.26°</td>
<td>23.74°</td>
<td>-3.10°</td>
<td>-2.19°</td>
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</tr>
<tr>
<td>A5</td>
<td>0.24°</td>
<td>24.84°</td>
<td>26.01°</td>
<td>0.57°</td>
<td>2.06°</td>
<td>0.91°</td>
</tr>
</tbody>
</table>

Table 5.2
Comparison of yaw $\phi(z)$ and pitch $\theta(z)$ angles for wind tunnel (WT), CFD real profile (CFD r.p.) and CFD fitted profile cases (CFD f.p.) at positions A2; - A5; for the inflow direction $\alpha = 270^\circ$ at 0.02 m above the bottom. Positive values of $\phi(z)$ and $\theta(z)$ represent counterclockwise rotation around the $z$ axis and clockwise rotation around the $y$ axis, respectively.

<table>
<thead>
<tr>
<th>point</th>
<th>WT $\phi(z)$</th>
<th>CFD r.p. $\phi(z)$</th>
<th>CFD f.p. $\phi(z)$</th>
<th>WT $\theta(z)$</th>
<th>CFD r.p. $\theta(z)$</th>
<th>CFD f.p. $\theta(z)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2</td>
<td>11.88°</td>
<td>2.85°</td>
<td>2.82°</td>
<td>0.08°</td>
<td>-2.18°</td>
<td>-2.16°</td>
</tr>
<tr>
<td>A2</td>
<td>2.80°</td>
<td>5.69°</td>
<td>5.98°</td>
<td>-1.55°</td>
<td>2.50°</td>
<td>2.61°</td>
</tr>
<tr>
<td>A3</td>
<td>24.81°</td>
<td>64.61°</td>
<td>64.60°</td>
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<td>5.46°</td>
<td>6.99°</td>
</tr>
<tr>
<td>A3</td>
<td>26.06°</td>
<td>63.60°</td>
<td>63.87°</td>
<td>9.04°</td>
<td>-28.13°</td>
<td>-28.34°</td>
</tr>
<tr>
<td>A3</td>
<td>18.89°</td>
<td>25.47°</td>
<td>25.79°</td>
<td>-5.24°</td>
<td>2.12°</td>
<td>1.94°</td>
</tr>
<tr>
<td>A4</td>
<td>18.67°</td>
<td>78.37°</td>
<td>78.14°</td>
<td>-5.25°</td>
<td>40.48°</td>
<td>31.99°</td>
</tr>
<tr>
<td>A4</td>
<td>17.02°</td>
<td>87.19°</td>
<td>86.46°</td>
<td>-4.93°</td>
<td>39.69°</td>
<td>33.65°</td>
</tr>
<tr>
<td>A5</td>
<td>12.27°</td>
<td>71.49°</td>
<td>71.31°</td>
<td>0.22°</td>
<td>15.58°</td>
<td>15.87°</td>
</tr>
<tr>
<td>A5</td>
<td>5.29°</td>
<td>34.49°</td>
<td>27.41°</td>
<td>-0.79°</td>
<td>23.32°</td>
<td>20.66°</td>
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</table>
Table 5.3
Comparison of yaw $\phi(z)$ and pitch $\theta(z)$ angles for wind tunnel (WT), CFD real profile (CFD r.p.) and CFD fitted profile cases (CFD f.p.) at positions A2$ _1$ - A5$ _2$ for the inflow direction $\alpha = 270^\circ$ at 0.02 m above the bottom. Positive values of $\phi(z)$ and $\theta(z)$ represent counterclockwise rotation around the $z$ axis and clockwise rotation around the $y$ axis, respectively.

<table>
<thead>
<tr>
<th>point</th>
<th>WT $\phi(z)$</th>
<th>CFD r.p. $\phi(z)$</th>
<th>CFD f.p. $\phi(z)$</th>
<th>WT $\theta(z)$</th>
<th>CFD r.p. $\theta(z)$</th>
<th>CFD f.p. $\theta(z)$</th>
</tr>
</thead>
<tbody>
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<td>A2$ _1$</td>
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<td>40.47°</td>
<td>-11.02°</td>
<td>-4.01°</td>
<td>-5.06°</td>
</tr>
<tr>
<td>A2$ _2$</td>
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<td>23.45°</td>
<td>24.07°</td>
<td>-5.38°</td>
<td>-2.53°</td>
<td>-1.66°</td>
</tr>
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<td>A3$ _1$</td>
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<td>83.07°</td>
<td>85.36°</td>
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<td>-56.73°</td>
<td>-62.94°</td>
</tr>
<tr>
<td>A3$ _2$</td>
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<td>85.05°</td>
<td>85.35°</td>
<td>-1.82°</td>
<td>59.67°</td>
<td>70.11°</td>
</tr>
<tr>
<td>A3$ _3$</td>
<td>23.81°</td>
<td>30.79°</td>
<td>40.58°</td>
<td>1.21°</td>
<td>5.09°</td>
<td>1.38°</td>
</tr>
<tr>
<td>A4$ _1$</td>
<td>-3.93°</td>
<td>-14.04°</td>
<td>-12.65°</td>
<td>-5.47°</td>
<td>27.49°</td>
<td>19.14°</td>
</tr>
<tr>
<td>A4$ _2$</td>
<td>-3.50°</td>
<td>0.63°</td>
<td>10.54°</td>
<td>-5.18°</td>
<td>-12.65°</td>
<td>-31.74°</td>
</tr>
<tr>
<td>A5$ _1$</td>
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<td>-6.86°</td>
<td>-28.80°</td>
</tr>
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<td>9.02°</td>
<td>1.42°</td>
<td>20.57°</td>
<td>9.67°</td>
</tr>
</tbody>
</table>
5.5 Performance metrics

In order to quantify the impact of the inflow conditions on urban wind flow prediction the statistical performance of both CFD cases was calculated using four validation metrics for the velocity magnitude and two validation metrics for the yaw and pitch angles (Chang and Hanna, 2004; Schatzmann et al., 2010; Gousseau et al. 2013). For the velocity magnitude the fractional bias ($FB$), normalized mean square
error (NMSE), correlation coefficient (R), and the fraction of data within a factor 1.3 (FAC1.3) were adopted; for the yaw and pitch angles the correlation coefficient R and the fraction of data within a factor 2.0 (FAC2.0) were used. The ideal values corresponding to complete agreement between CFD and WT results are \( FB = 0 \), \( NMSE = 0 \), \( R = 1 \) and \( FAC(1.3 \text{ and } 2.0) = 1 \). The reader is referred to Ricci et al. (2017b) for more details.

The validation metrics were calculated on horizontal planes for \( z = 0.02 \text{ m} \) above the bottom, for all measuring positions A and L (overall 25 positions, since there were no buildings present at the locations of the L measurement grid). Due to this limited number of measuring positions (18, 20 and 17 at \( z = 0.02 \text{ m} \) for \( \alpha = 240^\circ \), \( \alpha = 270^\circ \) and \( \alpha = 300^\circ \), respectively) FAC1.3 is a metric which by itself was not sufficiently representative.

### 5.5.1 Statistical performance: wind velocities at \( z = 0.02 \text{ m} \)

The results for a height of \( z = 0.02 \text{ m} \) above the bottom are given in Table 5.4. The same results are graphically displayed in Fig. 5.12.

In general, the statistical performance for the wind velocity ratio \( (U/u^*) \) confirmed the observations previously made in Section 5.4.2:

- a satisfactory agreement between both CFD cases and the WT case for \( \alpha = 240^\circ \);
- a similar performance of both CFD cases with respect to the WT case for \( \alpha = 270^\circ \) and \( \alpha = 300^\circ \).

For the incoming wind direction \( \alpha = 240^\circ \) the \( FB \) values of the real profile and fitted profile cases showed nearly the same distribution around the diagonal, indicating a similar agreement with WT results. A better correlation (R) with WT results was observed for the real profile case (77%) than for the fitted profile case (71%). A gap of 6% was also found in terms of FAC1.3, with a value of 89% for the real profile case and 83% for the fitted profile case. For \( \alpha = 270^\circ \) \( FB \), NMSE and FAC1.3 showed almost the same performance of the real and fitted profile cases, while the correlation coefficient (R) indicated a better agreement of the real profile case with the WT case compared to the fitted profile case. For \( \alpha = 300^\circ \) a better correlation (R) with WT results was found for the real profile case (59%) than for the fitted profile case (52%). A gap of 6% was observed in terms of FAC1.3, with a value of 56% for the real profile case and 50% for the fitted profile case.
Table 5.4
Validation metrics for mean wind velocity $U$ for CFD real and fitted profile cases, three inflow directions ($\alpha = 240^\circ$, $\alpha = 270^\circ$, $\alpha = 300^\circ$), and 25 measurement positions (A and L) at $z = 0.02$ m above the bottom. Also indicated are the number of measurement positions (samples) which were not blocked by the model and were therefore available for statistical analysis.

<table>
<thead>
<tr>
<th>$\alpha = 240^\circ$, $z = 0.02$ m</th>
<th>CFD r.p. $#$ WT</th>
<th>CFD f.p. $#$ WT</th>
<th>ideal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$FB$</td>
<td>-0.04</td>
<td>-0.07</td>
<td>0</td>
</tr>
<tr>
<td>$NMSE$</td>
<td>0.04</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>$R$</td>
<td>0.77</td>
<td>0.71</td>
<td>1</td>
</tr>
<tr>
<td>$FAC1.3$</td>
<td>0.89</td>
<td>0.83</td>
<td>1</td>
</tr>
<tr>
<td>samples</td>
<td>18</td>
<td>18</td>
<td>25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\alpha = 270^\circ$, $z = 0.02$ m</th>
<th>CFD r.p. $#$ WT</th>
<th>CFD f.p. $#$ WT</th>
<th>ideal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$FB$</td>
<td>0.11</td>
<td>0.10</td>
<td>0</td>
</tr>
<tr>
<td>$NMSE$</td>
<td>0.11</td>
<td>0.11</td>
<td>0</td>
</tr>
<tr>
<td>$R$</td>
<td>0.66</td>
<td>0.63</td>
<td>1</td>
</tr>
<tr>
<td>$FAC1.3$</td>
<td>0.56</td>
<td>0.56</td>
<td>1</td>
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<td>samples</td>
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<td>20</td>
<td>25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\alpha = 300^\circ$, $z = 0.02$ m</th>
<th>CFD r.p. $#$ WT</th>
<th>CFD f.p. $#$ WT</th>
<th>ideal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$FB$</td>
<td>0.12</td>
<td>0.11</td>
<td>0</td>
</tr>
<tr>
<td>$NMSE$</td>
<td>0.18</td>
<td>0.20</td>
<td>0</td>
</tr>
<tr>
<td>$R$</td>
<td>0.59</td>
<td>0.52</td>
<td>1</td>
</tr>
<tr>
<td>$FAC1.3$</td>
<td>0.56</td>
<td>0.50</td>
<td>1</td>
</tr>
<tr>
<td>samples</td>
<td>17</td>
<td>17</td>
<td>25</td>
</tr>
</tbody>
</table>

Figure 5.12 Comparison of numerical and experimental wind velocity ratios at the monitored positions A and L for three inflow directions: (a) $\alpha = 240^\circ$, (b) $\alpha = 270^\circ$, (c) $\alpha = 300^\circ$ at a height $z = 0.02$ m above the bottom. Dashed black lines correspond to 10% and 30% errors, as indicated.
5.5.2 Statistical performance: yaw and pitch angles at $z = 0.02$ m

The same procedure described in Section 5.5.1 was applied for yaw and pitch angles. However only two metrics were used in the present section: correlation coefficient $R$ and a fraction of data positions $FAC2.0$ instead of $FAC1.3$ in order to better appreciate the performance difference between both CFD cases. $FB$ and $NMSE$ could not be used since the yaw and pitch angles can assume both positive and negative values (Gousseau et al., 2013). The results for the three wind directions at a height of $z = 0.02$ m above the bottom are given in Tables 5.5 and 5.6 and Figs. 5.13 and 5.14. As indicated in Section 5.4.4 the discrepancies between CFD and WT results in terms of yaw and pitch angles were generally quite large.

5.5.2.1 Yaw angle

For $\alpha = 240^\circ$ the correlation coefficient $R$ of the real profile and fitted profile cases showed a satisfactory agreement with WT results. A gap of 6% was found in terms of $FAC2.0$, with a value of 89% for the real profile case and 83% for the fitted profile case. A similar trend was found for the wind direction $\alpha = 270^\circ$, where both of metrics showed similar performance for both CFD cases. For $\alpha = 300^\circ$ a slightly tighter distribution around the diagonal was found for the real profile case than for the fitted profile case. A gap of 6% was found in terms of $FAC2.0$, with a value of 35% for the fitted profile case and 29% for the real profile case (Table 5.5 and Fig. 5.13).

5.5.2.2 Pitch angle

In agreement with results already discussed in Section 5.4.4, Table 5.6 and Fig. 5.14 confirmed an unsatisfactory agreement between CFD and WT results for all incoming wind directions considered. However, the real profile case showed a better agreement compared to the fitted profile one in terms of $FAC2.0$. Gaps of 22%, 5% and 11% were respectively found for the wind directions $240^\circ$, $270^\circ$ and $300^\circ$, between real profile and fitted profile cases.
Table 5.5
Validation metrics for yaw angle $\phi(z)$ for CFD real and fitted profile cases, three inflow directions ($\alpha = 240^\circ$, $\alpha = 270^\circ$, $\alpha = 300^\circ$), and 25 measurement positions (A and L) at $z = 0.02$ m above the bottom. Also indicated are the number of measurement positions (samples) which were not blocked by the model and were therefore available for statistical analysis.

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$\gamma$</th>
<th>$R$</th>
<th>FAC2.0</th>
<th>samples</th>
</tr>
</thead>
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<tr>
<td>$240^\circ$, $0.02$ m</td>
<td>CFD r.p. vs WT</td>
<td>CFD f.p. vs WT</td>
<td>ideal value</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>0.85</td>
<td>0.84</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>FAC2.0</td>
<td>0.89</td>
<td>0.83</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>samples</td>
<td>18</td>
<td>18</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>$270^\circ$, $0.02$ m</td>
<td>CFD r.p. vs WT</td>
<td>CFD f.p. vs WT</td>
<td>ideal value</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>0.58</td>
<td>0.59</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>FAC2.0</td>
<td>0.45</td>
<td>0.45</td>
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<td>samples</td>
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<td>20</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>$300^\circ$, $0.02$ m</td>
<td>CFD r.p. vs WT</td>
<td>CFD f.p. vs WT</td>
<td>ideal value</td>
<td></td>
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<tr>
<td>R</td>
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<td>1</td>
<td></td>
</tr>
<tr>
<td>FAC2.0</td>
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<td>0.35</td>
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<td></td>
</tr>
<tr>
<td>samples</td>
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<td>17</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.13 Comparison of CFD and WT data of yaw angle $\phi(z)$ at positions A and L for three inflow directions: (a) $\alpha = 240^\circ$, (b) $\alpha = 270^\circ$, (c) $\alpha = 300^\circ$, at a height $z = 0.02$ m above the bottom. Dashed black lines correspond to a 50% error, as indicated.
Table 5.6
Validation metrics for pitch angle $\theta(z)$ for CFD real and fitted profile cases, three inflow directions ($\alpha = 240^\circ$, $\alpha = 270^\circ$, $\alpha = 300^\circ$), and 25 measurement positions (A and L) at $z = 0.02$ m above the bottom. Also indicated are the number of measurement positions (samples) which were not blocked by the model and were therefore available for statistical analysis.

<table>
<thead>
<tr>
<th>$\alpha = 240^\circ$, $z = 0.02$ m</th>
<th>CFD r.p. vs WT</th>
<th>CFD f.p. vs WT</th>
<th>ideal value</th>
</tr>
</thead>
<tbody>
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<tr>
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<th>CFD f.p. vs WT</th>
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<th>CFD f.p. vs WT</th>
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</tr>
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</tr>
<tr>
<td>samples</td>
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Figure 5.14 Comparison of CFD and WT data of pitch angle $\theta(z)$ at positions A and L for three inflow directions: (a) $\alpha = 240^\circ$, (b) $\alpha = 270^\circ$, (c) $\alpha = 300^\circ$, at a height $z = 0.02$ m above the bottom. Dashed black lines correspond to a 50% error, as indicated.
The impact of inflow conditions

5.6 Discussion and conclusions

In the present study the impact of different inflow conditions on wind flow modeling in an urban environment was investigated. A district of Livorno city (Italy), so called Quartiere La Venezia, was selected as a case study. 3D steady state RANS simulations were performed on a reduced scale model (1:300) of this district for three wind directions ($\alpha = 240^\circ$, $270^\circ$ and $300^\circ$). The results in terms of mean wind velocity ($U$), turbulent kinetic energy ($k$), yaw ($\phi$) and pitch ($\theta$) angles were compared with WT results obtained by testing the same reduced scale model at the Department of Civil, Chemical and Environmental Engineering (DICCA) of the University of Genoa. Several limitations to this study should be noted:

- The study was carried out on a single urban district.
- The computational model geometry was not perfectly coincident with the WT model.
- The number of measuring positions taken into account for the WT tests and CFD simulations was limited to 25.
- Due to the limitations of the WT equipment, mean wind velocities and velocity standard deviations were directly measured from 0 to 0.44 $z/z_{ref}$ (above the tunnel floor - by means of 15 measuring positions and from 0.9 and 1.0 $z/z_{ref}$ (near the top wall - by means of 8 measuring positions).
- Due to the size of the computational domain a 3D steady state RANS which is known to be deficient especially in separation zones.
- Although the WT is one of the more reliable methods used to validate CFD results, experimental uncertainties should always be critically assessed, such as those related to the flow angles. The range of the angular acquisition is $90^\circ$ and the uncertainty given by the supplier is +/- 0.5°. However, in regions where high flow gradients occur - for example near buildings walls - position inaccuracy may locally give rise to a significantly larger uncertainty which may affect the performance evaluation of both CFD cases.

In spite of the assumptions and limitations, this study showed that the choice of the inflow conditions (mean velocity, turbulent kinetic energy and turbulence dissipation rate profiles) did not strongly affect the quality of the results in terms of mean wind velocity values, especially in the lower part of the profiles. In contrast,
larger discrepancies were found in terms of turbulent kinetic energy values, yaw and pitch angles. In particular:

- The velocity contours showed small differences between the real profile and fitted profile cases for all wind directions considered, especially at lower heights.

- A better agreement, in terms of mean velocity profiles, between the real profile case and the WT case with respect to the fitted profile case was found for the wind direction $\alpha = 240^\circ$, for which it is best aligned with Canale Rosciano. An overestimation in the lower part of the profiles was obtained for the fitted profile case for this wind direction.

- The turbulent kinetic energy profiles showed an unsatisfactory agreement between CFD and WT cases for all analyzed wind directions, especially in the lower part of the domain. The real profile case showed a better agreement with WT results than the fitted profile case, especially in the higher part of the profiles. This was possibly caused by the fact that the turbulent kinetic energy profile of the real profile case was calculated using the measured velocity standard deviations.

- Small differences were found between both CFD cases and the WT case in terms of yaw angle, confirmed also by validation metrics ($R$ and $FAC2.0$) for the wind direction $\alpha = 240^\circ$. In contrast, unsatisfactory agreement of both CFD cases was confirmed by both metrics for $\alpha = 270^\circ$ and $\alpha = 300^\circ$.

- The pitch angle was scarcely predictable by the 3D steady state RANS approach. An unsatisfactory agreement between both CFD cases and WT results was found. Moreover, as for the turbulent kinetic energy, noticeable differences between real profile and fitted profile cases were observed for all the wind directions analyzed. This implies that the quality of the results (in terms of deviations of pitch angle) may be heavily affected by the inflow condition which is used.

In order to further reduce the gap between CFD simulations and WT tests in wind flow modeling over an urban environment further numerical investigations on the same urban model (at scale 1:300) are in progress to quantify the uncertainties concerning the computational setup and the modeling approach.
5.7 References


Burlando, M., Tizzi, M., Solari, G., 2017. Characteristics of downslope winds in the Liguria Region. *Wind and Structures (accepted).*


Chapter 6

The impact of turbulence models and roughness height

The accuracy and reliability of 3D steady state RANS simulations of wind flow in urban environments is affected by many factors, two of which are the turbulence model and the ground surface roughness height. Different $k$-$\varepsilon$ and $k$-$\omega$ turbulence models and surface roughness values are commonly adopted to predict wind flows in urban environments. However, the deviations of CFD results caused by the choice of these parameters remains to be quantified. In the present study this was done for a district of Livorno city (Italy) reproduced at reduced scale (1:300) for which earlier wind tunnel (WT) tests were performed. Mean wind velocity profiles obtained in the WT tests and CFD simulations were compared at 25 measuring positions for three wind directions. In order to quantify the impact of the considered parameters four validation metrics (FB, NMSE, R and FAC1.3) were used. The tested turbulence models (standard $k$-$\varepsilon$, realizable $k$-$\varepsilon$, RNG $k$-$\varepsilon$, standard $k$-$\omega$ and SST $k$-$\omega$) were shown to have a much larger effect on the results (in terms of mean velocity values) than the surface roughness height for the ranges investigated (for the first set, $k_s = 1.3 \times 10^{-3} \text{ m}$ consistent with a homogenous roughness length of the ground level $z_0 = 0.0033 \text{ m}$; for the second set, $k_{s,\text{mat}} = 4.0 \times 10^{-6} \text{ m}$ and $1.0 \times 10^{-6} \text{ m}$ consistent with different materials employed in the WT tests), especially for a WSW wind direction (9% and 2% difference in R between different turbulence models and roughness heights, respectively).
6.1 Introduction

Wind tunnel (WT) testing and Computational Fluid Dynamics (CFD) are among the most common techniques used to investigate different urban physics and wind engineering topics: pedestrian wind comfort, pollutant dispersion, indoor and outdoor ventilation, etc. (Murakami, 1997; Stathopoulos, 1997; Baker, 2007; Solari, 2007; Moonen et al., 2012; Meroney and Derickson, 2014; Blocken, 2014-2015a, Meroney, 2016; Tominga and Stathopoulos, 2016). The joint use of these two techniques can lead to a better understanding of the strengths and weaknesses of both (Murakami, 1990; Stathopoulos, 1997; Baker, 2007; Tominga and Stathopoulos 2013; Blocken, 2014, 2015a; Meroney, 2016). In CFD validation one can numerically reproduce the entire wind tunnel or, more commonly, a portion of it as the computational domain (Moonen et al., 2006). Nevertheless, the results of both methods are affected by many uncertainties and errors related to geometrical simplifications, boundary conditions, turbulence models, surface roughness height values and numerical approaches (AIAA, 1998; ERCOFTAC, 2000; Franke, 2006; Blocken, 2014). As a matter of fact, several best practice guideline documents were established to ensure the quality of CFD simulations on wind flow over urban environment (Casey and Wintergerste, 2000; Franke et al., 2007; Tominaga et al., 2008; Tamura et al., 2008; Blocken and Gualtieri, 2012).

In the last decades, several types of $k$-$\varepsilon$ and $k$-$\omega$ turbulence models (e.g. standard $k$-$\varepsilon$, realizable $k$-$\varepsilon$, RNG $k$-$\varepsilon$, standard $k$-$\omega$ and SST $k$-$\omega$) have been employed to investigate different urban physics and wind engineering problems, such as pedestrian wind comfort around buildings (Mochida et al., 2002; Janssen et al., 2013; Montazeri et al., 2013), wind flow over complex terrain (Balogh et al., 2012; Blocken et al., 2015b), pollutant dispersion in an urban environment (Gousseau et al., 2011a-b; Carpentieri, 2013; Blocken et al., 2016), cross ventilation (Ramponi and Blocken, 2012a-b; Perén et al., 2015a-b) and convective heat transfer for external building surfaces (Defraeye et al., 2010; Karava et al., 2011; Montazeri et al., 2015). Several authors published reviews of turbulence models (Ferziger and Perić, 1996; Wilcox, 1998; Pope, 2000; Cebeci, 2004; Hirsch, 2007; Versteeg and Malalasekera, 2007). However, it is worth to notice that none of the available turbulence models gives a totally accurate description of turbulence flows (Hirsch, 2007), and the best choice of turbulence model is often problem specific (Franke et al., 2007). As stated by Blocken (2014), although the list of computational works performed in the last decades about various urban physics and wind engineering
applications is huge, it is unclear to which extent the turbulence models may be affect the reliability of the results (e.g. in terms of mean velocity, pressure, temperature). For this purpose, in the first stage of the present work, the impact of different turbulence models on 3D steady state RANS simulations of wind flow in an urban environment reproduced at reduced scale will be analyzed in terms of mean velocity values.

Treatment of boundaries is one of the most important modeling tasks during the CFD evaluation of wind effects on obstacles (e.g. buildings and bridges) (Stathopoulos and Baskaran, 1990). The surface roughness imposed at the bottom of the computational domain and at the walls of the urban model may be a critical uncertainty for CFD simulations. As stated by Blocken et al. (2007a), three different regions of the computational domain with different surface roughness can be distinguished (Fig. 6.1). In the upstream and downstream regions the obstacles are modeled implicitly. This means that the obstacle geometries are not included in the computational domain with their actual shape and size but that their effect on the wind flow pattern is modeled using either the aerodynamic roughness length ($z_0$) or the equivalent sand grain roughness height ($k_s$) inserted in the wall functions applied to the bottom of the computational domain. In the central region of the domain, the obstacles (buildings, bridges, trees, etc.) are explicitly modeled (i.e. with their actual shape and size) and wall functions are applied to the surface of the obstacles (e.g. the walls and the roofs) and on the ground surface, e.g. on the streets, sidewalks, and grass plains. Two options exist: either a surface roughness height is inserted in these wall functions, representing the roughness of building walls, roofs, streets, etc., or these surfaces are assumed to be smooth (zero roughness). It is not clear how sensitive the numerical results are to different surface roughness values applied on the urban model surfaces (buildings, streets, etc.). For this purpose, in

![Figure 6.1](image)

**Figure 6.1.** Computational domain with building models for CFD simulation of ABL flow: (a) definition of inlet flow, approach flow and incident flow and indication of different parts in the domain for roughness modelling; (b) computational mesh with variable height of the wall adjacent cells along the length of the domain (figure by Blocken et al., 2007a).
the second stage of the present work, the impact of roughness height in the central part of the computational domain on 3D steady state RANS simulation results is investigated in terms of deviations in mean velocity.

The present study is part of a wider research project aimed at investigating the impact of several parameters: geometrical simplifications (Ricci et al., 2017a), inflow conditions (Ricci et al., 2017b), turbulence models and roughness height (the current work), and the turbulence modeling approach (e.g. RANS vs. LES; future work). For this scope a district, so called “Quartiere La Venezia” of Livorno city (Italy), was chosen as a case study. In a preliminary step WT tests were performed at a reduced scale (1:300) and the mean wind velocity profiles were measured at 25 positions located in the urban district (described in Section 6.2). A more extensive description of the WT setup and results is given in a previous publication (Ricci et al., 2017c). Afterward, CFD simulations were performed in two stages on the reduced scale model as WT. In the first stage CFD simulations were performed using three \( k-\varepsilon \) and two \( k-\omega \) turbulence models (standard \( k-\varepsilon \), realizable \( k-\varepsilon \), RNG \( k-\varepsilon \), standard \( k-\omega \) and SST \( k-\omega \)). In the second stage two different sets of surface roughness height (described in Section 6.3) were adopted. Therefore, mean wind velocity profiles of CFD simulations (of both stages) and WT results were separately compared at 25 measuring positions (the same above mentioned). In order to quantify the impact of the two considered parameters (i.e. turbulence models and surface roughness height) four validation metrics were used, separately, for the two stages: fractional bias \((FB)\), normalized mean square error \((NMSE)\), correlation coefficient \((R)\) and the fraction of data within a factor of 1.3 from experimental results \((FAC1.3)\).

The paper is organized as follows. Section 6.2 contains a short description of the selected urban area and the WT tests. In section 6.3 the computational domain, boundary conditions and solver settings are detailed. In sections 6.4 and 6.5 the results in terms of contours of amplification factor, mean wind velocity profiles, and validation metrics are shown. Finally, in Section 6.6 the discussion and conclusions are reported.

6.2 Description of urban model

The historical district Quartiere La Venezia is placed close to the port of Livorno which was monitored in the past by means of a series of instruments installed in the framework of the European Projects “Wind and Ports” (2009 - 2012) and “Wind, Ports and Sea” (2014 - 2015) (Solari et al., 2012; Burlando et al., 2015 and 2017) (Fig.
6.2a). The mean wind velocity scenarios obtained in the European project Wind and Ports (Solari et al. 2012) were used as reference to reproduce the ABL profile in the WT tests. Three wind directions ($\alpha = 240^\circ, 270^\circ, 300^\circ$) according to the prevalent ones detected by the anemometric station $A_{vp}3$ were considered (Fig. 6.2a). Atmospheric Boundary Layer Wind Tunnel (ABLWT) tests of wind flow in this area were performed on a reduced scale model (1:300) in the closed circuit ABLWT of the Department of Civil, Chemical, and Environmental Engineering (DICCA) of the University of Genoa (Italy) (Fig. 6.2b). The WT model was constructed using two different materials: medium density fiberboard (plywood) for the ground surface and buildings and PVC foamboard panels for roofs and bridges (Fig. 6.2b). Vertical mean wind velocity profiles were monitored by means of a multihole pressure probe at two sets of measuring positions, at 15 different heights above the bottom (Fig. 6.3). The first set consisting of 10 positions ($A_{1,1} - A_{5,2}$) was fixed on the urban model (such as to the turntable) and placed along “Canale Rosciano”, the main water canal of Livorno city (Fig. 6.3a). The second set consisted of a grid of 15 positions ($L_{1,1,5}$, $L_{2,1,5}$, $L_{3,1,5}$) was kept fixed with respect to the local reference system of the WT section (Fig. 6.3b). The reader is referred to Ricci et al. (2017c) for more details.

Figure 6.2 Pictures of Livorno city (Italy): (a) location of the test district (yellow circle), anemometric stations ($A_{vp}3$, $A_{vp}4$ and $A_{vp}6$) and LiDAR station, (b) WT model and (c) computational grid of Quartiere La Venezia at scale 1:300 for the incoming wind direction $\alpha = 240^\circ$. 
6.3 CFD simulations: computational settings and parameters

6.3.1 Computational domain

The best performing geometry analyzed in previous stage of this research project, so called approximated model, was selected for subsequent stages and for the current stage as well. The reader is referred to (Ricci et al, 2017a) for more information. A portion of the WT section was reproduced by the computational domain with a size of \( L \times W \times H = 5.5 \times 1.70 \times 1.35 \) m\(^3\), where the width \((W)\) and height \((H)\) were consistent with the WT cross section while the length \((L)\) reproduced the downstream part of the test section. Three different computational grids, one for each of the investigated wind directions \((\alpha = 240^\circ, 270^\circ \text{ and } 300^\circ)\), were generated according to best practice guidelines (Franke et al., 2007; Tominaga et al., 2008; Blocken, 2015a) and adopting the grid generation technique proposed by van Hooff and Blocken (2010). The computational domain counted 23.2 million cells for \(\alpha = 240^\circ\), 20.8 million cells for \(\alpha = 270^\circ\), and 19.9 million cells for \(\alpha = 300^\circ\). The minimum cell size was chosen equal to 0.0033 m close to the walls, in order to keep the \(y^+\) value in the log law range (between 30 and 300 for OpenFOAM).

6.3.2 Boundary conditions

At the inlet of the computational domain the mean wind velocity profile \(U(z)\), detected approximately 1 m upstream of the first building of the WT model, was reproduced. Likewise, velocity standard deviations \(\sigma_u(z)\), \(\sigma_v(z)\) and \(\sigma_w(z)\) measured in
the WT tests (at the same position aforementioned) were employed to calculate the
turbulent kinetic energy $k(z)$, turbulence dissipation rate $\varepsilon(z)$ and specific dissipation
rate $\omega(z)$ profiles. The turbulent kinetic energy $k(z)$ profile was calculated by Eq. (6-
1) (Tominaga et al., 2008). The turbulence dissipation rate $\varepsilon(z)$ and the specific
dissipation rate $\omega(z)$ profiles were calculated according to Eq. (6-2) (Tominaga et
al., 2008) and Eq. (6-3) (Wilcox, 1998) for CFD cases adopting the $k$-$\varepsilon$ and $k$-$\omega$
turbulence models, respectively.

$$k(z) = \frac{1}{2} (\sigma_u^2(z) + \sigma_v^2(z) + \sigma_w^2(z))$$

(6-1)

$$\varepsilon(z) = C_{\mu}^{0.5} k(z) \frac{d\bar{U}}{dz}$$

(6-2)

$$\omega(z) = C_{\mu}^{0.25} \frac{\sqrt{k(z)}}{l}$$

(6-3)

$$l = C_{\mu} \frac{k(z)^{1.5}}{\varepsilon(z)}$$

(6-4)

In Eq. (6-2) and (6-3) the model constant $C_{\mu}$ is equal to 0.09 and the turbulence
length scale $l$ is calculated in accordance with Eq. (6-4). At the bottom of the
computational domain and on the surface of the obstacles (e.g. buildings and
bridges) the standard wall functions were used adopting different values of
roughness height $k_s$ for the two stages. In the first stage, the impact of turbulence
models, a homogeneous value of roughness length $z_0$ equal to 0.0033 m,
corresponding to an equivalent sand grain roughness height $k_s = 0.0013$ m, was
adopted at the bottom. A value of $k_s$ equal to zero was used for the surface of the
obstacles (Fig. 6.4a). The value for the equivalent sand grain roughness $k_s$,
aforementioned, was calculated in accordance with Blocken et al. (2007a) as $k_s = 9.793 \frac{z_0}{C_o}$. $C_o$ (the roughness constant) was taken equal to 2.5 in order to comply
with the necessary condition $y_p > k_s$, where $y_p$ is the distance of the centroid of the
first near wall cell from the wall. In the second stage, the impact of roughness height, the
real roughness height values of the materials used in the WT testing ($k_{s,mat}$) were
employed according to the experimental values given by Hiziroglu and Kosonkorn
(2006) and Zhong et al. (2013). In particular, values of $k_{s,mat}$ equal to $4.0 \times 10^{-6}$ m
and $1.0 \times 10^{-6}$ m were assumed for the medium density fiberboard - MDF (buildings,
bridges and model ground surface) and for the steel (bottom) surfaces of the WT, respectively (Fig. 6.4b-c). For both stages, at the sides and top of the computational domain standard wall functions were employed using an aerodynamic roughness height $k_s$ equal to zero; at the outlet absolute zero static pressure was imposed.

### 6.3.3 Solver settings

The CFD simulations were carried out using the 3D steady state RANS approach and the open source software package OpenFOAM 2.3.0. In the first stage the turbulence models which are most commonly used for urban wind flow simulations were tested: standard $k$-$\varepsilon$ (SKE) (Jones and Launder, 1972), realizable $k$-$\varepsilon$ (RKE) (Shih et al., 1995), Renormalization Group (RNG) $k$-$\varepsilon$ (RNG) (Yakhot and Orszag, 1986), standard $k$-$\omega$ (SKO) (Wilkox, 1998), and Shear Stress Transport (SST) $k$-$\omega$ (SST) (Menter, 1997). In the second stage only the realizable $k$-$\varepsilon$ turbulence model was adopted. Second order discretization schemes were used for the convective and viscous terms of the governing equations. The SIMPLE algorithm was adopted to couple pressure and velocity fields (Versteeg and Malalasekera, 2007). All the
variables of interest (i.e. mean wind velocity, turbulent kinetic energy and turbulence dissipation rate) were monitored for a large amount of iterations: about 30,000 and 75,000 iterations when the $k$-$\varepsilon$ and $k$-$\omega$ turbulence models were respectively employed. The residuals reached the following minimum values for all the CFD simulations performed: $10^{-8}$ for the three components of momentum, $10^{-7}$ for the three velocity components and $10^{-6}$ for the turbulent kinetic energy, turbulence dissipation and specific dissipation rate. All CFD simulations were performed on a High Performance Computing (HPC) system at DICCA using a cluster node with 32 cores running in parallel at 1.4 GHz.

6.4 Impact of turbulence models

6.4.1 Contours of amplification factor

Fig. 6.5 shows contours of the wind amplification factor made at 0.02 m above the bottom and calculated as the local wind velocity magnitude divided by the inlet velocity magnitude at the same reference height, $U_{in,0.02m}$. All $k$-$\varepsilon$ turbulence models were found to exhibit almost the same wind flow patterns below 0.02 m above the bottom. Conversely, noticeable differences were found between two $k$-$\omega$ turbulence models. However, in order to highlight the biggest differences between the $k$-$\varepsilon$ and $k$-$\omega$ turbulence models, only the SKE and SKO results will be compared here. In general, for all wind directions considered, higher amplification factors were found for the SKE than for the SKO results (Fig.6.5a-f).

For wind directions $\alpha = 240^\circ$ and $\alpha = 270^\circ$ (Fig. 6.5a-d) the SKO predicted higher wind velocities compared to the SKE in two central places of the district: Canale Rosciano and Piazza Luogo Pio, respectively indicated in Fig. 6.5 by “CR” and “LP”. The same trend above described was found upstream and downstream of the district where the difference is much more pronounced. For the wind direction $\alpha = 300^\circ$ (Fig. 6.5e-f) Canale Rosciano and Piazza Luogo Pio were almost perpendicular to the incoming wind direction and were therefore sheltered by the upstream buildings. Both turbulence models (SKE and SKO) gave differences in amplification factors in the wakes of buildings along Canale Rosciano, at Piazza Luogo Pio and downstream of the district. Higher amplification factors were found for SKO than for the SKE, mostly at the entrance of Canale Rosciano and upstream of the district. Fig. 6.6 shows wind velocity contours of amplification factors in a vertical section for all five investigated turbulence models, superimposed on perspective views of the computational grid. Vertical sections were preliminarily
made along several lines of the computational domain (e.g. along the lines L1\_1.5, L2\_1.5 and L3\_1.5 previously described) and for all wind directions considered, in order to understand the different performance of the turbulence models adopted. Unlike the wind directions $\alpha = 240^\circ$ and $\alpha = 270^\circ$, wind direction $\alpha = 300^\circ$ showed flow separations inside the district (see Fig. 6.5e-f) where the different performance of the five turbulence models adopted was emphasized (Fig. 6.6). Finally, the vertical velocity contours made along the line L2\_1.5 was chosen as an example (see Fig. 6.6a and Fig. 6.3b) and normalized with respect to the maximum inflow wind velocity at 0.6 m above the bottom, $U_{in,0.6m}$. Despite the observed differences in wind amplification factors between $k$-$\omega$ and $k$-$\varepsilon$ turbulence models the urban canopy layer (UCL) and the roughness sublayer (RS) thicknesses were described similarly by all turbulence models, except for the SKO (Fig. 6.6). Indeed, significant differences were found between the SKO and the other turbulence models, both in the higher and lower parts of the contour (e.g. inside Canale Rosciano and Piazza Luogo Pio).

![Figure 6.5 Contours of wind amplification factor: comparison between SKE and SKO results for wind directions (a, b) $\alpha = 240^\circ$, (c, d) $\alpha = 270^\circ$ and (e, f) $\alpha = 300^\circ$. Horizontal section made at 0.02 m above the bottom. Canale Rosciano and Piazza Luogo Pio are respectively indicated by “CR” and “LP” in the figures.](image-url)
Figure 6.6 Wind velocity contours made along the plane L2 - L2’ (a) for the inflow wind direction $\alpha = 300^\circ$; comparison among CFD results adopting five turbulence models: (b) RKE, (c) SKE, (d) RNG, (e) SKO and (f) SST. Canale Rosciano and Piazza Luogo Pio are respectively indicated by “CR” and “LP” in the figures.
6.4.2 Vertical profiles of mean velocity

Mean velocity profiles were compared at 25 measuring positions (A and L) and 15 heights, from 0.02 to 0.6 m as previously described in Section 6.2 and Fig. 6.3. As an example, a comparison of CFD results obtained with all five turbulence models and WT results at positions A2 - A5, placed in the middle of Canale Rosciano, is shown in Fig. 6.7. In the abscissa the ratio $U/U_{in,0.6m}$ is reported; the ordinate shows the normalized height $z/z_{ref}$ with respect to the reference height $z_{ref} = 0.6$ m. In general, a similar wind velocity profile development inside Canale Rosciano (from positions A2 to A5) was found for all the CFD cases, consistent with WT results.

For the wind direction $\alpha = 240^\circ$ (Fig. 6.7a), all the CFD cases employing the $k$-$\varepsilon$ turbulence models showed almost the same performance and satisfactory agreement with the WT results. In contrast, clear discrepancies with WT data were found between SKO and SST. In particular the SKO showed significant overestimations, especially in the higher parts of the profiles. In contrast, in the lower parts (below $z/z_{ref} \approx 0.10$) the SKO gave similar results as others models, especially at positions A4 and A5.

For the wind direction $\alpha = 270^\circ$ (Fig. 6.7b) a similar trend as above described for $\alpha = 240^\circ$ was found. Nevertheless, due to the extensive leeward zones along Canale Rosciano (see also Fig. 6.5c-d) the agreement between WT and CFD results was not completely satisfactory, mostly in the lower part of the profiles (below $z/z_{ref} \approx 0.20$), where none of the turbulence models properly predicted the flow separations. All turbulence models showed an underestimation of velocity values in the lower part of the profiles and a quite perfect agreement with the WT results in the higher part, except for the SKO.

For the wind direction $\alpha = 300^\circ$ (Fig. 6.7c) large differences between results of the five turbulence models were detected in the lower part of the profiles. A wide part of Canale Rosciano was sheltered by the upstream buildings and flow separation and flow reversal likely occurred here (see also Fig. 6.6). Overall, also for this wind direction all $k$-$\varepsilon$ turbulence models showed better performance than the $k$-$\omega$ models.
Figure 6.7 Comparison of the vertical mean wind velocity profiles at the positions A2 - A5 for the inflow directions (a) $\alpha = 240^\circ$, (b) $\alpha = 270^\circ$ and (c) $\alpha = 300^\circ$, for the $k$-$\varepsilon$ turbulence models (RKE, SKE, RNG) and the $k$-$\omega$ turbulence models (SKO and SST). The inlet profile (black dashed line) is also shown for comparison.
6.4.3 Deviations caused by turbulence models

Four validation metrics were used to quantify the impact of turbulence models (Schatzmann et al., 2010): fractional bias (\(FB\)), normalized mean square error (\(NMSE\)), correlation coefficient (\(R\)) and the fraction of data within a factor of 1.3 (\(FAC1.3\)). The statistical performance of each CFD case was evaluated with respect to the WT results in terms of mean wind velocity values \(U\) in all measured positions (Chang and Hanna, 2004; Gousseau et al., 2013). The following equations were used:

\[
FB = 2 \frac{(U_{WT} - U_{CFD})}{U_{WT} + U_{CFD}} 
\]

\[
NMSE = \frac{(U_{WT} - U_{CFD})^2}{U_{WT} \cdot U_{CFD}} 
\]

\[
R = \frac{(U_{WT} - \overline{U}_{WT})(U_{CFD} - \overline{U}_{CFD})}{\sigma_{U_{WT}} \cdot \sigma_{U_{CFD}}} 
\]

\[
1/1.3 \approx 0.77 \leq \frac{U_{CFD}}{U_{WT}} \leq 1.3
\]

Here \(\overline{U}_{WT}\) is the mean wind velocity magnitude from the WT results, \(\overline{U}_{CFD}\) is the mean wind velocity magnitude from the CFD simulations using the five turbulence models, and \(\sigma\) is the standard deviation over a specific dataset. The ideal values corresponding to complete agreement between CFD and WT results are \(FB = 0\), \(NMSE = 0\), \(R = 1\) and \(FAC1.3 = 1\). The statistical performance of every CFD case was calculated in horizontal planes for three wind directions (\(\alpha = 240^\circ, 270^\circ\) and \(300^\circ\)), 25 measuring positions (A and L) and for two different reference heights (\(z = 0.02\) m and \(z = 0.10\) m above the bottom). Validation metrics for the three wind directions and at different reference heights are reported in Tables 6.1, 6.2 and 6.3; the velocity data are graphically displayed in Fig. 6.8 and 6.9. On the abscissae of Fig. 6.8 and 6.9 the mean velocity values \(U_{WT}\) of the WT tests are reported, normalized by the mean inlet wind velocity magnitude taken at the reference heights \(U_{in,0.02}\) and \(U_{in,0.1}\) (0.02 m and 0.1 above the bottom). The ordinates indicate the equivalent ratios \(U_{CFD}/U_{in,0.02}\) and \(U_{CFD}/U_{in,0.1}\) of the CFD data.
For the wind direction $\alpha = 240^\circ$ and the reference height $\zeta = 0.02$ m (Table 6.1a and Fig. 6.8a), $FB$ values confirmed the overestimation, in terms of velocity values, of CFD data with respect to WT data. Lower $FB$ values of the SKE and SST indicated a distribution closer to the diagonal of Figure 6.8a than for the SKO. The $NMSE$ showed almost the same performance for all turbulence models, with all results falling in a small parameter range (between 0.04 and 0.06). The $R$ indicated the best performance of the SKE (0.81), comparable with that of the RKE (0.79). Worse agreement with WT data was found for the RNG (0.73), SKO (0.74) and SST (0.72). $FAC1.3$ showed the same performance of the three $k$-$\varepsilon$ turbulence models (0.89), but a significantly decreased performance of the SKO (0.78) and SST (0.61) models. Nevertheless, metrics calculated at the lowest reference height may not be suitable to fully describe the performance of different turbulence models. For this reason the same validation metrics were also calculated for another reference height, $\zeta = 0.1$ m. According to the remarks previously made in Section 6.4.2 this height ($\zeta = 0.1$ m) represents approximately the height of the RS of the urban boundary layer (UBL) observed (Barlow, 2013, 2014). Therefore it could be significant for the understanding of wind flow patterns calculated with the different turbulence models.

For the wind direction $\alpha = 240^\circ$ and the reference height $\zeta = 0.1$ m (Table 6.1b and Fig. 6.9a) results for all turbulence models showed a satisfactory agreement with WT data for all the validation metrics considered, except for the SKO where all metrics indicated a worse performance than all other models considered here.

For the wind direction $\alpha = 270^\circ$ and the reference height $\zeta = 0.02$ m (Table 6.2a and Fig. 6.8b) all the turbulence models showed $FB$ values in a range of 0.23 - 0.25, except for the SKE which gave a value equal to 0.09. $NMSE$ values were almost the same for all the turbulence models except for SST which showed the worst agreement with WT data. This last trend was confirmed by the $R$ and $FAC1.3$, for which the SST also displayed inferior values.

For the wind direction $\alpha = 270^\circ$ and the reference height $\zeta = 0.1$ m (Table 6.2b and Fig. 6.9b) all turbulence models except for the RNG displayed an overestimation in terms of velocity values. As was the case for the wind direction $\alpha = 240^\circ$ the SKO again showed the worst agreement with WT data. This last trend was confirmed by the $R$ and $FAC1.3$, for which the SST also displayed inferior values.

For the wind direction $\alpha = 300^\circ$ and the reference height $\zeta = 0.02$ m (Table 6.3a and Fig. 6.8c) both the $FB$ and $NMSE$ values showed a better distribution around the diagonal for SKO and SST than the CFD cases employing the $k$-$\varepsilon$ turbulence models. A better $R$ between SST and WT data was found than for the
CFD cases using other turbulence models. Finally, \textit{FAC1.3} indicated that the SKO gave the worst performance.

For the wind direction $\alpha = 300^\circ$ and the reference height $\zeta = 0.1$ m (Table 6.3b and Fig. 6.9c) a similar trend as observed for the wind directions $\alpha = 240^\circ$ and $\alpha = 270^\circ$ was found.

Overall, all $k$-\(\varepsilon\) turbulence models showed consistently better performance than the $k$-\(\omega\) models for all wind directions analyzed, except for the wind direction $\alpha = 300^\circ$ and $\zeta = 0.02$ m where the \(FB\), the \textit{NMSE} and the \(R\) showed a better performance of SKO than the RKE, SKE and RNG. Therefore, in accordance with the choice made by the author in the previous stages of work (Ricci et al., 2017a-b), based on the negligible difference found between all the three $k$-\(\varepsilon\) turbulence models and on the results obtained in previous publications about 3D steady state RANS simulations aimed at predicting the urban wind flows (e.g. Janssen et al., 2013 and Blocken et al., 2016), the RKE was adopted for the next stage (i.e. the impact of roughness height on the CFD results).

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
\textbf{(a)} & $\zeta = 0.02$ m & SKE $\text{vs}$ WT & RKE $\text{vs}$ WT & RNG $\text{vs}$ WT & SKO $\text{vs}$ WT & SST $\text{vs}$ WT \\
\hline
\textit{FB} & -0.02 & -0.03 & -0.04 & -0.13 & -0.04 \\
\textit{NMSE} & 0.04 & 0.04 & 0.05 & 0.06 & 0.05 \\
\textit{R} & 0.81 & 0.79 & 0.73 & 0.74 & 0.72 \\
\textit{FAC1.3} & 0.89 & 0.89 & 0.89 & 0.78 & 0.61 \\
samples & 18 & 18 & 18 & 18 & 18 \\
\hline
\textbf{(b)} & $\zeta = 0.02$ m & SKE $\text{vs}$ WT & RKE $\text{vs}$ WT & RNG $\text{vs}$ WT & SKO $\text{vs}$ WT & SST $\text{vs}$ WT \\
\hline
\textit{FB} & -0.04 & -0.05 & -0.04 & -0.14 & -0.06 \\
\textit{NMSE} & 0.005 & 0.006 & 0.005 & 0.07 & 0.02 \\
\textit{R} & 0.88 & 0.87 & 0.88 & 0.73 & 0.74 \\
\textit{FAC1.3} & 1.0 & 1.0 & 1.0 & 0.83 & 0.96 \\
samples & 24 & 24 & 24 & 24 & 24 \\
\hline
\end{tabular}
\caption{Statistical performance of CFD cases employing five turbulence models, for the inflow direction $\alpha = 240^\circ$, at 25 measurement positions (A and L) and two reference heights: (a) $\zeta = 0.02$ m and (b) $\zeta = 0.1$ m above the bottom. Also indicated are the number of measurement positions (samples) that were not occupied by the model and were therefore available for statistical analysis (note that this depends on the wind direction as positions L were fixed with respect to the WT).}
\end{table}
Table 6.2
Statistical performance of CFD cases employing five turbulence models, for the inflow direction $\alpha = 270^\circ$, at 25 measurement positions (A and L) and two reference heights: (a) $z = 0.02$ m and (b) $z = 0.1$ m above the bottom. Also indicated are the number of measurement positions (samples) that were not occupied by the model and were therefore available for statistical analysis (note that this depends on the wind direction as positions L were fixed with respect to the WT).

<table>
<thead>
<tr>
<th></th>
<th>$z = 0.02$ m</th>
<th>SKE vs WT</th>
<th>RKE vs WT</th>
<th>RNG vs WT</th>
<th>SKO vs WT</th>
<th>SST vs WT</th>
</tr>
</thead>
<tbody>
<tr>
<td>FB</td>
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<td>0.25</td>
<td>0.24</td>
<td>0.09</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
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<td>0.12</td>
<td>0.11</td>
<td>0.11</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>0.82</td>
<td>0.80</td>
<td>0.80</td>
<td>0.73</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td>FAC1.3</td>
<td>0.47</td>
<td>0.47</td>
<td>0.53</td>
<td>0.47</td>
<td>0.37</td>
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<table>
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<th>RKE vs WT</th>
<th>RNG vs WT</th>
<th>SKO vs WT</th>
<th>SST vs WT</th>
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<tr>
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<td>0.02</td>
<td>-0.18</td>
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</tr>
<tr>
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<td>0.005</td>
<td>0.03</td>
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<tr>
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</tr>
<tr>
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<td>1.0</td>
<td>0.79</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
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<td>24</td>
<td>24</td>
<td>24</td>
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<td></td>
</tr>
</tbody>
</table>

Table 6.3
Statistical performance of CFD cases employing five turbulence models, for the inflow direction $\alpha = 300^\circ$, at 25 measurement positions (A and L) and two reference heights: (a) $z = 0.02$ m and (b) $z = 0.1$ m above the bottom. Also indicated are the number of measurement positions (samples) that were not occupied by the model and were therefore available for statistical analysis (note that this depends on the wind direction as positions L were fixed with respect to the WT).

<table>
<thead>
<tr>
<th></th>
<th>$z = 0.02$ m</th>
<th>SKE vs WT</th>
<th>RKE vs WT</th>
<th>RNG vs WT</th>
<th>SKO vs WT</th>
<th>SST vs WT</th>
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</thead>
<tbody>
<tr>
<td>FB</td>
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<td>0.31</td>
<td>0.27</td>
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<td>0.19</td>
<td></td>
</tr>
<tr>
<td>NMSE</td>
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<td>0.35</td>
<td>0.32</td>
<td>0.26</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>R</td>
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<td>0.53</td>
<td>0.57</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
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<td>0.47</td>
<td>0.35</td>
<td>0.41</td>
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</tr>
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</tbody>
</table>
The impact of turbulence models and roughness height

<table>
<thead>
<tr>
<th>(b)</th>
<th>( \zeta = 0.02 \text{ m} )</th>
<th>SKE vs WT</th>
<th>RKE vs WT</th>
<th>RNG vs WT</th>
<th>SKO vs WT</th>
<th>SST vs WT</th>
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</thead>
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<tr>
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<td>0.02</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>NMSE</td>
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<td>0.02</td>
<td>0.02</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
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<tr>
<td>R</td>
<td>0.85</td>
<td>0.75</td>
<td>0.76</td>
<td>0.82</td>
<td>0.82</td>
<td>0.66</td>
</tr>
<tr>
<td>FAC1.3</td>
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<td>0.87</td>
<td>0.92</td>
<td>0.71</td>
<td>0.71</td>
<td>0.71</td>
</tr>
<tr>
<td>samples</td>
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<td>24</td>
<td>24</td>
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</tr>
</tbody>
</table>

**Figure 6.8** Comparison of numerical and experimental data of wind velocity ratio at the monitored positions (A and L) for three inflow directions: (a) \( \alpha = 240^\circ \), (b) \( \alpha = 270^\circ \), (c) \( \alpha = 300^\circ \) at a height \( \zeta = 0.02 \text{ m} \) above the bottom. Dashed black lines correspond to 10% and 30% errors, as indicated.

**Figure 6.9** Comparison of numerical and experimental data of wind velocity ratio at the monitored positions (A and L) for three inflow directions: (a) \( \alpha = 240^\circ \), (b) \( \alpha = 270^\circ \), (c) \( \alpha = 300^\circ \) at a height \( \zeta = 0.1 \text{ m} \) above the bottom. Dashed black lines correspond to 10% and 30% errors, as indicated.
6.5 Impact of roughness height

6.5.1 Contours of amplification factor

Wind velocity contours of CFD case 1, employing a homogeneous roughness height \((k_s)\) value at the bottom (i.e. the ground level), and CFD case 2 adopting roughness height values correspond to the surface roughness of the materials used in the WT tests \((k_{s,mat})\) (see also Fig. 6.4), are compared in Fig. 6.10 through horizontal sections made at 0.02 m above the bottom. The contours were normalized with respect to the inlet wind velocity magnitude at the same reference height, \(U_{in,0.02m}\), for both models. In general, CFD case 2 showed higher amplification factors compared to CFD case 1, both in the internal part of the district (e.g. *Piazza Luogo Pio* and *Canale Rosciano*) and in external parts (such as upstream and downstream to the district). In particular, confinement effects on the lateral sides of both the computational domain and the WT test section (Figs. 6.10b,d,f) were emphasized in CFD case 2.

In Figs. 6.10a-b (\(\alpha = 240^\circ\)), since the ancient fortress of Livorno (called “Fortezza Antica”) and the bridge of “Viale della Cinta Esterna” (indicated in the figures by “F” and “bridge” respectively) impede the wind flow funneling along *Canale Rosciano* and *Piazza Luogo Pio*, the CFD cases showed almost the same wind flow pattern inside the district of *Quartiere La Venezia*. This phenomenon was better clarified by comparison with Figs. 6.10e-f (\(\alpha = 300^\circ\)), where in contrast the flow was funneled along *Canale Rosciano* through the passage between the bridge and the surrounding buildings. Higher amplification factors of CFD case 2, compared to the CFD case 1, were found upstream and on the lateral sides of the district.

In Figs. 6.10c-d (\(\alpha = 270^\circ\)), CFD case 2 showed a higher wind amplification factor than was found for CFD case 1, mostly in *Piazza Luogo Pio*, upstream and downstream of the district. A similar wind flow pattern to that found along *Canale Rosciano* for the previous wind direction was observed here. The bridge of *Viale della Cinta Esterna*, to a greater extent than the fortress, was an obstacle for the wind flow funneling along *Canale Rosciano* and *Piazza Luogo Pio*.

In Figs. 6.10e-f (\(\alpha = 300^\circ\)), CFD case 2 showed higher amplification factors compared to CFD case 1 in three different zones: between two buildings of *Piazza
Figure 6.11 shows the ratio $U/U_{in,0.6}$ corresponding to the wind velocity magnitude $U$ normalized with respect to the incoming wind velocity $U_{in,0.6}$ at $z = 0.6$ m on the abscissa and the normalized height $z/z_{ref}$ with the reference height $z_{ref} = 0.6$ m on the ordinate.

For the wind direction $\alpha = 240^\circ$ (Fig. 6.11a) both CFD cases showed almost the same performance at the four selected positions (A2 - A5), although higher
wind velocity values of CFD case 2 were found near the ground surface. The agreement between CFD and WT results was satisfactory.

Larger discrepancies between CFD and WT results were observed for the wind directions $\alpha = 270^\circ$ and $\alpha = 300^\circ$. In particular for the wind direction $\alpha = 270^\circ$ (Fig. 6.11b) differences between both CFD cases were found below $z/z_{ref} \approx 0.20$ at the four measuring positions. More pronounced differences between the two CFD cases were observed for the wind direction $\alpha = 300^\circ$. For this direction part of Canale Rosciano assumed an almost orthogonal orientation with respect to the incoming wind direction, as a result of which flow reversal probably occurred at positions A4 and A5 (Fig. 6.11c).

In order to better understand the performance of the two CFD cases six positions upstream of the district (P1 - P6) were monitored at 20 heights, from 0 to 0.6 m above the bottom for the wind direction $\alpha = 270^\circ$ (Fig. 6.12). Fig. 6.13 clearly shows the different streamwise development of the wind velocity profile for the two cases when the wind can flow freely through the upstream part of the computational domain. From position P2 to position P6, due to the difference in surface roughness height, the discrepancy between the two CFD cases becomes more pronounced, mostly in the lower part of the profiles. Indeed, results for CFD case 2 clearly show the development of an internal boundary layer due to the mismatch between the surface roughness height at the bottom of the domain and the roughness height corresponding to the inlet profile. In contrast, for CFD case 1, where the same roughness height was adopted both for the inlet profile and at the bottom of the domain, a perfect overlap between the inlet and local profiles is found for positions P1 to P6 (Fig. 6.13).

Overall, as stressed in Section 6.5.1, the specific morphology of the district and its orientation with respect to the wind direction affected the wind flow funneling inside the district. Smaller discrepancies in terms of velocity magnitude values were found along Canale Rosciano (A2 - A5) than in the upstream and downstream parts of the district (P1 - P6), where more pronounced discrepancies were found.
Figure 6.11 Comparison of the vertical mean wind velocity profiles at the positions A2 - A5 for the inflow directions (a) $\alpha = 240^\circ$, (b) $\alpha = 270^\circ$ and (c) $\alpha = 300^\circ$ for CFD case 1 and CFD case 2. The inlet profile (black dashed line) is also shown for comparison.
Figure 6.12 Location of measurements positions (P1-P6) superimposed on contours of wind velocity magnitude obtained from (a) CFD case 1 and (b) CFD case 2 for the wind direction $\alpha = 270^\circ$.

Figure 6.13 Comparison of vertical mean wind velocity profiles at the positions P1-P6 (see Figure 6.11) for the inflow direction $\alpha = 270^\circ$ for CFD case 1 and CFD case 2. The inlet profile (black dashed line) is also shown for comparison.
6.5.3 Deviations caused by roughness height

In order to quantify the impact of roughness height on wind velocity patterns in the district the four validation metrics which were introduced in Section 6.4.3 (FB, NMSE, R and FAC1.3) were also applied here. The statistical performance of CFD cases 1 and 2 was calculated in the horizontal plane for the three wind directions, 25 measuring positions and a reference height (full scale equivalent) of $z = 0.02$ m above the bottom. Validation metrics are reported in Table 6.4 and velocity data are graphically displayed in Fig. 6.14.

For a wind direction of $\alpha = 240^\circ$ the FB values indicated an underestimation of both CFD case results compared to WT data. In contrast, for $\alpha = 270^\circ$ and $\alpha = 300^\circ$ FB values of both CFD cases showed an overestimation of CFD data compared to the WT ones. A different trend with respect to previous one was found for the NMSE metric, which showed the same performance for CFD cases 1 and 2 for the wind directions $\alpha = 240^\circ$ and $\alpha = 270^\circ$. The NMSE value of CFD case 1 was larger than that of CFD case 2 for $\alpha = 300^\circ$, indicating worse performance. The R of both CFD cases were in general unsatisfactory. For all wind directions considered CFD case 2 performed better than CFD case 1. Finally, FAC1.3 showed the same performance of both CFD cases for the directions $\alpha = 240^\circ$ and $\alpha = 300^\circ$, but a significant difference of 10% in favor of case 1 for $\alpha = 270^\circ$.

Table 6.4

Validation metrics calculated for CFD cases 1 and 2 for three inflow directions ($\alpha = 240^\circ$, $270^\circ$, $300^\circ$) at 25 measurement positions (A and L) and at a reference height of $z = 0.02$ m above the bottom.

<table>
<thead>
<tr>
<th>$\alpha = 240^\circ$, $z = 0.02$ m</th>
<th>CFD case 1 vs WT</th>
<th>CFD case 2 vs WT</th>
<th>ideal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$FB$</td>
<td>-0.04</td>
<td>-0.10</td>
<td>0</td>
</tr>
<tr>
<td>$NMSE$</td>
<td>0.04</td>
<td>0.04</td>
<td>0</td>
</tr>
<tr>
<td>$R$</td>
<td>0.77</td>
<td>0.79</td>
<td>1</td>
</tr>
<tr>
<td>FAC1.3</td>
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<td>0.89</td>
<td>1</td>
</tr>
<tr>
<td>samples</td>
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<td>25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\alpha = 270^\circ$, $z = 0.02$</th>
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<th>CFD case 2 vs WT</th>
<th>ideal value</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.25</td>
<td>0.19</td>
<td>0</td>
</tr>
<tr>
<td>$NMSE$</td>
<td>0.13</td>
<td>0.13</td>
<td>0</td>
</tr>
<tr>
<td>$R$</td>
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<td>0.85</td>
<td>1</td>
</tr>
<tr>
<td>FAC1.3</td>
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\[ \alpha = 300^\circ, \ z = 0.02 \ m \]

<table>
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<tr>
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<th>CFD case 1 vs WT</th>
<th>CFD case 2 vs WT</th>
<th>ideal value</th>
</tr>
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<tr>
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|Figure 6.14| Comparison of CFD and WT data of wind velocity ratio at the monitored positions (A and L) for three inflow directions: (a) \( \alpha = 240^\circ \), (b) \( \alpha = 270^\circ \), (c) \( \alpha = 300^\circ \) at a height \( z = 0.02 \ m \) above the bottom. Dashed black lines correspond to 10% and 30% errors, as indicated.|

### 6.6 Discussion and conclusions

In this paper the impact of the turbulence models (first stage) and the roughness height (second stage) on CFD simulations of wind flow in an urban environment was evaluated. 3D steady state RANS simulations were performed on a district, so called "Quartiere la Venezia" placed in Livorno city (Italy), for three wind directions (\( \alpha = 240^\circ, 270^\circ \) and \( 300^\circ \)) at the same reduced scale (1:300) as previously performed WT tests. For both stages, CFD and WT results in terms of mean wind velocity profiles were compared at 25 measuring positions for 15 heights and for all wind directions analyzed. In order to quantify the agreement between CFD and WT results, four validation metrics (\( FB \), \( NMSE \), \( R \), and \( FAC1.3 \)) were used.

The main limitations of this study were:

- The study was performed for one particular historical district which is representative, in terms of geometrical and morphological features, of many Mediterranean cities.
WT tests and CFD simulations were performed only for the three locally prevailing wind directions.

Geometrical simplifications were adopted for the buildings and bridges of the computational grid. Flat roofs were used instead of pitched ones, and rectangular bridge decks were modeled instead of complex shapes.

3D steady state RANS approach was adopted, which is known to be deficient in the prediction of flow separation zones.

The $k$-$\varepsilon$ turbulence models were found to outperform the $k$-$\omega$ ones for all wind directions considered. In particular, considerable overestimations of mean wind velocity with respect to WT results were found when the standard $k$-$\omega$ turbulence model (SKO) was adopted, especially in the higher part of the profiles. This discrepancy was possibly due to the deficiency of the standard $k$-$\omega$ turbulence model (SKO) in predicting the shear stresses of adverse pressure gradient boundary layers and the free stream flows (Versteg and Malalasekera, 2007).

The effect of surface roughness was more pronounced in the upstream and downstream parts of the district. This was probably due to the fact that, inside the district, channeling and separation effects were more important for the wind flow pattern than wall shear stress due to surface roughness. At the monitored positions (A and L) and for all wind directions considered, significant differences in terms of mean velocity profiles were found between CFD case 1 and 2 near the ground. Conversely, small differences at roof height (approximately at $z/z_{ref} \approx 0.10$) where flow separation likely occurred. Since velocity values in these separation zones were low, and consequently the wall shear stresses were low as well, the surface roughness height had a limited effect on the results.

While the results obtained with different turbulence models usually affected the mean velocity profiles over the entire height (e.g. the standard $k$-$\omega$ turbulence model), the surface roughness height values affected only the lowest part of the profiles. From the engineering point of view this means that the choice of a simplified geometry and a specific turbulence model may be crucial for a large category of urban physics and wind engineering problems (e.g. wind loads and cross ventilation on high rise buildings). In contrast, the choice of different roughness height values and inflow conditions could be more relevant for urban physics and wind engineering problems aimed at investigating the wind flow pattern near the ground (e.g. pedestrian wind comfort).
The main conclusions on the impact of turbulence models were:

- Wind velocity contours showed a sensitivity to the selected turbulence model. Differences between $k-\varepsilon$ and $k-\omega$ turbulence models were found mostly in the external part of the district.
- The results of the CFD cases using the $k-\varepsilon$ turbulence models showed a better agreement with WT data than the CFD cases adopting a $k-\omega$ type turbulence model.

The main conclusions on the impact of roughness height were:

- Wind velocity contours near the bottom of the computational domain showed a high sensitivity to differences in surface roughness height. CFD case 2, employing the material surface roughness heights, showed very large amplification factors in the external part of the district compared to CFD case 1.
- In contrast with the above, mean velocity profiles inside the urban area were not heavily affected by the roughness height used, at least in part due to the locations of the analyzed measuring positions (A2$_2$ - A5$_2$) in the middle of Canale Rosciano. Wind flow funneling along Canale Rosciano partially happened only for the wind direction $\alpha = 300^\circ$, giving rise to the largest differences between any two CFD cases.

Overall, the investigation showed that the impact of the turbulence model was larger than the impact of roughness height. Wind flow modeling in urban areas is affected by many errors and uncertainties related to the inflow conditions, boundary conditions, turbulence models, numerical approaches, etc. Further investigation targeted at understanding the impact of the numerical approach by using Large Eddy Simulation (LES) would be a valuable extension of the present work.

6.7 References


Chapter 7
Conclusions

7.1 Summary of the results

Wind flow is a driving force for many phenomena related to the urban environment, such as air quality and pollutant dispersion, pedestrian wind comfort, indoor and outdoor ventilation, wind energy in buildings, etc. (Moonen et al., 2012; Blocken 2015). Despite its importance for human life in cities, however, urban flows are still far from being completely understood. This is due to the fact that they depend on many aspects of the urban environment that are difficult to properly determine and extremely variable from case to case, such as the geometric complexity of buildings and local thermal effects, thus inducing large uncertainties in the wind flow description (Chang and Meroney, 2003; Britter and Hanna, 2003; Baker, 2007; Fernando, 2010; Fernando et al., 2010). Two different approaches exist to investigate urban flows, which are nowadays extensively adopted for urban physics and wind engineering applications: numerical simulation based on Computational Fluid Dynamics (CFD) and experimental methods based on either field measurements or reduced scale atmospheric boundary layer wind tunnel (ABLWT) testing. However, the results of both techniques are dependent on a wide range of parameters, and validation with full scale measurements is required. This thesis presented experimental (wind tunnel tests) and numerical (CFD simulations) studies aimed at investigating the wind flow pattern in a historical district of Livorno city (Italy), so called “Quartiere La Venezia”.

The results of this thesis were presented in two parts and four chapters. Since the discussion of the results and the methodological limitations were already presented for each of these chapters, only the main findings of this thesis are presented in this section.

7.1.1 Part I: Wind tunnel tests

In Chapter 3, the selected urban area used for wind tunnel tests and CFD simulations was introduced. Two sets of wind tunnel tests were carried out on a reduced scale urban model (1:300) for three wind directions (α = 240°, 270°, 300°)
at the closed circuit ABLWT of the Department of Civil, Chemical and Environmental Engineering (DICCA) at the University of Genoa. The objective of the first part of this thesis was to investigate the urban canopy layer (UCL) inside the main curved street canyon of Quartiere La Venezia, and the urban boundary layer (UBL) development over the entire urban district.

The first set of tests, focused on the mean wind profiles at different positions (A1 - A5) along the main canal called “Canale Rosciano”, showed a strong reduction of the wind velocity profiles in the UCL, in particular for levels lower than 1.5 \( h_b \), where \( h_b \) represents the mean building height equal to 15.1 m at full scale equivalent. The second set of tests was carried out on a regular grid of points (L1 - L5 - L3), in order to investigate the wind flow pattern in the UBL. In particular, the development of the urban boundary layer with fetch was analyzed. It turned out that the parameters which characterize the wind velocity profile (the friction velocity, \( u^* \), the roughness length, \( z_0 \), and the zero plane displacement, \( d \)) followed quite a regular evolution as a function of distance in the domain (portion of the test section considered), after the discontinuity due to the transition between the incoming wind velocity profile (measured upstream of the wind tunnel model) and the first building of wind tunnel model. Indeed, a linear decreasing and increasing trends were observed for \( u^* \) and \( z_0 \), and \( d \) respectively.

The results were critically compared, in terms of \( u^* \) and \( z_0 \), with similar tests performed on an urban like roughness (Cheng and Castro, 2002) and a detailed urban model (Kastner-Klein, 2004) available in the literature. Specifically, a satisfactory agreement with Cheng and Castro (2002) was found as far as the variability of \( u^* \) was concerned. That provided confirmation of their conclusion that in the transition between surfaces with lower to higher \( z_0 \), the skin friction coefficient \( (C_f) \) does not remain unchanged. In contrast, the evolution of the \( z_0 \) over the district was different from the one reported by Cheng and Castro (2002), so that this parameter was probably more case specific than the \( u^* \). It is worth to notice that both results were consistent with the morphometric models for \( z_0 \): in Cheng and Castro (2002) the frontal area density did not change in the canopy and the \( z_0 \), immediately after the transition, was approximately constant. In the present case the frontal area density increased with fetch and the \( z_0 \) decreased accordingly. Similar considerations applied to the \( d \), which increased in accordance with the increase of plane area density of both wind tunnel models.
7.1.2 Part II: CFD simulations

In this part of the thesis, CFD simulations performed on the reduced scale urban area as the wind tunnel tests (1:300) were presented and discussed. A portion of the test section of the wind tunnel was reproduced by the computational domain and 3D steady state RANS simulations were performed for all wind directions measured in the wind tunnel tests. The objective of the second part of the thesis was to investigate the accuracy of the 3D steady state RANS approach in predicting the wind flow pattern for the selected case study. In particular, the impact of four computational parameters was investigated: geometrical simplifications, inflow conditions, turbulence models and roughness height. Hence, mean velocity profiles, turbulent kinetic energy profiles, and yaw and pitch angles were compared with wind tunnel measurements. Finally the statistical performance of every CFD case considered was evaluated using four validation metrics: fractional bias (FB), normalized mean square error (NMSE), correlation coefficient (R), and the fraction of data within a factor 1.3 and 2.0 (FAC1.3 and FAC 2.0). The statistical performance was calculated in horizontal planes for all wind directions considered, 25 measuring positions and two different reference heights $z = 0.02$ m and $z = 0.10$ m above the bottom (full scale equivalent $z = 6$ m and $z = 30$ m above sea level, corresponding to 3.5 m and 27.5 m above the ground surface, respectively).

Impact of geometrical simplifications

In Chapter 4 the deviations (in terms of mean velocity values) caused by two levels of geometrical simplifications of the urban area with respect to the wind tunnel data were analyzed. For this scope, two geometries with different degrees of precision were constructed: the simplified (coarser) and the approximated (finer) model. The former was obtained by representing groups of buildings as single bluff bodies with a height equal to the arithmetic average height of that building group. The latter was obtained by including buildings with their real ground plan and heights, but replacing pitched roofs with flat ones.

The study showed that the geometric details of the urban model can affect the numerical results (in terms of velocity values), especially in the lower part of the mean velocity profiles where they were directly influenced by the shapes of obstacles explicitly modeled (i.e. buildings and bridges). In spite of the known limitations in predicting wind flow pattern where non stationary phenomena likely occur, the 3D steady state RANS approach showed a satisfactory agreement with
the wind tunnel results when the finer geometry (approximated model) was employed. Velocity contours showed the largest differences between the approximated and simplified models mostly in the narrow streets and canal of the district for all wind directions considered. A better performance of the approximated model compared to the simplified model was observed for the wind direction $\alpha = 240^\circ$. For this wind direction gaps of 13% and 22% were respectively found in terms of $R$ and $FAC1.3$ at 6 m above sea level. For the wind directions $\alpha = 270^\circ$ and $\alpha = 300^\circ$, corresponding to a decrease of alignment between the incoming wind flow and the entrance of Canale Rosciano, gaps of 1% and 0% for the former wind direction and 18% and 0% for the latter were respectively found in $R$ and $FAC1.3$ at 0.02 m above the bottom. Furthermore, it is worth to note that although the geometric details can affect the wind flow pattern inside the urban area, the two CFD geometries outcome a comparable estimation of roughness sublayer (RS) thickness.

**Impact of inflow conditions**

In Chapter 5 the deviations with respect to the wind tunnel data (in terms of mean velocity values, yaw and pitch angle values) caused by two different inflow conditions were analyzed. The approximated model, which gave the best performance in the previous stage, was employed for the current stage as well.

The first set of inflow conditions, so called real profiles, was based on the mean velocity profiles and the velocity standard deviations detected during the wind tunnel tests (approximately 1 m upstream of the wind tunnel model). The turbulent kinetic energy and the turbulence dissipation rate profiles were calculated from the wind tunnel measurements (above mentioned) using the equations proposed by Tominaga et al. (2008). The second set of inflow conditions, so called the fitted profiles, consisted of the wind velocity profile calculated by fitting the measured mean velocity profile (above mentioned) to a logarithmic law. The turbulent kinetic energy and the turbulence dissipation rate profiles were calculated using the equations proposed by Richards and Hoxey (1993).

This study showed that the choice of the inflow conditions (mean velocity, turbulent kinetic energy and turbulence dissipation rate profiles) did not strongly affect the numerical results in terms of mean velocity values. A better agreement, in terms of mean velocity profiles, between the real profile case and the wind tunnel case with respect to the fitted profile case was found for the wind direction $\alpha = 240^\circ$. 
at 0.02 m above the bottom. For this wind direction differences in R and $FAC1.3$ of 6% were found. For the wind directions $\alpha = 270^\circ$ and $\alpha = 300^\circ$ and the same reference height ($z = 0.02$ m), negligible differences between real profile and fitted profile cases were found in terms of mean velocity values. For the same wind directions, the agreement of numerical and wind tunnel results was found to be unsatisfactory.

Turbulent kinetic energy profiles showed an unsatisfactory agreement between numerical and wind tunnel cases for all analyzed wind directions, approximately for the entire height of the domain. The real profile case showed a better agreement with wind tunnel results than the fitted profile case, especially in the higher part of the domain. This was possibly caused by the fact that the turbulent kinetic energy profile of the real profile case was calculated using the measured velocity standard deviations. Validation metrics were not calculated for turbulent kinetic energy.

Small differences in terms of yaw angle, also confirmed by validation metrics ($R$ and $FAC2.0$), were found between real profile and fitted profile cases with respect to the wind tunnel case for the wind direction $\alpha = 240^\circ$. Differences of 1% and 6% were found in terms of $R$ and $FAC2.0$ between the real profile and fitted profile cases. In contrast, unsatisfactory agreement of both CFD cases was confirmed by both metrics for $\alpha = 270^\circ$ and $\alpha = 300^\circ$ in terms of $R$ and $FAC2.0$.

The pitch angle was scarcely predictable by the 3D steady state RANS approach. The real profile case showed a better agreement compared to the fitted profile one in terms of $FAC2.0$ with respect to the wind tunnel data. Indeed, differences between real profile and fitted profile cases of 22%, 5% and 11% were respectively found for the wind directions $240^\circ$, $270^\circ$ and $300^\circ$.

**Impact of turbulence models**

In the first part of Chapter 6 the deviations with respect to the wind tunnel data (in terms of mean velocity values) caused by the turbulence models were investigated. Five turbulence models were tested: standard $k-\epsilon$, realizable $k-\epsilon$, RNG $k-\epsilon$, standard $k-\omega$ and SST $k-\omega$.

Velocity contours showed a sensitivity to the selected turbulence models; the largest differences between $k-\epsilon$ and $k-\omega$ turbulence models were found outside the investigated urban district. The $k-\epsilon$ turbulence models were found to outperform the $k-\omega$ turbulence models for all wind directions considered. In particular,
considerable overestimations of mean velocity values with respect to wind tunnel results were found when the standard $k-\omega$ turbulence model was adopted, mostly in the higher part of the mean velocity profiles. This discrepancy was possibly due to the deficiency of the standard $k-\omega$ turbulence model in predicting the shear stresses of adverse pressure gradient boundary layers and the free stream flows (Cebeci, 2004; Versteeg and Malalasekera, 2007). For the wind direction $\alpha = 240^\circ$, at 0.02 m above the bottom, the R indicated the best performance of the standard $k-\varepsilon$ turbulence model (0.81), comparable with that of the realizable $k-\varepsilon$ model (0.79). Worse agreement with wind tunnel data was found for the RNG $k-\varepsilon$ (0.73), standard $k-\omega$ (0.74) and SST $k-\omega$ (0.72) turbulence models. In contrast, unsatisfactory agreement for all CFD cases was found in all metrics for the directions $\alpha = 270^\circ$ and $\alpha = 300^\circ$. In this study, the validation metrics calculated at 0.02 m above the bottom did not fully describe the performance differences between turbulence models. The same validation metrics was therefore also carried out for another reference height of $\zeta = 0.1$ m ($\zeta = 30$ m full scale equivalent). This height represented approximately the height of the RS (Barlow, 2014). For all wind directions and the reference height $\zeta = 0.1$ m, the CFD cases here analyzed (for each turbulence model), showed a satisfactory agreement with wind tunnel data for all the validation metrics considered, except for the standard $k-\omega$ model where all metrics indicated considerably worse performance than all other models considered here.

**Impact of roughness height**

In the second part of Chapter 6 the deviations with respect to the wind tunnel data (in terms of mean velocity values) caused by two different sets of roughness height were investigated. For the first set, so called CFD case 1, a homogeneous value of roughness height $k_s = 0.0013$ m was adopted at the bottom of the computational domain; a value of $k_s$ equal to zero was used for the obstacles explicitly modeled (e.g. buildings and bridges). In the second set, so called CFD case 2, the real roughness height values of the materials used in wind tunnel testing ($k_{s,\text{mat}}$) were adopted for the different walls of the computational domain (i.e. bottom, ground floor, buildings and bridge surfaces).

Velocity contours near the bottom of the computational domain showed a high sensitivity to differences in surface roughness height mostly upstream and downstream of the urban district for all wind directions considered. Indeed, CFD case 2, employing the material surface roughness heights, showed larger
amplification factors in the external part of the urban district compared to CFD case 1. At the monitored positions (A and L) and for all wind directions considered, significant differences in terms of mean velocity profiles were found between CFD case 1 and 2 near the ground. Conversely, small differences at roof height (approximately at \( z/z_{ref} \approx 0.10 \)) where flow separation likely occurred. Since mean velocity values in these separation areas were low, and consequently the surface shear stresses were low as well, the surface roughness height had a limited effect on the results. In particular, mean velocity profiles inside the urban district were not heavily affected by the roughness height used, at least in part due to the locations of the analyzed measurement positions (A_2 - A_5) in the urban district. The \( R \) showed a better performance of CFD case 2 than CFD case 1: discrepancies of 2%, 6% and 1% between both CFD cases were respectively found for the wind directions \( \alpha = 240^\circ, \alpha = 270^\circ \) and \( \alpha = 300^\circ \).

### 7.2 Conclusions

Wind flow modeling in urban areas is a challenging task due to the wide range of physical and computational parameters involved. The wind tunnel tests performed on Quartiere La Venezia confirmed earlier findings (Fernando, 2010; Barlow, 2013 and 2014) that the UCL and RS are dominated by a variety of complex factors (i.e. geometries and local thermal effects), and the logarithmic law no longer holds in these layers. 3D RANS simulations were able to reproduce wind flow pattern on the same reduced scale urban model for only one (\( \alpha = 240^\circ \)) of the wind directions considered. In contrast, for the wind directions which outcome extensive leeward zones (\( \alpha = 270^\circ \) and \( \alpha = 300^\circ \)), where flow separation and flow reversal phenomena possibly occurred, 3D steady state RANS approach showed noticeable limitations to properly predict the wind flow pattern. Nevertheless, comparison with the wind tunnel results showed that CFD simulations can provide a satisfactory estimation of the UCL and RS thicknesses for all wind directions considered. Furthermore, the sensitivity analyses of four computational parameters, i.e. geometrical simplifications, inflow conditions, turbulence models and roughness height, clearly emphasized the impact of these parameters on the results (e.g. in terms of mean wind velocity).

The analyses showed that although the geometrical simplifications may be crucial (i) to reduce the computational cost, (ii) to avoid the deterioration of results (due to Reynolds number effects) and (iii) to avoid convergence problems and
maximize numerical accuracy, they can strongly modify the aerodynamic features of the urban area, leading to a significant effect on the wind flow pattern, especially inside the UCL and RS. The study confirmed the importance of the criteria adopted to construct and simplify the CFD geometries: the floor plan, the height and architectural details of buildings, the shapes of bridge decks, the streets and the street furniture, the sidewalks and the trees. Most of these elements are accurately reproduced by wind tunnel model commonly used as a benchmark for CFD simulations, and they should be accurately included in the CFD geometries as well to improve the agreement between wind tunnel and numerical results. However, this study showed that the geometrical simplifications, although one of the most important aspects, is not the only source of uncertainty.

The study showed that mean velocity values in the urban district were affected by different inflow conditions used, albeit to a lesser extent than by the geometrical simplifications. Turbulent kinetic energy values measured in the urban district were much more affected by inflow conditions than the mean velocity profiles. Overall, both mean velocity and turbulent kinetic energy profiles were found to be dependent on the inflow conditions imposed at the inlet of the computational domain. Furthermore, the incoming profiles (in terms of mean velocity and turbulence intensity) detected upstream of the wind tunnel model were non uniform in the spanwise direction, and the numerical results were found to be sensitive to this non uniformity as well.

Significant discrepancies, described in the previous section, between $k-\varepsilon$ and $k-\omega$ turbulence models were observed inside the UCL for the wind directions which outcome the most extensive leeward zones where flow separation and flow reversal likely occurred. The study showed that the $k-\varepsilon$ turbulence models (standard and realizable) were more suitable to reproduce wind flow pattern in an urban environment than the $k-\omega$ turbulence models.

The roughness height was probably more case specific than the other computational parameters analyzed, due to the specific morphology of the district and its orientation with respect to the incoming wind direction. Moreover, the effect of different surface roughness heights was more pronounced in the external part of the urban district (such as upstream and downstream of the urban district). This was probably due to the fact that channeling and separation effects inside the urban district (which are dependent on the aerodynamic features of the obstacles explicitly modeled) were more important, for the wind flow pattern, than wall shear stress (due to surface roughness).
Overall, the analyses carried out in this thesis showed that, while the inflow conditions and the roughness height affect only the lower part of the velocity profiles near the ground surface, i.e. in the UCL, the choice of geometries with different levels of detail and the turbulence models may also affect the higher parts of the profiles, i.e. the RS or even the entire UBL. From the engineering point of view this means that the choice of a simplified geometry and a specific turbulence model may be crucial for a large category of urban physics and wind engineering problems (e.g. wind loads and cross ventilation on high rise buildings). In contrast, the choice of different roughness height values and inflow conditions could be more relevant for urban physics and wind engineering problems aimed at investigating the wind flow pattern near the ground (e.g. pedestrian wind comfort).

7.3 Future work

The present thesis is part of a wider research project aimed at predicting wind flows in historical districts typical of many Mediterranean cities. In this wider project full scale measurements were performed by means of a monitoring network consisting of 29 anemometric stations installed in six ports on the Mediterranean Sea (Livorno, La Spezia, Genova, Savona, Vado, and Bastia) (Solari et al., 2012). Simulations were also performed using a nesting technique, which realizes an information exchange from coarser (WINDS) to finer (CFD) grids (Solari et al., 2012; Burlando et al., 2015). This thesis presented wind tunnel tests carried out on a reduced scale model of “Quartiere La Venezia” for three wind directions corresponding to the prevalent ones for the strongest winds. The mean wind velocity scenarios obtained during the European project “Wind and Ports” (Solari et al. 2012) by means of the WINDS model (Wind Interpolation by Non Divergent Schemes), anemometric data, and the digital land cover maps of the CORINE project were used as reference for the choice of the incoming flow profiles in the wind tunnel tests. Based on this an ABL profile with a specific aerodynamic roughness length and friction velocity was reproduced in the wind tunnel tests. However, irrespective of the accuracy of the wind measurements, extrapolation based on single point data can cause large uncertainties in the mean velocity profile, especially over complex terrain and geometries (e.g. buildings, bridges, trees). This uncertainty can be reduced, in principle, using instruments able to directly measure the vertical wind velocity profile such as Sonic Detection and Ranging (SoDAR) or Light Detection and Ranging (LiDAR) wind profilers. For this purpose, 3 LiDAR stations were recently installed in the ports of Livorno, Savona and Genoa in the framework of the
European Project “Wind, Ports and Sea” (Burlando et al., 2015). The LiDAR placed in the port of Livorno is near the area of interest, Quartiere La Venezia. Furthermore, the monitoring network is expected to grow in the future. It will include instruments able to measure the wind flow (in terms of mean velocity and velocity standard deviations) within the UCL, in particular along Canale Rosciano, which could be directly related to the actual wind flow blowing from the sea. Therefore, CFD simulations on the full scale urban area could be performed using different approaches (e.g. RANS, URANS, DES, LES) to investigate the dependence of the urban flows on the geometrical scale of the analysis. In the long term, therefore, this district is supposed to become an important cross validated benchmark that will provide the scientific community with direct full scale measurements, wind tunnel tests and CFD simulations of a real urban area.

Although the CFD calculations performed in this thesis clarified to which extent four different computational parameters may affect the numerical results, further investigations concerning the computational uncertainties and errors are needed. Indeed, the study showed that the 3D steady state RANS approach cannot be considered a suitable and reliable technique to completely describe the wind flow pattern in a urban area. Overestimation and underestimation of mean velocity or pressure values may be crucial for a wide range of urban physics and wind engineering problems (e.g. wind loads, cross ventilation, heat transfer, pedestrian wind comfort and safety, pollutant dispersion and air quality). For this purpose, a future intention should be to perform CFD simulations on the same reduced scale urban area using different unsteady approaches such as Unsteady Reynolds-averaged Navier-Stokes (URANS), Large Eddy Simulations (LES) and Detached Eddy Simulation (DES) to understand how sensitive the solution (e.g. in terms of mean velocity, turbulence intensity values, and pressure values) is to the numerical approach which is adopted.

In general the computational settings (e.g. boundary conditions, turbulence models, discretization schemes) play a key role in the CFD simulation process, and the correct choice of all of them becomes crucial when the computational domain is huge and computationally demanding. Hence, in order to provide a more complete description of the deviations caused by the majority of the computational parameters commonly involved on urban wind flows simulations, further sensitivity analyses (e.g. about the discretization schemes and algorithm solvers) are imperative to ensure a satisfactory agreement with wind tunnel results.
7.4 References


Curriculum vitae

Alessio Ricci was born in 1982 in Atri, Italy. He graduated in Architecture from the University of Chieti (Italy) in 2010 with a graduation project on the “CFD simulations of tall buildings”. In the period 2006-2007 (with Program Socrates Erasmus) and in the period 2007-2008 (with Program Visiting Students) he studied at the Faculty of Architecture at Polytechnic University of Valencia (Spain). In 2012, he started his PhD in Structural and Geotechnical Engineering at University of Genoa (Italy), with a scholarship funded by the Italian Ministry of Education, University and Research (MIUR). In 2013 he was a visiting PhD student at the Department of the Built Environment at the Eindhoven University of Technology (the Netherlands). In 2015 he started his double PhD between University of Genoa and the Eindhoven University of Technology. During his PhD Alessio was involved in educational activities as teaching assistant of “Structural Engineering” at the Department of Civil, Chemical and Environmental Engineering and of “Structural Mechanics” at the Department of Naval Architecture and Electrical Engineering of the University of Genova. In 2013, he worked on a research project about “Wind tunnel and CFD models of a vertical axis wind turbine (VAWT) with power augmentation guide vanes (PAGV)”. In 2015, he was involved in another research project about “CFD simulations on an oven booth for boats”. Alessio has published two papers in international (ISI) journals. From 2014 to 2016 he attended six international conferences in the wind engineering field and he is member of the Italian Association for Wind Engineering (ANIV). Alessio is reviewer for the ISI journals “Journal of Wind Engineering and Industrial Aerodynamics” and “Sustainable Cities and Society”. 
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