Effects of atmospheric stratification on flow and dispersion in the urban environment

PhD Thesis

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June 2019
“An experiment is a question which science poses to Nature, and a measurement is the recording of Nature’s answer.”

Max Planck (1858-1947)
Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other University. This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration, except where specifically indicated in the text.

Davide Marucci
June 2019
Acknowledgements

First of all, I would like to thank my supervisor Dr. Matteo Carpentieri, who gave me the opportunity to undertake my doctorate and guided me throughout this last three and a half years. Many thanks also to my co-supervisor Dr. Philip E. Hancock and to Prof. Alan Robins for answering all my many questions.

A big thanks goes to Dr. Paul Hayden for the assistance and motivation he gave me during the experimental campaigns, as well as giving me the opportunity to contribute to the laboratory work with my MATLAB code. I am also grateful for the help received from the other EnFlo laboratory and group staff, in the persons of Dr. Paul Nathan, Mr. Allan Wells, Dr. William Lin, Miss Zoë Ansell, Ms. Shradha Parkhouse and Ms. Zilla Gardiner.

Many thanks to the many people in my office, with whom I shared my working hours and enjoyed most of my free time, some of them became my housemates and one my best friend.

I also want to express my gratitude to the Department of Mechanical Engineering Science and the EPSRC agency for funding my research.

But above all, this PhD gave me the opportunity to meet Michela, to whom I am most grateful.
Abstract

Atmospheric stratification involves differences in the air density caused by a positive (stable) or negative (unstable) vertical gradient of virtual potential temperature. The stability of the layer depends on the stratification and affects the atmospheric boundary layer depth and structure as well as velocity, temperature and turbulence properties.

In the first phase of the work, artificially thickened stable and unstable boundary layers were simulated in the EnFlo wind tunnel over a very rough surface, by means of spires, roughness elements and heaters. The effect of different parameters was investigated (among them, inlet temperature profile, capping inversion and surface roughness). These boundary layers were then employed as approaching flow for two idealised urban model geometries.

A regular array of rectangular blocks was considered as geometry while a pollutant tracer was released from a point source at ground level. Mean and fluctuating velocities, temperatures and concentrations were sampled, together with heat and pollutant fluxes. The analysis of the data revealed that even in case of weak stratification there are important modifications inside and above the canopy on both the urban boundary layer and the plume characteristics.

Finally, the combined effects of a stable approaching flow and local surface heating were investigated in a bi-dimensional street canyon geometry. This was an entirely novel experimental design and the results highlighted how both local and incoming stratification can significantly affect the flow and dispersion at a microscale level in a complex way that depends on the particular case of study.

This work sheds more light on the effects of stratification and encourages further work on the topic. The experimental database produced during the project is unique and of high quality. It can assist in developing, improving and validating numerical models, as well as developing parametrisations for simpler models.
List of publications during the thesis research


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## Nomenclature

### Roman Symbols

- $A$: Free fitting parameter in Gaussian distribution representing the maximum value
- $A_d$: Mean lot area
- $A_f$: Mean frontal area
- $A_p$: Mean plan area
- $c$: Pollutant concentration
- $c_p$: Specific heat capacity at constant pressure
- $C_*$: Normalised pollutant concentration
- $d$: Displacement height
- $d_h$: Displacement height in the mean temperature vertical profile
- $E$: Mass of water vapour per unit volume per unit time being created by a phase change from liquid or solid.
- $e$: \( \frac{1}{2} (u'^2 + v'^2 + w'^2) \)
- $Ec$: Eckert number
- $f$: Dimensional frequency
- $f_c$: Coriolis parameter
- $F_i$: Power spectral density of the i-quantity as function of the wave number
- $Fr$: Froude number
- $G$: Geostrophic value of velocity
Nomenclature

$H$  Building/street canyon height

$H_R$  Roughness element height

$k$  Von Karman constant

$k_1$  Turbulence wave number

$K_i$  Pollutant concentration eddy diffusivity in the i-direction

$L$  Monin-Obukhov length

$L_H$  Turbulence length scale around building

$L_p$  Latent heat associated with the phase change of $E$

$L_R$  Generic length scale

$L_{SC}$  Street canyon length

$N$  Number of independent samples

$n$  Non-dimensional frequency

$N_{BV}$  Brunt-Väisälä frequency

$n_δ$  Non-dimensional frequency for the ML

$P$  Air pressure

$Pe$  Peclet number

$Pr$  Prandtl number

$Q$  Pollutant source strength, mass per unit time

$q$  Water vapour specific humidity

$q_{1,2}$  Two generic measuring quantities

$q_L$  Liquid water specific humidity

$Q^*_j$  Component of net radiation in the $j^{th}$ direction.

$q_T$  Total specific humidity of air

$R$  Gas constant
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r )</td>
<td>Mixing ratio of water vapor</td>
</tr>
<tr>
<td>( Re )</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>( Re_\delta )</td>
<td>Reynolds number referred to the boundary layer top</td>
</tr>
<tr>
<td>( Re_L )</td>
<td>Reynolds number based on the Monin-Obukhov length and friction velocity</td>
</tr>
<tr>
<td>( Re_s )</td>
<td>Roughness Reynolds number</td>
</tr>
<tr>
<td>( Ri )</td>
<td>Gradient Richardson number</td>
</tr>
<tr>
<td>( Ri_b )</td>
<td>Bulk Richardson number</td>
</tr>
<tr>
<td>( Ri_\delta )</td>
<td>Bulk Richardson number referred to the boundary layer top</td>
</tr>
<tr>
<td>( Ri_{\text{app}}^\delta )</td>
<td>Bulk Richardson number of the approaching flow referred to the boundary layer top</td>
</tr>
<tr>
<td>( Ri_f )</td>
<td>Flux Richardson number</td>
</tr>
<tr>
<td>( Ri_H )</td>
<td>Bulk Richardson number referred to the building height</td>
</tr>
<tr>
<td>( Ri_{\text{Local}} )</td>
<td>Local Richardson number, introduced to quantify the local stratification due to surface heating</td>
</tr>
<tr>
<td>( r_L )</td>
<td>Mixing ratio of liquid water in the air</td>
</tr>
<tr>
<td>( Ro )</td>
<td>Rossby number</td>
</tr>
<tr>
<td>( S_i )</td>
<td>Power spectral density of the i-quantity as function of the frequency</td>
</tr>
<tr>
<td>( S_{qt} )</td>
<td>Net moisture source term</td>
</tr>
<tr>
<td>( StErr )</td>
<td>Standard error</td>
</tr>
<tr>
<td>( T )</td>
<td>Absolute temperature</td>
</tr>
<tr>
<td>( t )</td>
<td>Time</td>
</tr>
<tr>
<td>( T_0 )</td>
<td>Generic timescale</td>
</tr>
<tr>
<td>( T_{\text{total}} )</td>
<td>Total time trace length</td>
</tr>
<tr>
<td>( U_{2H} )</td>
<td>Mean streamwise velocity at ( x/H = 0 ) and ( z/H = 2 ) above the canyon</td>
</tr>
<tr>
<td>( U_R )</td>
<td>Generic velocity scale</td>
</tr>
</tbody>
</table>
Nomenclature

\( U_{REF} \) Reference velocity measured by the sonic anemometer

\( u_* \) Friction velocity

\( u, v, w \) Streamwise, lateral and vertical velocity (e.g. \( u = U + u' \))

\( U_{z_R} \) Wind velocity at the reference height \( z_R \)

\( W \) Street canyon width

\( w_* \) Scaling velocity in the ML for CBLs

\( W_* \) Vertical velocity normalised with a reference velocity

\( x, y_{plume} \) Pollutant plume horizontal axes

\( z_0 \) Aerodynamic roughness length

\( z_{0h} \) Thermal roughness length

\( z' \) Difference between height and displacement length \((z - d)\)

\( z_R \) Reference height

**Greek Symbols**

\( \alpha \) Mean wind power-law exponent

\( \delta \) Boundary layer depth

\( \delta_{ij} \) Kronecker delta

\( \Delta \Theta \) Difference between temperature at the top of the boundary layer and floor temperature

\( \Delta \Theta_{HOT} \) Difference between \( \Theta_{HOT} \) and \( \Theta_{2H} \)

\( \Delta \Theta_{MAX} \) Maximum temperature difference between floor and free-stream flow set at the inlet

\( \Delta \Theta_R \) Generic difference of temperature scale

\( \Delta \Theta_s \) Stable boundary layer strength

\( \varepsilon \) Turbulence dissipation rate

\( \varepsilon_{ijk} \) Alternating unit tensor

\( \Gamma \) Dry adiabatic lapse rate
Nomenclature

\( \lambda \)  
Wavelength

\( \lambda_f \)  
Frontal area density

\( \Lambda_i \)  
Integral length scale of the i-quantity

\( \lambda_m \)  
Wavelength associated with the energy peak in the frequency-weighed spectrum

\( \lambda_p \)  
Plan area density

\( \mu \)  
Free fitting parameter in Gaussian distribution representing the offset

\( \nu \)  
Kinematic viscosity

\( \nu_c \)  
Pollutant molecular diffusivity

\( \nu_q \)  
Molecular diffusivity of water vapour in the air

\( \nu_\theta \)  
Thermal diffusivity

\( \Omega_R \)  
Generic angular velocity scale

\( \phi \)  
Earth latitude

\( \phi_\varepsilon \)  
Non-dimensional form of the dissipation rate of turbulence kinetic energy

\( \phi_{m,h} \)  
Functional forms for velocity and temperature in the SL

\( \psi_{m,h}(\zeta) = \int_{z_0}^{(z-d)/L} \left[ 1 - \phi_{m,h}(\zeta) \right] \frac{d\zeta}{\zeta} \)

\( \sigma_i \)  
Standard deviation in the i-direction (x, y, z or h, the latter stating for horizontal) of a Gaussian distribution

\( \sigma_{u,v,w,\theta,c} \)  
Standard deviation of the velocity (x, y or z component), temperature or concentration

\( \theta \)  
Potential temperature

\( \Theta_0 \)  
Air temperature close to the surface

\( \Theta_{2H} \)  
Mean temperature at \( x/H = 0 \) and \( z/H = 2 \) above the street-canyon

\( \Theta_\delta \)  
Air temperature at the BL top

\( \Theta_{GROUND} \)  
Temperature of the ground measured inside the street-canyon

\( \Theta_{HOT} \)  
Temperature of the the heated canyon surface
Nomenclature

$\Theta_\infty$  Temperature of the free-stream flow set at the inlet

$\Theta_R$  Generic temperature scale

$\Theta_{REF}$  Generic reference mean virtual potential temperature

$\theta_*$  Friction temperature

$\tilde{\theta}_*$  Scaling temperature in the ML for CBLs

$\theta_v$  Virtual potential temperature

$(\overline{w'\theta'})_0$  Vertical kinematic heat flux at the surface

$\zeta$  $z/L$

Superscripts

− (overline)  Time average

'  Fluctuating quantity

Subscripts

0  Value at, or close to, the ground

i  Generic index, or Cartesian index

Acronyms / Abbreviations

ABL  Atmospheric Boundary Layer

ACH  Air Exchange rate

AH  Street canyon with neutral approaching flow and all internal surfaces heated

AR  Canyon aspect ratio

BL  Boundary Layer

CBL  Convective boundary Layer

CFD  Computation fluid dynamics

CFL  Constant Flux Layer

GH  Street canyon with neutral approaching flow and ground heating
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBL</td>
<td>Internal Boundary Layer</td>
</tr>
<tr>
<td>ISL</td>
<td>Inertial Sub-Layer</td>
</tr>
<tr>
<td>LDA</td>
<td>Laser Doppler Anemometry</td>
</tr>
<tr>
<td>LES</td>
<td>Large-Eddy Simulation</td>
</tr>
<tr>
<td>LH</td>
<td>Street canyon with neutral approaching flow and leeward wall heated</td>
</tr>
<tr>
<td>ML</td>
<td>Mixed layer</td>
</tr>
<tr>
<td>NBL</td>
<td>Neutral boundary Layer</td>
</tr>
<tr>
<td>NH</td>
<td>Street canyon isothermal case</td>
</tr>
<tr>
<td>PCH</td>
<td>Pollutant Exchange rate</td>
</tr>
<tr>
<td>PIV</td>
<td>Particle Image Velocimetry</td>
</tr>
<tr>
<td>RANS</td>
<td>Reynolds-averaged Navier-Stokes</td>
</tr>
<tr>
<td>RSL</td>
<td>Roughness Sub-Layer</td>
</tr>
<tr>
<td>SAH</td>
<td>Street canyon with stable approaching flow and all internal surfaces heated</td>
</tr>
<tr>
<td>SBL</td>
<td>Stable boundary Layer</td>
</tr>
<tr>
<td>SGH</td>
<td>Street canyon with stable approaching flow and ground heating</td>
</tr>
<tr>
<td>SLH</td>
<td>Street canyon with stable approaching flow and leeward wall heated</td>
</tr>
<tr>
<td>SL</td>
<td>Surface layer</td>
</tr>
<tr>
<td>SNH</td>
<td>Street canyon isothermal case</td>
</tr>
<tr>
<td>SWH</td>
<td>Street canyon with stable approaching flow and windward wall heated</td>
</tr>
<tr>
<td>TKE</td>
<td>Turbulent Kinetic Energy</td>
</tr>
<tr>
<td>UBL</td>
<td>Urban Boundary Layer</td>
</tr>
<tr>
<td>UCL</td>
<td>Urban Canopy Layer</td>
</tr>
<tr>
<td>WH</td>
<td>Street canyon with neutral approaching flow and windward wall heated</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Background of the study

Due to rapid urbanisation, air pollution in the urban environment is an increasing problem, especially in developing countries. It has been estimated that every year more than one billion people are exposed to outdoor air pollution and that urban air pollution is associated with up to one million premature deaths and one million pre-native deaths (Kura et al., 2013). Together with ordinary exposure to pollution, another threat to the human health is represented by incidents involving the release in the atmosphere of toxic gases or radioactive substances. For example, the Bhopal disaster is considered the world’s worst industrial accident: it happened in India in 1984 and affected 500 thousand people causing more than 3700 deaths. The Chernobyl disaster is also well known, it caused an estimate of 4000 deaths due to the dispersion of radioactive material. A further possible risk of extraordinary exposure to harmful substances is the intentional release of poisonous gas following a terrorist attack.

The capacity for prediction of gas and particle dispersion can assist in preventing health hazards and planning emergency procedures. Such capability relies on the modelling and understanding of the urban aerodynamics and pollutant transport process. Factors that contribute to the complexity of the problem are the urban morphology (very often highly three-dimensional and heterogeneous), the variability of pollutant sources (e.g. emissions from traffic vehicles, industrial plants, domestic heating) and meteorological conditions. With respect to the latter, atmospheric stratification may play an important role. It involves variations in temperature and humidity with height. A near-adiabatic profile of potential temperature is present in a neutrally stratified atmosphere, where vertical motions of fluid particles are neither amplified nor damped, while an unstable (or convective) stratification is characterised by an enhancement of vertical movements and stable flows are characterised by attenuated vertical motion. The
stability of the layer depends on the stratification and affects the atmospheric boundary layer depth and structure as well as velocity, temperature and turbulence profiles within it.

Non-neutral stratified conditions are frequently found in atmospheric flows. In urban areas, a large predominance of non-neutral atmosphere was documented, for example, by Wood et al. (2010) over the city of London, UK, with convective cases happening three times more frequently than stable. In addition to atmospheric stratification, buoyancy effects on the flow may also be caused by local sources of heating (e.g. differential heating of building walls or ground due to solar radiation or human activity). Louka et al. (2002), for instance, found temperature gradients up to 10°C in the vicinity of the sun-heated walls in Nantes. Other field studies measured surface temperature differences in urban canyons up to 9°C (Idczak et al., 2007, Bourbia and Awbi, 2004), 14°C (Nakamura and Oke, 1988, Santamouris et al., 1999), or even 18°C (Aliabadi et al., 2017). At the microscale range, hence, both atmospheric and local effects may be significant and are worth to be investigated. Three broad approaches exist to investigate urban stratification: field measurement campaigns, laboratory experiments and computational simulations.

Field investigations are typically carried out either in existing urban areas or by building dedicated structures, the latter allowing a better control over the site layout (an example is Dallman et al., 2014, who used shipping containers to simulate an urban canyon, or Nottrott et al., 2011, who employed an array of over 500 concrete cubes aligned in a field). In both cases fixed stations or mobile traverses can be used, also in combination with satellite imagery. All these studies are, though, affected by the problem of lack of control over climate conditions. This issue is particularly concerning in urban aerodynamics, where many variables play important roles (e.g. wind direction and intensity, atmospheric stability, raining and humidity, traffic related pollution, etc.). Long field measurements are needed and the data has to be filtered to meet strict acceptance criteria, with the result that often only a small part of the total acquired data can be used for the desired purpose. Another problem is related to the large scale of field sites, which would require, in turn, a large acquisition area.

Laboratory experimentations allow to overcome such limitations. In fact, the desired experimental conditions can be accurately controlled and maintained constant throughout all the measurement duration. At the same time the reduced scale limits the domain size significantly. These two points, though, come with other limitations. In fact, the accurate reproduction of a realistic urban boundary layer in the laboratory is not trivial, in particular when stratification is taken into account. Moreover, the reduced scale may pose/enhance problems of measuring probe disturbances (such as blockage) and measuring spatial resolution (the latter also highly dependant on the chosen measuring technique). Laboratory facilities that can be used for stratification studies include water tanks, water channels and wind tunnels.
Finally, computational simulations, also called computational fluid dynamics (CFD), involve the mathematical resolution and/or modelling of fluid flow governing equations. Depending on the modelling technique, CFD may allow a complete temporal and spatial simulation of the domain of interest, with at the same time free control over individual parameters and boundary conditions. A major disadvantage is represented by the questionable accuracy and validity of assumptions done on the resolved and/or modelled scales and parameters, the latter mostly resulting by the necessity to save computational time and power requirements (it should be stressed, though, that a detailed discussion over the limitations and advantages of the technique is not of interest here). To account for this uncertainty, CFD simulations need to be validated against field and/or laboratory studies.

1.2 Research problem and objectives

In urban environments at neighbourhood and street scales, stratification effects are clearly significant both on processes at the top of the boundary layer and in the outer suburbs and semi-rural areas surrounding dense cities (Hunt et al., 2004). Most of the studies in the literature focus only on neutral flows due to the difficulties on studying atmospheric stratification both experimentally and numerically.

In particular, laboratory scale simulations are rare (only a few can be listed, among them Uehara et al., 2000 and Kanda and Yamao, 2016), since worldwide only a few facilities are capable of simulating non-neutral flows and the development of the correct experimental methodology is very time-consuming. A predetermined method to experimentally simulate stratified boundary layers in wind tunnel does not exist yet. The usage of artificial thickening devices (spires), even though common practise for neutral boundary layers, is still to be fully investigated in non-neutrally stratified conditions (even though some dedicated studies already exist; see e.g. Hancock et al., 2013, Hancock and Hayden, 2018), where also thermal boundary conditions become important.

From the computational side, more efforts have been spent and the literature is more extensive, spanning from studies over idealised geometries (e.g. bi-dimensional street canyon or array of cuboids) up to considering real part of cities. Recently there have also been attempts to numerically investigate realistic wall heating patterns as effect of sun radiation over three-dimensional urban configurations (Nazarian et al., 2018), as opposed to uniformly heated surfaces (to which laboratory experiments are still confined).

Despite these steps forward, the proper validation of CFD numerical models in case of local or external thermal stratification remains challenging without high quality experimental datasets that could be used for comparison.
This research aims to fill the gap by investigating the effect of atmospheric stratification in urban environments both for the aerodynamics and pollutant dispersion. It has been divided into three phases:

1. simulation of urban-like stable and convective boundary layers in the EnFlo wind tunnel

2. study of the effects of stratification on aerodynamics and dispersion, employing an urban-like array of buildings and the boundary layers developed in the previous phase (here applied as approaching flow to the model)

3. study of the effects of local heating of walls and streets in combination with a stably stratified incoming boundary layer over a bi-dimensional street canyon.

The first part is essential to enhance the wind tunnel simulation technique and it is preparatory for the following phases. In both the second and third part an idealised and regular model geometry has been chosen. In fact, despite the fact that simulations over realistic part of cities have already been attempted so far in the laboratory (see e.g. Yassin et al., 2005) and computational simulations as well (e.g. Saitoh et al., 1996, Huang et al., 2008), a regular and idealised geometries will be more beneficial in this phase in which stratification effects have still to be well isolated and identified. Moreover, a simple idealised geometry is easier to be implemented in computational studies in case validation against the produced dataset is of interest. Finally, it should be highlighted the complete novelty of studying a case with coupled local and incoming flow stable stratification, for which neither laboratory nor computational works have been attempted so far (to the knowledge of the author).

The experimental database produced during the project is unique, of high quality and extremely useful in filling a large gap in the current knowledge, as previously highlighted. It will assist in developing, improving and validating numerical models, as well as developing parametrisations for simpler models.

1.3 Outline of the thesis

The thesis is structured into seven chapters. Ch. 2 is a review of the literature of atmospheric stratification, focussing on laboratory techniques of simulation and its effects over urban aerodynamics and dispersion. The methodology regarding simulation and measurement techniques is debated in Ch. 3. The following three chapters introduce and detail the results obtained for the three parts of the project: wind tunnel simulation of artificially thickened stable and convective boundary layers (Ch. 4), effects of stable and convective stratified approaching flow on an array of buildings (Ch. 5) and, finally, effects of a neutrally and stably stratified...
approaching flow in combination with local heating on a bi-dimensional street canyon (Ch. 6). The main findings and conclusions of this thesis are drawn in Ch. 7, together with a discussion of the limitations of this work and recommendations for future research.
Chapter 2

Literature review

2.1 Introduction

This chapter focuses on the analysis of the literature and introduces the main concepts, forming the background of what will be investigated in the following chapters. Sec. 2.2 deals with the atmospheric boundary layer, with particular focus on the thermal stratification and its effects, introducing also some important parametrisations which allow to describe it. In Sec. 2.3 the problem of physical modelling of the atmospheric boundary layer is discussed. Scaling criteria for laboratory experiments will be introduced; then, a series of wind tunnel studies involving the simulation of stratified atmospheric boundary layers will be presented, with particular attention to the experimental set-up for the boundary layer generation. Sec. 2.4 provides a general introduction on dispersion theory, with particular attention on the urban dispersion modelling. Sec. 2.5 presents the main works on the stratification effects on flow and dispersion in urban areas. The focus is on the idealised geometries and the section is divided into isolated obstacles, array of buildings and bi-dimensional street canyons. Both studies dealing with incoming flow stratification and local source of heating will be considered. Finally, Sec. 2.6 summarises the literature survey and highlights the research gaps.

2.2 Atmospheric boundary layer

The atmospheric boundary layer (ABL) constitutes the lowest part of the atmosphere and it is the most critical for us because we live and breathe there. Moreover, important aspects as microclimate, dispersion of pollutants and the hydrologic cycle are directly determined inside this layer, in which exchanges of momentum, heat and moisture between the Earth surface and
atmosphere occur. As described by Kaimal and Finnigan (1994), the ABL is normally divided into two regions:

- a *surface layer* (usually 10-20% of the total height), characterised by approximately constant vertical shear stress and predominant influence of surface friction and gradient of temperature on the wind structure;

- a remaining region in which the shear stress is not constant and the earth’s rotation plays a role in the determination of the wind structure.

The ABL is affected by many phenomena and aspects: ground morphology (presence of buildings, forests, seas or hills and mountains), wind intensity and direction, humidity, temperature, clouds, precipitation and so on. In the following the focus will be on the effect of stratification and how this affects and shapes the ABL.

### 2.2.1 Urban boundary layer

Roth (2000) defines the urban boundary layer (UBL) as the part of ABL influenced by the presence of the urban area. A series of vertically stacked layers can be identified, depending on their dynamical characteristics.

The urban canopy layer (UCL) develops from ground level up to about roof level. The flow is characterised by high inhomogeneity and sensitivity to local urban morphology, so that the immediate surroundings directly influence dynamic and thermal processes.

The roughness sub-layer (RSL) includes the UCL and can reach a depth of about two to five times the buildings height. The building wakes still have an influence in this region, even though the turbulence and mixing phenomena contribute to gradually hide the effect of a single building. Nevertheless, the flow is three-dimensional and vertical diffusion and horizontal advection have the same importance (Dallman et al., 2013).

The layer above the RSL, is called inertial sub-layer (ISL) or constant-flux layer (CFL). Here the effects of individual building wakes disappear and only an average of building morphology is relevant for the turbulence. As pointed out by Roth (2000), the velocity mean profile follows the logarithmic law, or the diabatic version from Monin-Obhukov similitude (see Sec. 2.2.5), which again applies.

The upper part of the UBL is constituted by a region with varying shear stress up to the transition to the free stream atmosphere. Even though still little is known about this layer, the surface roughness is not deemed to have an influence on the turbulence structure (Roth, 2000). A schematic diagram of the mentioned layers can be found in Fig. 2.1.
2.2.2 Stratification: classification

The stratification is created by differences in the density of the air, which in turn depends on variation of temperature, humidity and pressure. In order to take into account all of them in a single quantity the virtual potential temperature was introduced. In particular, the potential temperature \( \theta \) is the temperature of an air parcel adiabatically displaced to a pressure level \((P_0)\) of 1 bar. If its absolute temperature is \( T \) and the pressure \( P \), the potential temperature is

\[
\theta = T \left( \frac{P_0}{P} \right)^{R/c_p} \tag{2.1}
\]

where \( R \) is the gas constant and \( c_p \) the specific heat capacity at constant pressure. To account for the air humidity the virtual potential temperature \( \theta_v \) is introduced, defined as

\[
\theta_v = \theta (1 + 0.61r - r_L) \tag{2.2}
\]

where \( r \) is the mixing ratio of water vapor and \( r_L \) is the mixing ratio of liquid water in the air. \( \theta_v \) is, hence, the temperature which dry air must have to have the same density and pressure as moist air.

The ABL can generally be classified in three categories from a static point of view: neutral (NBL), stable (SBL) and unstable (also called convective, CBL) depending on the capability
for buoyant convection. The NBL is characterised by a dry adiabatic potential temperature lapse rate $\Gamma$

$$\Gamma = -\frac{dT}{dz} = \frac{g}{c_p} = \frac{9.81 \text{ ms}^{-2}}{1005 \text{ J K}^{-1} \text{kg}^{-1}}$$

and absence of convection. Air parcels moving up and down have exactly the same density as the surrounding air and so their vertical motions are neither amplified nor reduced. Conversely, in a SBL vertically displayed fluid parcels tend to return to their initial height. Such a stable stratification happens whenever the surface is cooler than the air and a sub-adiabatic lapse rate is generated. Finally, when less-dense air underlies denser air, the boundary layer is called statically unstable (normally accompanied by a super-adiabatic lapse rate). In this event, convective motions are encouraged, helping mixing the air and resulting in a stabilisation of the system (Stull, 1988).

Unfortunately, the knowledge of the temperature lapse rate alone is often not sufficient to classify the atmospheric stability. In fact, the local definition may fail in case of convective mixed layers (see Sec. 2.2.3) in which the excess of buoyancy, not the ambient lapse rate, affects the rise or descent of thermals. In other words, in order to correctly determine the stability, either knowledge of the whole virtual potential temperature vertical profile is required, or measurement of the turbulent buoyancy flux must be made.

The static stability concept illustrated above only accounts for thermally generated turbulence but it does not contain information about wind-shear generated turbulence. For this reason, a dynamic stability parameter needs to be introduced. One of the most widely used parameters is the Richardson number, representing the ratio of buoyancy to shear forces. Three different versions of the number exist, but for all of them a positive Richardson number indicates stable stratification while a negative unstable. Before defining them some symbolic conventions have to be defined. $U, V$ and $W$ represent the streamwise, lateral and vertical components of the velocity along, respectively the $x$, $y$ and $z$ directions. Such components, as well as scalars (e.g. the temperature $\theta$), can be divided into a mean part (denoted with an overline and capital letter, e.g. $\overline{\Theta}$) and a fluctuating part (denoted by a prime, e.g. $\theta'$)

$$u(t) = \overline{U} + u'(t)$$
$$v(t) = \overline{V} + v'(t)$$
$$w(t) = \overline{W} + w'(t)$$
$$\theta(t) = \overline{\Theta} + \theta'(t)$$
2.2 Atmospheric boundary layer

An overbar overlining a square fluctuating quantity indicates a variance (e.g. $\overline{u'^2}$), two quantities a covariance (e.g. $\overline{u'w'}$). Having said that, it is useful now to briefly introduce the turbulence kinetic energy (TKE) budget equation. Following Kaimal and Finnigan (1994) and Stull (1988)

$$\frac{\partial TKE}{\partial t} = \frac{g}{\Theta_{REF}} (\overline{w'\theta'_v}) - (\overline{u'w'}) \frac{\partial \overline{U}}{\partial z} - \frac{\partial (\overline{w'e})}{\partial z} - \frac{1}{\rho} \frac{\partial (\overline{w'p'})}{\partial z} - \varepsilon$$

(2.4)

in which horizontal homogeneity is assumed and subsidence neglected. $TKE = \frac{1}{2} (u'^2 + v'^2 + w'^2)$, $\Theta_{REF}$ is a reference temperature, $e = \frac{1}{2} (u'^2 + v'^2 + w'^2)$, $\rho$ is the air density and $\varepsilon$ the dissipation rate. The first term on the right side accounts for the buoyant production or consumption according to the sign of the vertical heat flux ($\overline{w'\theta'_v}$). The second term is the mechanical production and is nearly always positive, while the others represent in the order the turbulent transport, pressure transport and viscous dissipation.

The flux Richardson number is obtained by the ratio between the buoyant production and mechanical production of the TKE

$$Ri_f = \frac{\frac{g}{\Theta_{REF}} (\overline{w'\theta'_v})}{(\overline{u'w'}) \frac{\partial \overline{U}}{\partial z}}$$

(2.5)

The main limitation of $Ri_f$ is that, involving factors related to turbulent correlation (e.g. knowledge of turbulent fluxes), it can be used to determine whether turbulent flows become laminar but not the opposite. Assuming that kinematic fluxes are proportional to the vertical gradient of the mean quantity, which is the basis of the K-theory (see Sec. 2.4.1), the gradient Richardson number is obtained:

$$Ri = \frac{g}{\Theta_{REF}} \frac{\partial \overline{\theta}}{\partial z} \left( \frac{\partial \overline{U}}{\partial z} \right)^2$$

(2.6)

$Ri$ is based on the knowledge of local gradients. Since this is rarely possible in field observations, we can approximate $\frac{\partial \overline{\theta}}{\partial z}$ with $\frac{\Delta \overline{\theta}}{\Delta z}$ and $\frac{\partial \overline{U}}{\partial z}$ with $\frac{\Delta \overline{U}}{\Delta z}$ so that

$$Ri_b = \frac{\frac{g}{\Theta_{REF}} \Delta \overline{\theta} \Delta z}{(\Delta \overline{U})^2}$$

(2.7)

This number is called bulk Richardson number and is referred to two points at different heights: one usually coincides with the ground while the other may be variable depending on the case of study (it could be, e.g., the building height or the boundary layer depth).
2.2 Atmospheric boundary layer

Another important stability parameter is the ratio of height $z$ to the scaling length $L$ (Monin-Obukhov length), which is obtained by differentiating the expression of the logarithmic velocity profile (see Sec. 2.2.5) and substituting it into the flux Richardson number,

$$\zeta = \frac{z}{L} = -\frac{g}{\Theta_{REF}} \frac{w'\theta'}{u_*^3/kz} \quad (2.8)$$

where $u_*$ is the friction velocity ($= \left[ - (u'w')_0 \right]^{1/2}$) and $k$ the von Karman constant. Kaimal and Finnigan (1994) stated that this quantity is more useful than $Ri$ because $L$ can be assumed constant through the surface layer. As for $Ri$, $L$ is negative for CBLs and positive for SBLs. In very stable and unstable conditions the ratio $\delta/|L| \gg 1$, while in weak stratification $\delta/|L| > 1$, finally $\delta/|L| \ll 1$ for NBL.

2.2.3 Convective boundary layer

A CBL is dominated by buoyancy mechanisms generated by heat transfer from a warmer underlying surface. Typically, a CBL is divided into three different layers (Fig. 2.2): the surface layer (SL), the mixed layer (ML) and the entrainment (or inversion) zone.

In the SL the temperature profile is sub-adiabatic: the potential temperature decreases rapidly in the first few centimetres above the ground, while in the remainder of the SL the gradient decreases smoothly with height, which is close to zero at the top of the SL. The other meteorological variables change quickly with the height. Nevertheless, Stull (1988) pointed out that the logarithmic wind profile can be still employed (in the diabatic form, according to Monin-Obukhov theory, see Sec. 2.2.5).

![Fig. 2.2 Vertical profiles of the main quantities in the CBL, after Stull (1988). $G$ is the geostrophic value of velocity.](image-url)
2.2 Atmospheric boundary layer

In the entire ML, which constitutes the major part of the CBL, gradients of velocity, temperature and shear stress ($\overline{u'w'}$) continue to be close to zero. In fact, the strong vertical mixing of this region helps to conserve such quantities.

In the entrainment region gradients become larger as the temperature rises in a capping inversion. Convective thermals penetrate this zone and free atmospheric air is entrained in the ML as thermals sink back.

The height of the whole CBL is often measured referring to the point in which the heat flux has a minimum (usually at about the middle of the entrainment zone, often at the height where the capping inversion is strongest, Stull, 1988). CBLs can be up to 2 km high.

As highlighted by Fedorovich (2004), despite the various flow-field patterns they can present, the studied CBLs are usually divided in two categories regarding their spatial/temporal evolution: one is statistically quasi-homogeneous in a horizontal plane (meaning that its statistical properties do not vary in the horizontal plane but only with height $z$), while the other considers horizontally evolving CBL from initial neutral or stable condition on a heated underlying surface. Another classification refers to the presence or less of wind shear which contributes to the generation of turbulence. The case of absence of wind shear is called “shear-free” CBL. In the literature, a $\delta/L$ ratio between $-10$ and $-5$ is indicated as threshold for CBL in which the buoyancy produced turbulence becomes predominant over the mechanically produced (Rau and Plate, 1995). The effect of surface roughness on the CBL (investigated in laboratory by Fedorovich et al., 1996 and Fedorovich and Kaiser, 1998) was found to be responsible for modifications in the turbulence production, associated to an increment of the velocity variances near the surface compared to the shear-free case.

2.2.4 Stable boundary layer

A SBL is normally observed during night-time (for this reason sometimes called nocturnal boundary layer), when the radiative cooling of the Earth’s surface creates a profile of potential temperature rising with height. That being said, the SBL is generally more difficult to study than the CBL. In fact, turbulence levels are much lower due to the effect of buoyancy forces and so harder to be measured. Moreover, wave motions can arise and their co-existence with turbulence complicates the data interpretation. The SBL is normally much less probable to be found in quasi-steady conditions compared to the CBL and, consequently, its structure tends to evolve (Caughey, 1982). Another issue is the variety of types of SBL. The weakly stable case is the easiest and more well known. An example of the typical vertical profiles of temperature and velocity is shown in Fig. 2.3.

The mean wind increases with height reaching a maximum close to the BL top, a maximum that is typically larger than the geostrophic value. The potential temperature, also increases
with height reaching a maximum close to the top of the SBL. The greatest temperature gradient is near the ground, decreasing smoothly toward neutral with height.

If the increment of potential temperature is larger than the adiabatic lapse rate, also the gradient of absolute temperature becomes positive, phenomenon which is called “inversion”. A way to quantify the SBL strength is the difference between the potential temperature on top of the BL, \( \Theta_\delta \), and close to the surface, \( \Theta_0 \),

\[
\Delta \Theta_s = \Theta_\delta - \Theta_0
\]  

This quantity can be considered as proportional to the amount of cooling that has occurred since SBL formation. Stull (1988) gives typical magnitudes for SBL strength from zero at transition (generally after sunset) to values on the order of 15°C by morning, depending on the turbulence intensity and cloud cover.

The height of the SBL is often difficult to determine due to an absence of a strong demarcation. Typical conditions that can be considered to identify \( \delta \) are: the height where \( \partial \Theta / \partial z \) approaches zero, \( \bar{u}'\bar{w}' \approx 0 \) or also where the mean velocity \( \bar{U} \) is maximum. SBLs grow to depths of about 100 to 500 m (Stull, 1988).

Strong SBLs are more difficult to describe since they may behave quite differently. While for the weakly SBL it has been shown that the turbulence tends to decrease with the height up to the top, in the very stable case this is not necessarily true, in fact it may even increase with height. Moreover, wave motions become more relevant as soon as the turbulence decreases and this complicates the study. Due to the high variability of situations, a unique description of strong stability is not available yet (Mahrt, 2013).
The effect of roughness on the SBL was studied in laboratory by Ohya et al. (1997), Ohya (2001) and Williams et al. (2017). They concluded that the turbulence characteristics (appropriately normalised by the friction velocity and surface heat flux) are not substantially affected, with just small modifications due to local changes of stability. They also identify a bulk Richardson number threshold (ranging from 0.10 to 0.25) above which Reynolds stresses do not scale with the friction velocity anymore.

### 2.2.5 Similarity functional forms

In the UBL, the wind profile for neutral condition is frequently parametrised as (Britter and Hanna, 2003)

\[
U(z) = \frac{u_*}{k} \ln \left( \frac{z - d}{z_0} \right)
\]  

(2.10)

where \(d\) is called displacement height and \(z_0\) is the aerodynamic roughness length. The former (also called zero-plane displacement) is representative of the height above ground where zero wind speed is achieved as effect of flow obstacles (e.g. buildings or trees), while the latter is a parameter which accounts for the effect of surface roughness on the wind flow. Another well-used form is the so-called power law wind profile

\[
U(z) = U_{zR} \left( \frac{z}{z_R} \right)^\alpha
\]  

(2.11)

where \(z_R\) is a reference height and \(U_{zR}\) the velocity measured at that height. \(\alpha\) is a coefficient that characterises the slope of the wind profile.

As far as non-neutrally stratified ABLs are concerned, the Monin-Obukhov similarity (Monin and Obukhov, 1954) is a well established and universally recognised theory to scale the SL. It is based on the hypothesis that parameters such as gradients, variances and covariances are function of only \(\zeta\) if normalised by appropriate power of the friction velocity \(u_*\) and temperature \(\theta_*\), the latter defined as

\[
\theta_* = -\left( \frac{\overline{w\theta}}{u_*} \right)_0
\]  

(2.12)

where, for simplicity, from now on the subscript “\(v\)” of virtual potential temperature is omitted.

In this framework the non-dimensional forms of the wind shear and temperature gradient in the SL (which is function of \(\zeta\)) are given by

\[
\phi_m(\zeta) = \frac{kz}{u_*} \frac{\partial U}{\partial \zeta}, \quad \phi_h(\zeta) = \frac{kz}{\theta_*} \frac{\partial \Theta}{\partial \zeta}
\]  

(2.13)
2.2 Atmospheric boundary layer

From the integration between \( z_0 \) and \( z \) the logarithmic expression for the mean streamwise velocity and temperature is obtained for the general diabatic case in the SL

\[
\overline{U}(z) = \frac{u_\ast}{k} \left[ \ln \left( \frac{z - d}{z_0} \right) - \psi_m(\zeta) \right]
\]

(2.14)

\[
\overline{\Theta}(z) - \Theta_0 = \frac{\theta_\ast}{k} \left[ \ln \left( \frac{z - d}{z_{0h}} \right) - \psi_h(\zeta) \right]
\]

(2.15)

where \( z_{0h} \) is the thermal roughness length. In the NBL \( \psi_m \) is equal to zero (leading to Eq. 2.10), while for the general diabatic case

\[
\psi_{m,h}(\zeta) = \int_{z_0 - \zeta z_0}^{(z - d)/L} \left[ 1 - \phi_{m,h}(\zeta) \right] \frac{d\zeta}{\zeta}
\]

(2.16)

The parametric functions \( \phi_m \) and \( \phi_h \) are normally determined by fitting with field or experimental data. The most widely used and simplest forms are the Businger-Dyer relations (Kaimal and Finnigan, 1994)

\[
\phi_h = \phi_m^2 = (1 - 16\zeta)^{-1/2} \text{ for } \zeta < 0
\]

(2.17)

\[
\phi_h = \phi_m = 1 + 5\zeta \text{ for } \zeta \geq 0
\]

(2.18)

but others have been proposed. In this regard see also Högström (1988) for a comprehensive review.

Finally, also \( Ri \) and \( Ri_f \) can be expressed in the Monin-Obukhov theory framework as function of \( \zeta \)

\[
Ri(\zeta) = \zeta (\phi_h/\phi_m^2)
\]

(2.19)

\[
Ri_f(\zeta) = \zeta / \phi_m
\]

(2.20)

For the ML of the CBL, the length scale is considered to be the BL depth \( \delta \), while the velocity and temperature scales are, respectively

\[
w_\ast = \left[ \frac{g}{\Theta_{REF}} \left( \frac{w^\prime \theta^\prime}{\theta_0} \right)_0 \delta \right]^{1/3}, \quad \tilde{\theta}_\ast = \left( \frac{w^\prime \theta^\prime}{\theta_0} \right)_0 / w_\ast
\]

(2.21)

so that statistical properties of turbulence, normalised with \( w_\ast \) and \( \tilde{\theta}_\ast \), are only functions of \( z/\delta \), as proposed by Willis and Deardorff (1974) and summarised by Kaimal and Finnigan (1994).
2.3 Physical modelling of the ABL

2.3.1 Experimental approaches

Since observational studies are intrinsically limited by uncontrollable weather conditions and limits in the instrumentation, the possibility of laboratory simulation in controlled flow conditions (thus excluding some of the uncertainties of nature) has led to studies in specially designed facilities. Water tank experiments contributed extensively to the understanding of CBLs (e.g., Willis and Deardorff, 1974, who simulated a CBL by heating the water from the bottom). Another approach is represented by the saline tanks (like the one in Hibberd and Sawford, 1994), in which the stratification is generated by differences in the salinity level instead of temperature. However, as pointed out by Fedorovich (2004), these two techniques “omit or treat rather indirectly the effects of wind shears on the turbulence regime”, effect which may become even more important in case of very rough surfaces, such as urban environments.

Other laboratory approaches allow to better simulate the wind shear by means of employing water channels or wind tunnels. The former use water as the working fluid pumped in a closed-loop channel, while the latter employ air. In the following the wind tunnel approach will be introduced in more detail. Stratification can be reproduced in different ways: the usage of heat exchanger is the most common, however other methods exist, among them the injection of heated air, gases of different molecular weight, or even latent heat absorption or release during phase change (Meroney, 1998). Heat exchangers are generally placed at the inlet section and on the floor, but also on the lateral walls and on the ceiling to reduce heat losses and compensate the natural non-adiabatic behaviour of test section walls. Moreover, in order to help establishing steady conditions in the flow, heat exchangers (with the purpose of cooling the air after the test section) should be considered at the outlet section. The turbulence level and structure can be controlled by employing devices like vortex generators and roughness elements, fences, grids, screens and jets. For a review of the capabilities of some existing thermally stratified wind tunnels see Meroney (1998), Meroney and Melbourne (1992), even though they are now a little outdated. Another important aspect for wind tunnel simulations is the design of the ceiling, since it constrains the growth of the BL, causing a blockage effect that is not present in the free atmosphere. The presence of the ceiling also determines the development of an upper BL that “virtually” reduces the wind tunnel cross-section, hence imposing a further acceleration of the free stream flow and resulting in a non-zero-pressure gradient condition. To eliminate this issue, some wind tunnels have a locally-raised roof (in some cases adjustable).
2.3 Physical modelling of the ABL

2.3.2 Scaling criteria

Scaling criteria are used in order to guarantee a correct reproduction of the ABL at a different scale. They have been laid down by Snyder (1981) for atmospheric diffusion modelling. The criteria include dimensionless parameters obtained from the non-dimensionalisation of the governing equations of fluid motion (Appx. A).

- Reynolds number: \( Re = \frac{L_R U_R}{\nu} \)
- Rossby number: \( Ro = \frac{U_R}{\Omega_R L_R} \)
- Bulk Richardson number: \( Ri_b = \frac{\Delta \Theta_R g L_R}{U_R^2} \)
- Eckert number: \( Ec = \frac{U_R^2}{L_R C_p \Theta_R} \)
- Peclet number: \( Pe = Re \cdot Pr \) (with Prandtl number: \( Pr = \frac{\nu}{\nu_\theta} \))

where \( L_R, U_R, \Omega_R, \Theta_R \) and \( \Delta \Theta_R \) are reference length, velocity, angular velocity, temperature and difference of temperature, respectively. \( \nu \) is the kinematic viscosity and \( \nu_\theta \) is the thermal diffusivity.

The Rossby number, which is a measure of the local acceleration against the Coriolis acceleration, is impossible to match in a standard wind tunnel. However, the Rossby number similarity should be taken into account only when simulating SBL or NBL in relatively flat terrain with a length scale greater than 5 km (Snyder, 1972). Moreover, when modelling flow over complex terrain Snyder (1985) pointed out how local acceleration is expected to be more significant than in flat terrain; therefore in such cases the Rossby number may be ignored even for length scales significantly larger than 5 km. As far as the CBL is concerned Meroney (1998) stated that, given the strong mixing, surface generated stress should dominate most situations for at least 2 to 5 km. Other authors proposed different length scales (for a discussion see Meroney and Melbourne, 1992, Snyder, 1972).

The Reynolds number similarity depends on the fluid properties and the flow speed. Since in wind tunnel studies the fluid is the same as the full-scale case, the similarity can only be ensured by adjusting the flow velocity. Assuming, for example, a scale factor of 1/200, this would lead to a wind tunnel speed 200 times larger than at full scale, clearly not feasible. However, many arguments were presented about the independence from the Reynolds number. For this purpose, Snyder (1972) proposed that a value of the roughness Reynolds number \( Re_* = u_* z_0 / \nu \) greater than 2.5 was sufficient to ensure an aerodynamically rough surface (while other authors indicate slightly different thresholds, see e.g. Snyder and Castro, 2002). This criterion has been defined for NBL and extended by various authors (see e.g. Hancock...
2.3 Physical modelling of the ABL

and Pascheke, 2014) also to non-isothermal cases. Recently, though, the extension of Reynolds number independence criteria to non-isothermal cases has been questioned by Chew et al. (2018) (for more details see the paper review in Sec. 2.5.3).

The Peclet number depends only on the fluid (i.e. air) and the Reynolds number, so similar arguments for neglecting the latter are used also in this case. The Eckert number starts to be significant only for very large velocities, not normally contemplated in dispersion problems, hence it can be ignored as well. The primary importance of the bulk Richardson number in the scaling of stratified flows has been already discussed in Sec. 2.2.2. Another quantity to quantify the stratification level is the Froude number \( Fr = \frac{Ri}{Fr} - 1 \), sometimes used in place of the bulk Richardson number.

Finally, the similarity of the dimensionless boundary conditions must be respected as well. This includes the distribution of temperature and roughness over the area of interest, the longitudinal pressure variation, and the vertical velocity and temperature distribution of the approaching flow (Cermak, 1971).

2.3.3 Simulations of SBLs in the wind tunnel

The work by Arya (1975) is among the earliest attempts to investigate stratified BLs properties in a wind tunnel. The BLs were allowed to grow over a water cooled smooth test section floor \((28 \times 1.8 \times 1.8 \text{ m})\), reaching a height of 0.5-0.7 m (depending on stability). Even though both CBLs and SBLs were simulated (ranging from \( Ri_\delta - 0.33 \) to 0.10, where the bulk Richardson number \( Ri_\delta \) is referred to the BL top \( \delta \)), turbulence properties were investigated only for the latter. The free stream velocity varied from 3 to 9 m/s (equivalent to a \( Re_\delta \) from 1.1 to \( 3.5 \times 10^5 \)) to produce different stratification levels. Stability was found to modify the entire mean velocity profile as well as normalised turbulence intensities and fluxes. In this regard, the streamwise heat flux was observed to be several times the vertical, in accordance with field data. Spectral analysis showed that the inertial sub-range was reduced with increasing stratification, in part because of the reduction in the \( Re_\delta \) applied to vary the stratification. Moreover, they observed the wavenumber corresponding to the peak energy increasing with incrementing stability (see Appx. B for an introduction of spectral analysis).

Ohya et al. (1997) employed a similar wind tunnel to carry out simulations of SBLs on a smooth surface. Slower free-stream velocities were used (ranging from 0.8 to 3.0 m/s), exploring the effect of a stronger stratification (from \( Ri_\delta = 0.12 \) to 1.33). Velocity and temperature fluctuations, as well as momentum and heat fluxes were found to decrease with increasing stability, up to a point in which they collapsed close to zero near the surface (characteristic that was associated with strong SBL). The threshold between weak and strong stratification was identified in a value of the \( Ri_\delta \) of 0.25. For the strongest stability the peak in the velocity spectra
was observed moving to smaller wavenumbers, indicating that large-scale slowly fluctuating motions dominated the flow.

Ohya (2001) reproduced similar $Ri_\delta$ values on a shorter test section ($13.5 \times 1.5 \times 1.2$ m) but growing over a rough surface (obtained by means of oval ring chains as roughness elements). The turbulence profile shapes were comparable with Ohya et al. (1997), but much greater turbulence intensities and fluxes were measured, as effect of the increased roughness. The presence of internal gravity waves in the lower part of the strong SBLs was also suggested from cross-spectrum analyses.

Ohya and Uchida (2003) attempted the simulation of SBLs starting from a near-linear temperature profile imposed at the inlet section by means of heat exchangers. This was the main difference compared to Ohya (2001) (where a polynomial vertical profile of temperature, see Stull, 1988, was adopted, instead). The mean temperature profiles presented a reduction of the gradient above the BL, while the mean velocity profiles were similar. The temperature fluctuation intensity for the weak stability cases was remarkably different from Ohya (2001) due to the relatively large gradient of mean temperature in the middle and upper part of the BL. Moreover, in the near-linear temperature case the gravity waves seemed to be present for all heights and stability levels.

Hancock and Pascheke (2014) investigated the usage of spires (Irwin, 1981) to artificially thicken the SBL in the EnFlo wind tunnel, aiming to develop BLs properties approximately horizontally homogeneous, suitable for wind turbine wake studies in low roughness conditions (found in offshore wind farms over the sea). The selected spires reached the full height of the test section, and this was found to generate excessive turbulence above the boundary layer top, in terms of Reynolds shear stress. A linear inlet temperature was used, similarly to Ohya and Uchida (2003). This generated a BL temperature profile which was approximately linear in the downstream flow above the BL, condition that they called of strong “imposed” stability, this despite the relatively weak surface stability ($\delta/L$ was only 0.4, while $Ri_\delta$ was 0.11). The steep gradient of inlet temperature was found to produce a steep gradient also in the temperature variance. The latter behaved as in Ohya and Uchida (2003), namely a decrease with increasing $z$ followed by a rise. Both the studies attributed it to the too large rise of mean temperature in the same region.

In order to improve the simulation technique, building on lessons learnt from previous experiments, Hancock and Hayden (2018) employed spires scaled down to 40% compared to the ones in Hancock and Pascheke (2014). Attention was also given to find the most appropriate inlet temperature profile. The easiest solution of imposing a uniform inlet temperature and allowing the stability to grow thanks to the cooling effect of the floor was initially explored. However, they found that with this configuration the upper part of the layer remained unaffected.
by the non-neutral stratification, with a mean temperature constant with height, while temperature fluctuation and heat fluxes approached zero at lower heights than the momentum flux. This behaviour was likely caused by the advection downstream of the uniform temperature at the inlet and enhanced by the reduced level of turbulence. At this point they introduced a new technique to set the inlet temperature profile. This is illustrated in the following:

- flow generators and roughness elements were removed, letting a SBL to grow only by friction with the cooled floor, starting from a uniform inlet temperature profile;

- the mean temperature profile was measured downstream and the resulting profile was applied as inlet temperature with spires and roughness in place again. The profile had to be stretched to fit the desired BL height and difference of temperature;

- a direct application of such an initial condition created an undesired large peak in the middle region of the temperature fluctuation graph. Therefore, the original gradient had to be reduced applying corrective factors until the best solution was found.

This procedure gave rise to smooth profiles of velocity and temperature fluctuations with both momentum and heat fluxes approaching zero at the same height. The authors also investigated the effect of a length of uncooled region of floor after the inlet, finding a dependency of the shear stress $u'w'$ profile from this parameter.

Conversely from all previously mentioned works, Williams et al. (2017) developed SBLs by heating the wind tunnel roof ($5 \times 1.2 \times 0.9$ m). Both smooth and rough surfaces were considered. For weak and moderate stability conditions, streamwise and vertical turbulence were found to reduce proportionally to each other. The effect of roughness was to shape the entire mean velocity and temperature profiles by means of reducing mixing, while only small differences in the scaled turbulence profiles were observed, attributed mostly to changes in local stratification ($Ri$). For strong stability, instead, they found a marked change with turbulence stresses collapsing and no longer scaling with wall stress. Conversely from Ohya et al. (1997) and Ohya (2001) this was observed to happen for lower $Ri_\delta$ (0.1 and 0.15 for smooth and rough surface, respectively). Moreover, the turbulence was found to be damped prevalently in the outer flow, instead of near the surface.

### 2.3.4 Simulations of CBLs in the wind tunnel

The effect of buoyancy on the characteristics of CBLs developing over a heated smooth and rough surface was investigated by Rey et al. (1979) (test section $10 \times 1.0 \times 1.2$ m). Neither capping effect from stable stratification nor flow generators were considered, resulting in a BL depth of 0.2-0.4 m. Mean and turbulent quantities as well as spectra were compared with field
2.3 Physical modelling of the ABL

data and Monin-Obukhov theory and the resulting discrepancies were attributed to imperfect flow homogeneity (due to a too small wind tunnel cross-section of only $1 \times 1.2$ m) and low Reynolds number ($Re_\delta = 3.3 \div 5 \times 10^4$). Decisively larger was the wind tunnel used by Sada (1996) to simulate a CBL with weak capping inversion for dispersion studies (test section $20 \times 3.0 \times 1.5$ m). The weakness of the inversion did not prevent the vertical spread of the plume in the upper part of the CBL (from either a ground level or elevated source release). Nevertheless, the author found that the Deardorff ML similarity (see Sec. 2.2.5) convective scaling also applies to the wind tunnel simulation.

Fedorovich investigated the CBL in a series of works carried out in the UniKa wind tunnel at the University of Karlsruhe, Germany ($10 \times 1.5 \times 1.5$ m). The closed-circuit wind tunnel has a unique design, provided with ten individual and insulated layers, each equipped with independent fan and heater that allow the shaping of velocity and temperature profiles at the inlet section. Modification of the turbulence regime due to the effect of surface shear was investigated by Fedorovich et al. (1996) and, more in detail, by Fedorovich and Kaiser (1998) for a horizontally evolving CBL. In both studies the inlet velocity was uniform and equal to 1 m/s. A strong temperature inversion (compared to Sada, 1996) was applied above 300 mm while the BL was allowed to grow over a smooth heated surface (reaching a height of 400 mm after 7 m). In the bulk of the BL, surface shear was found to contribute to the turbulence production towards larger wave numbers, producing a conspicuous increment of the velocity variances near the surface for shear-to-buoyancy production ratios $u_* / w_*$ equal and larger than 0.3, with respect to the shear-free case. Moreover, surface shear was claimed to be the cause of the elongation and flatness in the production ranges (at lower frequency) of the measured velocity spectra. Fedorovich et al. (2001) further investigated the enhanced bottom roughness by means of increasing the roughness by a factor of 10. This modification was found to affect the entire CBL turbulence, enlarging both the horizontal and vertical velocity variance, other than increasing their longitudinal variability. Also the growth rate of the CBL was slightly increased by the large surface roughness.

The case of horizontally-evolving CBL capped by a strong inversion was also analysed by Ohya and Uchida (2004) for a range of instability levels with $Ri_\delta$ varying from $-0.23$ to $-0.74$ (obtained reducing the velocity instead of increasing $\Delta \Theta$) so that both shear-dominated and convection-dominated (more unstable) cases were simulated. It is important to highlight here that no surface roughness elements were used in this study. The critical value of $u_* / w_*$, which divides the two types, was found to be 0.4, close to the one indicated by Fedorovich and Kaiser (1998). The measured velocities and temperature were almost constant from 20 to 80% of the BL height due to vigorous convective mixing (as expected in a ML). They also observed an interesting reduction of the streamwise velocity variance and Reynolds shear stress
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**Table 2.1** List of wind tunnel studies on simulation of thermally stratified boundary layers.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Stratification</th>
<th>Floor</th>
<th>Spires</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SBL</td>
<td>CBL</td>
<td>Smooth</td>
</tr>
<tr>
<td>Arya (1975)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Ohya et al. (1997)</td>
<td>X</td>
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<td>Ohya (2001)</td>
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<td>Hancock and Pascheke (2014)</td>
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<td>Williams et al. (2017)</td>
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<tr>
<td>Rey et al. (1979)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Sada (1996)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Fedorovich et al. (1996)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Fedorovich et al. (2001)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ohya and Uchida (2004)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Hancock et al. (2013)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

(if normalised by $w_*$) when instability increased. Also a minimum in the vertical heat flux was detected (as found in field measurements), confirming the effectiveness of the capping temperature inversion.

Conversely from the other works presented so far, Hancock et al. (2013) investigated the usage of spires (as done for the SBL by Hancock and Pascheke, 2014) to reproduce an artificially-thickened weak CBL with and without a weak capping inversion. An iterative method was developed to determine the temperature profile to apply at the inlet: starting from a uniform inlet temperature, the temperature profile measured downstream was used as new inlet profile for another attempt and so on, until a natural equilibrium was established, in which inlet and downstream temperature profiles had the same shape. The results for mean and turbulent velocity and temperature agreed well with the weakest instability case by Ohya and Uchida (2004). The BL depth was 1.3 times deeper compared to the uniform inlet temperature case. Further comparisons were made with “standard forms” of mean and turbulent quantities (Willis and Deardorff, 1974), finding significant differences which were attributed to the effect of shear, even though the use of the spires may have played an important role. Other parametric relations were then proposed to take into account the surface shear also in the ML scaling.

The above mentioned works are listed in Tab. 2.1 for both SBL and CBL cases.
2.4 Pollutant dispersion and scaling considerations

2.4.1 Theoretical basis of dispersion

The main point in dispersion modelling is the evaluation of the instantaneous concentration field \( c(x,y,z,t) \), assuming that the pollutant is introduced at a mass per unit time rate \( Q \) into a domain with a given set of boundary conditions. Assuming pollutant mass conservation in a control volume (Eulerian approach):

\[
\frac{\partial c}{\partial t} + u_i \frac{\partial c}{\partial x_i} = \nu_c \frac{\partial^2 c}{\partial x_i^2} + Q
\] (2.22)

in which \( u_i \) represents the three components of the wind velocity in the control volume, while \( \nu_c \) is the pollutant molecular diffusivity. Such equation, combined with the Navier-Stokes equations (see Appx. A), gives the mathematical foundation of dispersion modelling of a passive tracer. Any pollutant release is considered to be “passive” if the pollutant introduction does not affect the density of the fluid in which it disperses, and at the same time the pollutant is released without initial excess of momentum.

It is important to note that Eq. 2.22 is linear in \( c \), hence the concentration field in case of multiple sources can be described as superposition of the single concentration field produced by each source. After the application of Reynolds averaging (see Appx. A in this regard) on Eq. 2.22, the expression for the time averaged value of concentration \( \overline{C} \) (where \( \overline{C} = c - c' \)) is given by:

\[
\frac{\partial \overline{C}}{\partial t} + U_i \frac{\partial \overline{C}}{\partial x_i} = \nu_c \frac{\partial^2 \overline{C}}{\partial x_i^2} - \frac{\partial \left( \overline{u'_i c'} \right)}{\partial x_i} + Q
\] (2.23)

Pollutant transport can be divided into two components: “advection” and “diffusion”. Advection consists in the transport of pollutant due to the mean wind velocity (represented by the second term on the left hand side of Eq. 2.23). Conversely, diffusion is caused by molecular processes (first term on the right hand side) and turbulent mass transfer (second term), the former being less significant in large Reynolds number flows. Moreover, thanks to diffusion the pollutant is spread in multiple directions compared to the mean wind velocity.

According to the “K-theory”, kinematic fluxes \( \overline{u'_i c'} \) can be approximated as a function of the mean concentration gradient

\[
\overline{u'_i c'} = -K_i \frac{\partial \overline{C}}{\partial x_i}
\] (2.24)
2.4 Pollutant dispersion and scaling considerations

Table 2.2 $\sigma_y$ and $\sigma_z$ formulas recommended by Briggs (1973) for $10^2 < x < 10^4$ m and urban conditions.

<table>
<thead>
<tr>
<th>Stability class</th>
<th>$\sigma_y$ (m)</th>
<th>$\sigma_z$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-B</td>
<td>$0.32x(1 + 0.0004x)^{-1/2}$</td>
<td>$0.24x(1 + 0.001x)^{1/2}$</td>
</tr>
<tr>
<td>C</td>
<td>$0.22x(1 + 0.0004x)^{-1/2}$</td>
<td>$0.20x$</td>
</tr>
<tr>
<td>D</td>
<td>$0.16x(1 + 0.0004x)^{-1/2}$</td>
<td>$0.14x(1 + 0.0003x)^{-1/2}$</td>
</tr>
<tr>
<td>E-F</td>
<td>$0.11x(1 + 0.0004x)^{-1/2}$</td>
<td>$0.08x(1 + 0.0015x)^{-1/2}$</td>
</tr>
</tbody>
</table>

in which $K_i$ is called “eddy diffusivity” in the i-direction. Substituting Eq. 2.24 in 2.23 and neglecting the effect of molecular diffusion, the so-called “advection-diffusion” equation is obtained

$$\frac{\partial C}{\partial t} + U_i \frac{\partial C}{\partial x_i} = K_i \frac{\partial^2 C}{\partial x_i^2} + Q$$  \hspace{1cm} (2.25)

The K-theory represents a simple method for turbulence closure of diffusion and for this reason is widely employed in dispersion studies. However, it comes with several limitations. The first of them is on the size of the scales of turbulent motion (eddies) that can be considered, being limited by the diffusing puff or plume dimension. Moreover, $K_i$, conversely from $\nu_c$, is not a fluid property, but changes with time, space and flow type. Hence, a general method to specify the eddy diffusivity still does not exist.

Assuming simple boundary conditions, Eq. 2.25 admits analytical solutions. For example, in case of an isolated and continuous point source in an unbounded uniform flow field of velocity $U$, ignoring along-wind diffusion, the solution is

$$C(x,y,z) = \frac{Q}{2\pi U \sigma_y \sigma_z} e^{-\frac{x^2}{2\sigma_x^2}} e^{-\frac{y^2}{2\sigma_y^2}}$$  \hspace{1cm} (2.26)

This equation corresponds to a Gaussian distribution of pollutant in the y and z directions, with $\sigma_y$ and $\sigma_z$ standard deviations in each direction. The latter two parameters are related to $K_y$ and $K_z$ (Eq. 2.24) by the relation $\sigma_i^2 = 2K_i x / U$. However, they are usually calculated with empirical relations as a function of the distance $x$ from the source and atmospheric stability conditions. An example are the relations proposed by Briggs (1973) as a function of the Pasquill-Gifford stability classes, reported in Tab. 2.2 for urban areas (for the stability classes see Appx. E).
Table 2.3 Urban dispersion scales (according to Munn, 1981)

<table>
<thead>
<tr>
<th>Scale</th>
<th>Horizontal length scale (m)</th>
<th>Time scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microscale</td>
<td>$0 \div 10^2$</td>
<td>Seconds</td>
</tr>
<tr>
<td>Neighbourhood scale</td>
<td>$10^2 \div 2 \times 10^3$</td>
<td>Minutes</td>
</tr>
<tr>
<td>Urban scale</td>
<td>$5 \cdot 10^3 \div 5 \times 10^4$</td>
<td>Hours</td>
</tr>
<tr>
<td>Regional scale</td>
<td>$10^5 \div 10^6$</td>
<td>Days</td>
</tr>
</tbody>
</table>

2.4.2 Urban dispersion modelling

The main difference between urban dispersion models and other dispersion models has to be found in the complexity of the obstacle geometries, other than in the variety and amount of sources distributed over the entire urban area, dealing with peculiar effects of non-homogeneous UBL and urban heat island on dispersion. Complex boundary conditions are associated with the three dimensional shape of the urban canopy. At the same time complex effects of meteorology on advection and diffusion, as well as thermal effects occurring in urban areas, contribute in complicating the problem, involving a wide range of different scales.

About the urban scales, Munn (1981) proposed a broad classification on the basis of the horizontal length and time scale, as shown in Tab. 2.3. Hall et al. (1996) suggested another way of defining dispersion scales for the urban environment, on the basis of the evolution of a plume within the urban canopy, by comparing the plume width with the dominant length scale of the turbulence around the buildings ($L_H$). Three scales were so defined: “near-field” (plume width $\ll L_H$), “intermediate-field” (plume width $\approx L_H$), “far-field” (plume width $\gg L_H$). These dispersion scales cover the range correspondent to the microscale and neighbourhood scale defined by Munn (1981).

Other than the scale, urban dispersion modelling also depends on the building geometries which are considered. In the simplest representation they can be constituted by a single building (e.g. a cuboid). A more complex representation is by considering an array of buildings. An array is typically defined as an ordered extensive group of buildings, containing at least 3 to 5 rows of buildings which are sufficiently close together for their wakes to interfere (Robins and Macdonald, 2000). The distance between buildings is an important parameter and a widely used criterion for classifying flows in building groups and arrays. In this regard Hussain and Lee (1980) identified three broad types of flow within an array of buildings:

- “isolated roughness”: the distance between buildings is so large that their wakes re-attach on the ground with a significant decay, so that a strong mutual interaction is precluded. The resultant flow field can be modelled as a superposition of flow fields around each building considered separately.
2.4 Pollutant dispersion and scaling considerations

a) Isolated roughness flow

b) Wake interference flow
c) Skimming flow

Fig. 2.4 Building array flow regimes (Oke, 1988)

- “wake interference”: the space between buildings is large enough to allow the flow above the buildings to penetrate down to the ground, but not enough for a significant decay of the wake in the street. Complex flow patterns are generated, strongly coupled with the flow above, which leads to an increment of aerodynamic roughness.

- “skimming flow”: the buildings are close enough to make the flow above relatively de-coupled from the one underneath, so that the canopy is seen as a flat rough surface by the flow. Inside the canopy stable recirculation vortices occur, with channelled flow and the presence of relatively stagnant areas.

Oke (1988) illustrated the three types as in Fig. 2.4. The magnitude of the spacing between the buildings is the main contributor in determining the threshold between each type of flow. Hence, a general definition of building spacing in an array has to be introduced. In this regard, two parameters come to help, they are

- plan area density: \( \lambda_p = \frac{A_p}{A_d} \)
- frontal area density: \( \lambda_f = \frac{A_f}{A_d} \)

where \( A_d \) is the mean lot area, \( A_p \), is the mean plan area, and \( A_f \) is the mean frontal area. Considering as example a uniform height array of cubes, Hussain and Lee (1980) found the isolated roughness region to occur when \( \lambda_p < 0.08 – 0.1 \), the wake interference in case
0.09 < \lambda_p < 0.17 and the skimming flow for \lambda_p > 0.15 - 0.21. It should be observed, though, that other aspects must be taken into account to identify the flow regime, like the building arrangement and shape, as well as the wind direction.

Alongside with array of buildings, “street canyons” (also referred as “urban canyons”) are a widely studied case. It is ideally referred to as a street with buildings lined up along the two sides, and very extended in this direction (Nicholson, 1975). However, in common practice a broader definition has been often applied, including also urban roads which are not necessarily continuously flanked by buildings on both sides, hence allowing some openings (intersections) on the sides of the canyon (Vardoulakis et al., 2003).

At least three parameters are needed to describe the geometry of a urban canyon: the building height \( H \), the canyon width \( W \) and length \( L_{SC} \), as illustrated in Fig. 2.5a, with the ratio \( H/W \) known as canyon aspect ratio (but other parameters, like the roof shape and building width may be introduced, as well). Oke (1988) identified the flow regime thresholds for a street canyon using these three geometric quantities (see Fig. 2.5b).

A further simplification of the geometry is represented by considering an infinite length for \( L_{SC} \) and wind direction perpendicular to the canyon axis, case which is normally referred to as a “bi-dimensional street canyon”. In practical cases, a street canyon can be assumed behaving like a bi-dimensional one if the length \( L_{SC} \) is greater than 10H (Moonen et al., 2011). In this case the flow pattern in the central cross-section can be taken as representative of the bi-dimensional canyon, providing that the effects of the lateral velocity component (along the street canyon axis) and the effects of side vortices are not significant.

Finally, “asymmetrical” canyons have unequal height buildings on the two sides, but in most studies canyons are assumed “symmetrical”, with the same building height on both sides.
2.5 Buoyancy effects on flow and dispersion in idealised urban geometries

2.5.1 Isolated building

One of the first documented studies performed in laboratory to assess the effect of stable thermal stratification dispersion around an isolated cube is reported by Yang and Meroney (1970). A 150 mm Plexiglas model was introduced in a 25 m long meteorological wind tunnel. Both smoke visualizations and quantitative tracer sampling were attempted. For the latter a radioactive gas (Krypton-85) was released either upstream or downstream of the model, sampled by a Geiger-Mueller counter (see Yang and Meroney, 1970 for a description of the technique). In the region up to 5 building heights downstream of the model the dispersion behaviour was found dominated by mechanical turbulence. Further downstream, instead, a SBL with $Ri_H = 0.15$ was found to produce an 8% increment in ground level concentration compared to a NBL. Moreover, stable stratification was responsible of a smaller lateral spreading, while in the vertical direction the plume growth was frozen.

Influence of stable stratification on the diffusion in a cube wake was also studied by Snyder (1994) by means of towing the model in a salt-water stratified tank. The approaching flow was uniform and laminar, dye was released from the leeward side of the cube and concentration sampled up to 6 building heights downstream. Stratification was found not to have any effect on concentration in the cavity region (close to the building) for Froude numbers larger than 2.5 (where $Fr = U_H/N_B H$), hence concluding that stable stratification very rarely would have any effect in the building downwash. Snyder (1994) results were compared with RANS (Reynolds-averaged Navier-Stokes) simulations by Zhang et al. (1996). On the basis of their results they pointed out that under stable stratification the downward vertical velocity would tend to increase, which in turn would cause an increment in the shear stress and TKE. In fact, if in strong SBLs this tendency is suppressed by a large damping of the turbulent motions, under slightly stable stratification such suppression would not be strong enough to avoid an increase in TKE due to increased shear stress. In other words, the TKE downstream of the obstacle may be expected to increase in case of weak SBLs. Similar conclusions were drawn by Santos et al. (2009), who also performed RANS on a single cube case.
Maré (2003) performed experimental investigations of flow and dispersion around a cube in the EnFlo wind tunnel under stable stratification (with Monin-Obukhov lengths either larger or smaller than the building height, 100 mm). Velocity measurements were performed by means of laser Doppler anemometry (LDA) downstream of the building recirculation region. Streamwise and vertical velocity fluctuations showed very little dependence on stability and also the Reynolds stress showed no significant variation (not supporting the hypothesis by e.g. Zhang et al., 1996). Ground level pollutant release, detected by a fast-flame ionization detector (FFID), was found to produce a narrower plume in the most stable case, but still fitting the Gaussian plume formula.

Finally, a cube was also taken into account by Yassin (2013) and the rooftop emission from a stack evaluated under different stability conditions in a $10 \times 1.0 \times 1.2$ m wind tunnel. The BLs were artificially thickened by means of Irwin’s spires, achieving a depth of $5H$. The level of stability achieved was quite weak, quantified in a $Ri_H$ of 0.023 and $-0.016$ for the SBL and CBL cases, respectively. Velocity and temperature measurements were performed with a split film and a cold-wire simultaneously. Pollutant measurements were acquired separately with a FFID. They found an increment in the vertical velocity in the near wake of the cube in case of stable stratification, a reduction in case of unstable. Concentration was found increased below roof height under stable stratification and reduced under unstable, even though the scatter in the data was quite high and differences were small, likely due to the very weak stratification level.

### 2.5.2 Array of buildings

The paper by Uehara et al. (2000) is one of the most cited experimental works on thermal stratification, thanks also to the wide range of stability levels which were tested. It deals with an array of aligned cubes (100 mm) placed in the test section of a $24 \times 3 \times 2$ m meteorological wind tunnel. Stratification (ranging from $Ri_H = -0.21$ to 0.79) was achieved by means of heating/cooling the floor and uniformly heating the inlet air temperature. LDA coupled with a cold-wire were employed to measure velocity and temperature. Measurements were all performed scanning the central vertical cross-section downstream a cube up to $z/H$ equal 1.5, while a single vertical profile extended up to $7H$ (boundary layer top). The aerodynamic roughness length was about $0.1H$ and displacement height $0.64H$, almost invariant with stratification (despite the quite large $Ri_H$ achieved). SBL was found to reduce the velocity inside and above the canopy, until the point in which real stagnation regions formed in the bottom (for $Ri_H$ larger than 0.4), hence altering the entire cavity eddy. Conversely, CBL was found to have opposite effects, strengthening the downward velocities and the reverse flow in the canopy. This resulted in vertical mixing which reduced the temperature difference, hence weakening the buoyancy effects. Shear stresses and turbulence in the canopy were found largely
sensitive to stratification, with such effects extending also to the internal boundary layer (IBL) forming over the canopy (estimated to reach a height of $2.5H$). It should be stressed here that, due to the three-dimensional geometry, strong 3D lateral effects are expected, which are not considered in that work. In fact, the geometry can hardly be considered a street canyon, even though these results were widely used to validate bi-dimensional street canyon simulations.

Another very interesting work is the one conducted by Kanda and Yamao (2016) with a staggered array of cubes (with height either equal to the base edge or double this length). The same wind tunnel as in Uehara et al. (2000) was employed to simulate both a SBL and a CBL ($Ri_\delta = 0.21$ and $-0.27$, respectively), tested against NBL. Velocity and heat fluxes were acquired with a three-component LDA coupled with a cold-wire for only a single vertical profile on the canopy. Concentration measurements were also performed separately with a FID (sampling rate 1 Hz) from a ground level passive point source release. The analysis of the velocity and temperature statistics revealed how the flow was stratified also inside the canopy, determining a sensible reduction of turbulence in case of SBL and an increment for CBL. A CFL region was identified above the canopy, whose extension was increased in case of CBL, but insensitive to the different canopy heights. Concentration measurements revealed a clear stratification effect even close to the source (two base edges downstream). The plume depth and width were found affected by stratification, both these parameters were smaller in the SBL case and larger in the CBL one, compared to the NBL reference. In particular, for the SBL the plume width variation was larger than the plume depth modification compared to the NBL case. Moreover, for the cubes the ratio of the maximum concentration value along the plume centreline in the stratified cases compared to NBL was found to vary monotonically with the longitudinal distance from the source. Conversely, for the taller canopy the ratio was rather constant. Pollutant fluctuations were not acquired due to the low sampling frequency of the employed measurement technique (the same can be said for the pollutant fluxes).

Allegrini (2018) considered a generic urban area consisting of four 3D street canyons, which were formed by 25 buildings and surrounded by other 17 buildings, most of them rectangularly shaped and with the same height. The ground inside one of the canyons was heated and the effect of buoyancy investigated by means of particle image velocimetry (PIV) in wind tunnel. Fig. 2.6 shows the contour plots of the velocity on a vertical and lateral cross-section. The heated case presented completely different lateral flow patterns, which affected also the vertical one, destroying the typical single vortex structure observed in the isothermal case (Fig. 2.6a). Their results highlight how the buoyancy can act increasing the three-dimensionality of a flow. It is important to note that this result differs from the ones typically obtained for 2D canyons (presented in the next section), in which the ground heating does not modify strongly the single vortex structure. Allegrini (2018) also investigated cases with different roof shapes and
heights, as well as different lengths of the street canyon buildings. In all the cases significant modifications in the flow were observed.

Quite a few studies investigated array of buildings with buoyancy forces employing the large-eddy simulation (LES) technique. In the following the most significant will be introduced. Inagaki et al. (2012) simulated a full-height daytime CBL over a square array of aligned cubes with imposed ground and roof heat flux. They showed that the turbulent organized structures above the canopy are correlated to the strong upward motion that occurs within the cavity of the arrays. In particular, they classified the instantaneous flow patterns in the cavity as flushing and cavity eddy events, with the former being related to strong upwards motion and the latter characterised by a prevalent vortical motion in a single cavity. Flushing events appeared to occur frequently below low-speed fluid streak regions.

A similar geometry and methodology was also considered by Park and Baik (2013), with the difference that the CBL was developed by means of setting a fix ground temperature (larger than the air above) and compared with no heating case, with the focus on the thermal effects on turbulent coherent structures. The model was validated with Uehara et al. (2000)'s results only considering mean streamwise velocity and temperature. In the no-heating case, streamwise-elongated structures characterised by a low-speed region appeared above the building array. In the bottom-heating case, also plume-shaped structured appeared together with the streamwise-elongated structures determining an increment in the magnitude of vertical turbulent momentum flux, partly due to ejections.

A staggered array of cubes was studied by Xie et al. (2013). Mean velocity and turbulent statistics were set at the inlet with a turbulence generator (see Xie et al., 2013 for more details) while the surfaces were adiabatic. For the stratified cases the same turbulence setting employed for the neutral were maintained, with the justification that only weak stratification was considered. For the stratified cases, different profiles of inlet mean and fluctuating temperature were tested and did not show significant differences, provided that the same $Ri_H$ was matched. The latter ranged from $-0.2$ to $0.2$. Results showed that the velocity fluctuation field was expected to differ more from neutral conditions in the case of CBL, while in case of SBL the block size dominated the turbulent flow as in the NBL. Also a realistic geometry was considered in this study but it will not be discussed here.

A similar geometry was investigated by Boppana et al. (2014), but in this case the stratification was achieved by means of setting a constant either positive or negative heat flux on the bottom surface. They found the turbulence intensity being significantly affected by ground heating and cooling. The turbulent integral length scales from the two-point spatial correlations were observed to be reduced in both streamwise and vertical directions by stable stratification.
Fig. 2.6 Contour plots of mean streamwise velocity and streamlines for a 3D street canyon. Vertical cross-section for $y/H = 0$ (upper panel) and lateral cross-section at $z/H = 0.5$ (lower panel) with and without ground heating (indicated in red). Free-stream wind direction is from left to right. Adapted from Allegrini (2018).
when compared to the neutral case, while in case of ground heating only the vertical integral length scale was found to be increased.

Tomas et al. (2016) simulated the effect of stable stratification on flow and dispersion from a line source over an array of aligned cubes. They found that under weakly SBL ($Ri_δ = 0.15$) the depth of the IBL after 24 rows of cubes was 14% shallower compared to NBL, while the TKE was reduced by 21%. On the other hand, the area-averaged street concentration level in SBL was found to be 17% larger than for the NBL thanks to the decreased streamwise advection and pollutant trapping in the IBL. It should be noted, though, that they simulated an approaching-flow with smooth-wall properties, hence not representative of a rural boundary layer. Moreover, the linear source is expected to be less sensitive to stratification effects than a point source, allowing only variations in the vertical plume depth.

Shen et al. (2017) simulated a SBL developing over an array of align cubes. Their model was validated using results from Kanda and Yamao (2016). Different plan area densities $λ_p$ were investigated, ranging from isolated roughness to skimming flow (namely, $λ_p$ from 0.007 to 0.25, respectively). A point source ground level pollutant release was also considered. Results showed that the reduced advection velocity in the SBL is the cause for the larger concentration in the canopy. In areas with large $λ_p$ the leeward wall recirculation tends to trap the pollutant in the canopy, increasing the pollutant mixing. Moreover, the SBL appeared to suppress concentration fluctuations (normalised by the mean concentration).

Jiang and Yoshie (2018) employed the same array of align cubes but with a weak CBL case ($Ri_H = −0.15$, based on the velocity and temperature at roof height) and a linear source. The simulation was validated against wind tunnel results. In the experiments the CBL was obtained just by means of heating the floor with no spires in the inlet (the resulting BL depth was limited to about 4 building heights). The measuring set-up consisted of a split film, cold-wire and FFID, as described by Yoshie et al. (2007). LES results showed that a primary recirculation region was formed inside the canopy, similar to the one observed in bi-dimensional street canyons (see e.g. Cheng and Liu, 2011b in this regard). The turbulent pollutant fluxes were found to considerably contribute to the pollutant transportation, especially for the pollutant inflow rate at the side canyon surfaces and for outflow rate at the top. However, turbulence was observed to have almost no contribution to the pollutant inflow rate for the top surface.

Nazarian and Kleissl (2016) and Nazarian et al. (2018) considered an array of aligned cubes and rectangular buildings, respectively. Conversely from most of the literature, here a case with realistic non-uniform heating of all the surfaces was investigated. They stressed the importance of considering a three-dimensional heating for studies of thermal comfort, for which they supported the introduction of two different Richardson numbers, one based on the vertical gradient of temperature, the second on the horizontal one. From a flow field point of
view they observed the insurgence of significant modifications only in the larger Richardson cases ($Ri_H \approx -0.21$). But their most interesting conclusion is that the concentration field was mainly affected by the overall heating of the surfaces and a detailed three-dimensional heating was found superfluous in this regard.

Finally, Sessa et al. (2018) employed the dataset produced in the present study to validate their LES simulation for a rectangular array of blocks with different levels of SBL (ranging from $Ri_\delta 0.21$ to 1.0). Pollutant release from either a linear or a point source was also modelled. Mean velocity, Reynolds stresses and mean concentrations were in good agreement with the wind tunnel experiments. The mean concentration below the canopy in case of line source for $Ri_H = 1$ was twice as large as the one for $Ri_H = 0.2$, while for the same stratification cases the concentration from the point source was four times larger. This was partially attributed to contemporary decrease of both lateral and vertical scalar spreading in the case of point source release. The vertical turbulent fluxes from the line source release in several streamwise locations confirmed the decrease of the vertical scalar mixing for increasing stratification. Finally, they also observed a reduction with increasing stratification of the height where the vertical flux became negligible.

### 2.5.3 Bi-dimensional street canyon

#### Effect of stable stratification

Throughout these sub-sections, if not otherwise specified, the employed geometry is a bi-dimensional street canyon with AR of one.

To the knowledge of the author no laboratory experiments have been undertaken on this topic, while only two detailed LES numerical works can be listed.

Cheng and Liu (2011b) simulated a street canyon in which buoyancy was achieved by setting a constant temperature on the ground surface. The domain was formed by three consecutive street canyons with cyclic boundary conditions employed in the horizontal directions for the flow and temperature, but only in the lateral direction for the pollutant. The latter was released from the entire ground surface by imposing there the concentration value. By varying the stable stratification from $Ri_H 0$ to 0.35 they found a persistence of the skimming flow pattern, characterised by the presence of a main large vortex with air descending into the canyon along the windward wall and raising up along the leeward. Despite this, the mean flow was strongly suppressed at the ground-level leeward corner. A layer of stagnant air formed locally, isolated from the primary recirculation. This calm region enlarged the very slow secondary recirculation at the ground-level leeward corner, hence modifying the characteristic flow pattern significantly. At the ground level also the turbulence was found strongly suppressed by stable stratification,
while a slight turbulence enhancement was observed at the core and upper windward regions. This was explained as a consequence of the increased vertical velocity gradient at the roof-level and the decelerating primary recirculation. Finally, the pollutant concentration was found significantly increased at ground level due to the local reduction in mean flows and turbulence, while in the canyon region above the increment was smaller. Turbulent and mean pollutant fluxes appeared noticeably reduced by stratification.

Also Li et al. (2016) considered periodical boundary conditions for the air flow in the streamwise and spanwise directions, but in a smaller domain (of size $2H \times H \times 4H$) including only one canyon. The air temperature at the top of the domain and at the bottom was fixed and the difference determined the stratification (equivalent to $Ri_H 0, 0.1, \text{and } 0.188$). Pollutant was here released from a line source at the centre of the canyon. They reported effects on the mean velocity similar to what found by Cheng and Liu (2011b), highlighting the reduction in the updraft and downdraft close to the walls, as well as the appearing of a stagnant region near the street level decoupled from the main vortex. This changing, together with the reduced turbulence, caused the pollutant to pool, with half of the mass emitted by the source being trapped in the lower 15% of the canyon for the larger $Ri_H$. They also reported the appearing of a negative turbulent vertical pollutant flux region close to the leeward wall, that contributed to the worse ventilation properties experienced in the SBL case compared to NBL.

**Effect of unstable stratification: ground heating**

Allegrini et al. (2013) performed wind tunnel experimentation on a 2D isolated cavity. For the approaching flow no artificial thickening was employed, while a PIV technique was used to acquire the flow field in the cross-section. Different heating configurations were investigated, windward wall heated, leeward wall heated, ground heated, and all the three surfaces heated. Stratification was varied by changing either the wall temperature or the free-stream velocity (obtaining Froude numbers from 0.7 to 17), while the incoming flow remained neutral and without artificial thickening devices. Ground heating was found to be responsible for an increment in the street canyon velocity (the largest among the investigated configurations), caused by buoyancy that accelerates the flow. The acceleration takes place in particular at the leeward wall, where the heated air starts rising. The TKE was increased as well, especially at the bottom corner of the windward wall, since there buoyancy is acting against the main flow direction. Data produced in these experiments were used later by Allegrini et al. (2014) to validate RANS simulations on the same cases. They highlighted that CFD can be useful to predict flows in buoyant urban street canyons, capturing the general flow structure. However, they pointed out that more detailed validation studies are needed to analyse the detailed flow structures with measures of the heat fluxes at least in the top plane of the street canyon.
2.5 Buoyancy effects on flow and dispersion in idealised urban geometries

Li et al. (2010) investigated the case of ground heating with linear pollutant source by means of LES simulations. The domain was very small, being limited to $2H \times H \times 2H$. Despite this, interesting results were obtained by varying the ground temperature to get $Ri_H$ ranging from $0$ down to $-2.4$. Despite the flow pattern being mainly unaltered, both the streamwise flow near the ground and at roof-level were accelerated up to 5 times. The same can be said for the updraft and downdraft near the canyon walls, for which ground heating was found to increase particularly the first. As far as the turbulence increment is concerned, it was found mostly located near the shear layer at roof-level. The pollutant concentration patterns, similarly to the mean flow, were not significantly altered by ground heating, but averaged concentrations in the canopy were found reduced by up to 10% (and increased above). Finally, a region of larger turbulent vertical pollutant flux was identified close to the leeward wall, responsible for part of the ventilation improvement (as shown in Fig. 2.7).

Li et al. (2012) further extended the results by Li et al. (2010) by considering different AR (0.5, 1, 2). For the two new configurations ground heating was found to modify more the mean flow and concentration pattern compared to what observed for the unity AR case. Li et al. (2016) considered ground heating, in addiction to the ground cooling case previously presented. Results were similar to what described by Li et al. (2010). However, here also the quadrant analysis was mentioned (see Appx. C), observing how in the case of ground heating pollutant ejections are increased at the expense of sweeps, respect the isothermal case.

Cheng and Liu (2011b) also simulated ground heating cases, with $Ri_H$ of $-0.06$ and $-0.11$. Similarly to Li et al. (2010), they too reported no significant modifications compared to the isothermal case in the flow pattern, despite an increment in the velocity values. A monotonic increase in the turbulence by enhancing the ground heating was also observed. As for pollutant
removal, despite an increase compared to the isothermal case, the vertical pollutant flux structure appeared unchanged, with mean fluxes dominating in the canopy and turbulent ones at roof level. Turbulent fluxes in the canopy were found concentrated towards the windward wall, the opposite than what reported by Li et al., 2010. Part of this might be due to the different source type modelled (linear and located at the centre of the canyon for Li et al., 2010, a release from the entire street surface for Cheng and Liu, 2011b). For what concerns the mean concentration, it was observed being well-mixed in the canopy and lowered compared to the neutral case.

Park et al. (2012) conducted LES simulation on the effect of differential walls and ground heating with $Ri_H = 2.5$. As previous authors, they found the flow pattern with ground heating unchanged with respect to the isothermal case. TKE profiles only at the vertical centreline of the canyon are reported. The ground heated case was the one which produced the largest intermittency and TKE in the canopy, compared with the wall heated cases, with the maximum value found at half the canyon height. Above the canopy all the TKE values are enhanced compared to the isothermal case up to the top of the domain. This is likely due to the cyclic boundary conditions employed which contribute to develop an almost unstable BL. Vertical profiles of vertical heat and pollutant flux are also given at the canyon centreline, the latter emitted from the entire ground surface. Both the fluxes are found to peak at roof level, with a second maximum close to the bottom due to the fluctuations near the scalar source (considering as scalar both heat and pollutant). The effect of the heating on the turbulence structure was also considered by means of quadrant analysis. Bottom heating was found to increase significantly ejections contributions over sweeps on the momentum flux at roof level, while the opposite was observed in the roughness sub-layer region (at $2.5H$).

Effect of differential wall heating: leeward wall heated

Allegrini et al. (2013) found the leeward wall heated case strengthening the main vortex, without changing the pattern. The velocities were lower than in the ground heated case since the residence time in the canyon of the hot air was shorter (smaller distance between heated surface and canyon top). The TKE was also increased, but since buoyancy acted in the same direction of the flow, this increment was less accentuated than in the other cases. Moreover, larger values of TKE were found close to the windward wall, despite the fact that only the opposite wall was heated.

Cai (2012b) performed LES simulations with roofs and either leeward or windward wall heated, with $Ri_H$ ranging from $-0.14$ to $-2.14$, obtained by setting a fixed temperature on the surfaces. For the leeward wall heating case the flow pattern was found nearly symmetrical about the canyon vertical centreline, with a small secondary vortex located on the windward wall lower corner only. The influence of the heated wall was also found on the flow above
the canopy, with the main vortex extending now to this region as well. As far as the TKE is concerned, Cai (2012b) found that the heated wall did not contribute to increase the turbulence in its vicinity (as also noted by Allegrini et al., 2013). The TKE increased linearly with an increment of the wall temperature. The warming effect on the temperature in the canyon was found mostly confined in a narrow region around the heated wall. On average, the heating in the canopy was smaller than in the windward wall heated case. In fact, since the temperature fluctuations were advected more above the roof and little was entrained into the canyon.

Cai (2012a) extended further the investigation by including a scalar release from either the street surface or the building walls to the cases previously illustrated. In Fig. 2.8 the contour graphs obtained for the mean concentration are reported. For the leeward wall heated case Cai (2012a) found that the plume was mainly influenced by the primary vortex. Mean vertical pollutant fluxes dominated in the canopy for $z/H$ between 0.2 and 0.9, while closer to the source on the ground and at roof level the turbulent component was found determinant.

Park et al. (2012) found the flow in the leeward wall heated case faster than the other configurations (conversely from what observed by Allegrini et al., 2013). Also the vertical velocity above was found enhanced due to buoyant mixing, with the flow pattern extending slightly above the canyon (as also noted by Cai, 2012b). The maximum TKE was found at roof level with a sharp increment, attributed to the activity of the turbulent eddies, mainly generated by shear instability, more than buoyancy forces. The maximum for the heat flux along vertical canyon centreline was observed above the canopy (at around $1.2H$), coherently with the fact that the major part of the heat vacated rapidly the canopy, while inside only a very

![Fig. 2.8 Mean concentration field of the scalar released from the street surface (where unity concentration was imposed) for either leeward (a) or windward (b) wall heating (building roof is heated as well). Free-stream wind direction is from left to right. LES simulation from Cai (2012a).](image-url)
small percentage of the heat flux was observed. At the same location also the maximum for the pollutant flux was found.

**Effect of differential wall heating: windward wall heated**

Allegrini et al. (2013) for the windward wall heated case observed the formation of a counter-rotating vortex along the heated wall which increases its dimensions with the stratification level. The shape of this flow pattern, though, was quite singular (not found in other works) and appeared to change strongly with the stratification level. This behaviour may have been influenced by the fact that the approaching flow was not realistic (no thickening was employed) and by the choice of a cavity as geometry. The largest TKE values were found at the upper windward corner where the cold air enters the canyon, hitting the warmer air, which is rising due to buoyancy at the windward wall.

Kovar-Panskus et al. (2002) performed experiments on a 2D cavity with heated windward wall, as well. Velocity was acquired with LDA and temperature with thermocouples. The stratification ranged from Froude numbers of 0.3 to 2. The flow pattern was found affected by the heating, causing a reduction of the mean velocity, the latter, though, not showing signs of updrafts rising close to the heated wall. Streamlines presented a winding pattern, but this aspect was not commented further. The TKE was found to peak at the upper windward building corner for the weakest stratification case, the location moving down along the windward wall increasing the heating. The maximum temperature was found close to the windward heated wall, at a height depending on the level of stratification (higher for stronger stratification).

For the windward heated wall Cai (2012b) found a counter-rotating secondary vortex developing. As result the main vortex centre appeared shifted towards the windward upper corner. The TKE was increased along the heated wall due to the interaction between the main vortex and the thermally driven updrafts. Such increment was found to depend linearly on the wall temperature (as for the leeward wall heating case). This case was also found more efficient in heating the air inside the canopy than the leeward case. Cai (2012a) found that the concentration plume (Fig. 2.8) was largely influenced by the stronger vertical turbulent dispersion, also due to the weakened primary circulation. In the canopy the vertical turbulent pollutant flux was comparable or larger than the mean one. The total flux was also observed to be smaller than in the leeward wall heating case. Despite this, averaged concentration in the canopy were 22% lower. Concentration fluctuations in the canopy were found to be up to 50% the mean concentration value, more than for the leeward heating case.

Park et al. (2012) found the primary vortex shrunk, with a winding flow appearing between this vortex and the windward wall. They attributed this phenomenon to the opposite action of mechanical and thermal forcing. Mean velocity was strongly damped by the buoyancy. The
TKE at the canyon vertical centreline was found to monotonically increase with the height up to the roof level. Heat flux peaked at roof level, but were heavily reduced compared to the other cases due to the modified flow pattern. Turbulent pollutant flux peaked at a height of $0.2H$ along the canyon centreline and not at rooftop, since at roof the shear was weak as result, again, of the modified flow pattern. From results of the quadrant analysis on the momentum flux, in this case ejections and sweeps were found to contribute in a similar amount at roof level.

Very recently, Chew et al. (2018) performed RANS and LES simulations on street canyon at full and reduced scale in isothermal and windward wall heated thermal conditions. They observed that the flow field remained similar varying the Reynolds number from $10^4$ to $10^6$ (by varying the scale of the model) in the isothermal case, hence confirming the Reynolds number independence. At the same time, though, for the wall heated case at the two scales with different Reynolds but matching the Richardson number they observed significant buoyancy effects only in the lower Reynolds number case with LES simulation, while RANS continued to predict significant effects in both the scales. They concluded that a non-isothermal case may not be Reynolds number independent, even though the isothermal is, and suggested to be careful in extending conclusions obtained with reduced scale model to the full scale case. They also concluded that RANS may be not suitable to simulate buoyant flow at full scale.

**Effect of heating all cavity surfaces**

Allegrini et al. (2013) also considered the case where all the internal surfaces (windward, leeward wall and ground) were heated at the same temperature. This resulted in a strengthening of the main vortex, but with lower velocities compared to the leeward wall or ground heating alone, since in this case the windward wall heating contributed opposing the flow. The TKE registered in the canopy was the largest since more heat was provided, causing stronger buoyancy effects. TKE largest values were found close to the windward wall. A mass imbalance was observed in this case analysing the vertical velocities. As possible explanation they mentioned the air density differences or possible 3D flows with components out of the cross-section plane. Temperatures were also measured with larger values found close to the heated walls.

Tabs. 2.4 and 2.5 list all the experimental and numerical studies reviewed in this section.
## 2.5 Buoyancy effects on flow and dispersion in idealised urban geometries

Table 2.4 List of experimental studies on buoyancy effects with idealised urban models. “WiTu” is for wind tunnel, while “WaTa” for water tank.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Facility</th>
<th>Incoming BL</th>
<th>Local heat</th>
<th>Dispers.</th>
<th>Model geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snyder (1994)</td>
<td>WaTa</td>
<td></td>
<td></td>
<td>X</td>
<td>Single cube</td>
</tr>
<tr>
<td>Yassin (2013)</td>
<td>WiTu</td>
<td></td>
<td></td>
<td>X</td>
<td>Single cube</td>
</tr>
<tr>
<td>Uehara et al. (2000)</td>
<td>WiTu</td>
<td></td>
<td></td>
<td>X</td>
<td>Aligned cubes</td>
</tr>
<tr>
<td>Kanda and Yamao (2016)</td>
<td>WiTu</td>
<td></td>
<td></td>
<td>X</td>
<td>Staggered cubes</td>
</tr>
<tr>
<td>Allegrini (2018)</td>
<td>WiTu</td>
<td></td>
<td></td>
<td>X</td>
<td>3D canyons AR 1</td>
</tr>
<tr>
<td>Allegrini et al. (2013)</td>
<td>WiTu</td>
<td></td>
<td></td>
<td>X</td>
<td>2D cavity AR 1</td>
</tr>
<tr>
<td>Kovar-Panskus et al. (2002)</td>
<td>WiTu</td>
<td></td>
<td></td>
<td>X</td>
<td>2D cavity AR 1</td>
</tr>
</tbody>
</table>

Table 2.5 List of computational studies on buoyancy effects with idealised urban models. The cases of ground heating and incoming CBL are here not distinguished, since in many simulations periodical boundary conditions do not allow to distinguish them.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Method</th>
<th>Incoming BL</th>
<th>Wall heating</th>
<th>Dispers.</th>
<th>Model geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhang et al. (1996)</td>
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<td>X</td>
<td>X</td>
<td>Single cube</td>
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<tr>
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<td>X</td>
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<td></td>
<td>X</td>
<td></td>
<td>Aligned cubes</td>
</tr>
<tr>
<td>Park and Baik (2013)</td>
<td>LES</td>
<td></td>
<td>X</td>
<td></td>
<td>Aligned cubes</td>
</tr>
<tr>
<td>Xie et al. (2013)</td>
<td>LES</td>
<td>X X</td>
<td>X</td>
<td>X</td>
<td>Staggered cubes</td>
</tr>
<tr>
<td>Boppana et al. (2014)</td>
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<td></td>
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</tr>
<tr>
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<td>X</td>
<td>Aligned cubes</td>
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<td>X X</td>
<td>X</td>
<td>Aligned cubes</td>
</tr>
<tr>
<td>Jiang and Yoshi (2018)</td>
<td>LES</td>
<td></td>
<td>X</td>
<td>X</td>
<td>Aligned cubes</td>
</tr>
<tr>
<td>Nazarian and Kleissl (2016)</td>
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<td>X X</td>
<td>X X</td>
<td>X</td>
<td>Aligned rectangular blocks</td>
</tr>
<tr>
<td>Nazarian et al. (2018)</td>
<td>LES</td>
<td></td>
<td>X X</td>
<td>X X</td>
<td>Aligned rectangular blocks</td>
</tr>
<tr>
<td>Sesso et al. (2018)</td>
<td>LES</td>
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<td>X</td>
<td></td>
<td>2D canyon AR 1</td>
</tr>
<tr>
<td>Cheng and Liu (2011b)</td>
<td>LES</td>
<td></td>
<td>X X</td>
<td>X</td>
<td>2D canyon AR 1</td>
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<tr>
<td>Li et al. (2016)</td>
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<td>Li et al. (2010)</td>
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<td>X</td>
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<td>X</td>
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<tr>
<td>Park et al. (2012)</td>
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<td></td>
<td>X X</td>
<td>X</td>
<td>2D canyon AR 1</td>
</tr>
<tr>
<td>Cai (2012a)</td>
<td>LES</td>
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<td>X</td>
<td>X X</td>
<td>2D canyon AR 1</td>
</tr>
<tr>
<td>Cai (2012b)</td>
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<td>X</td>
<td>X X</td>
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<td>Chew et al. (2018)</td>
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<td></td>
<td>X X</td>
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<td>2D canyon AR 1</td>
</tr>
</tbody>
</table>
2.6 Literature review: summary and final remarks

2.6.1 Physical simulation of non-neutrally stratified boundary layers

Few works can be found in the literature about wind tunnel simulations of non-neutrally stratified ABLs, mostly due to the scarcity of suitable facilities and the high cost of the experiments. Among these studies, the majority do not consider the use of artificial thickening devices, or just employ simpler devices (like fences or blocks) and this results in horizontally evolving shallow BLs. Such BLs are not suitable for dispersion studies with urban models, since the BL depth would be too similar to the building height.

In the stable stratification case, a systematic study of the effect of upstream conditions (e.g. inlet temperature profiles) has been performed by Hancock and Hayden (2018), also employing spires, for low roughness offshore cases. High roughness conditions (suitable for urban boundary layers) have not been attempted yet and further study is necessary as a common experimental practice is not defined. The same can be said for CBLs, where Ohya’s and Fedorovich’s studies focussed more on simulating the overlying inversion than the surface and mixed layers. Hancock et al. (2013), again, provided interesting solutions for the simulation of artificially thickened CBLs but such methodology needs to be verified for higher roughness conditions.

2.6.2 Atmospheric stratification and buoyancy effects on aerodynamics and dispersion properties in the urban environment

The literature review analysed the major publications dealing with the simulation of buoyancy effects in idealised urban geometry. From the experimental point of view, only a very limited amount of studies have been attempted so far.

The case of stable and unstable incoming flow over either an aligned or staggered array of cubes has been investigated by Uehara et al. (2000) and Kanda and Yamao (2016), respectively. The former focused on a cross section downstream a block, with just one vertical profile scanning the entire boundary layer depth. Moreover, neither heat fluxes nor pollutant concentration measurements were attempted. Kanda and Yamao (2016) expanded further with measurements of heat fluxes and mean concentration for a point source release. But still only one full-height vertical profile was acquired and no concentration fluctuations and fluxes were sampled. Moreover, only one stable and one unstable case were considered. The concentration and turbulence measurements in and above the canopy revealed important effects of the stratification, encouraging further studies in this direction.
As far as the effect of local heating are concerned, the 2D cavity case has been investigated by Kovar-Panskus et al. (2002), considering only the windward wall heating, while Allegrini et al. (2013) extended the cases by including also the leeward wall and the ground heating. Moreover, only Kovar-Panskus et al. (2002) employed thickening devices and roughness elements to realistically shape the incoming flow, but none of the them considered a non-neutrally stratified approaching flow or attempted tracer concentration measurements. In both studies, only velocity fluctuations were sampled, while only mean temperatures were shown.

More efforts have been made in computational studies and different works have been produced so far, in particular in recent years. LES can provide a detailed insight in the turbulence and dispersion phenomena, but can produce reliable results only if properly validated. Allegrini et al. (2014) in this regard pointed out that “to analyse the detailed flow structures and heat fluxes a validation study with more detailed temperature and flow measurements at the top plane of the street canyon needs to be conducted”. The lack of extensive experimental data is hence an issue that needs to be solved to better understand the importance and the effects of thermal stratification on urban ventilation and pollutant dispersion.
Chapter 3

Methods

3.1 Introduction

In this chapter the equipment and techniques used to perform the experiments, as well as the choice of the urban models, will be discussed, starting from a description of the EnFlo meteorological wind tunnel and continuing with a general presentation of the acquisition and instrumentation systems employed to record the data. A section is dedicated to the flow generator design. The measurement set-ups for each experimental campaign are better detailed in a final section.

3.2 EnFlo wind tunnel

The EnFlo meteorological wind tunnel was employed to perform the flow measurements (Fig. 3.1). It is a suck-down open-circuit wind tunnel with a test-section 20 m long, 3.5 m wide and 1.5 m high. By means of two side-by-side fans, the flow speed can be varied in the range 0.3-2.5 m/s.

Three different coordinate systems were employed throughout all the work. For the boundary layer generation part (Ch. 4) the x-axis was in the streamwise direction, measured from the working-section inlet; the y-axis was in the lateral direction, measured from the wind tunnel centreline; the z-axis represented the vertical, starting from the floor. In the experiments over the building array (Ch. 5) two measuring systems were introduced. The first, called “wind tunnel coordinate system”, was aligned with the previous one, but with the origin of the x-axis moved to 14 m from the inlet, at the centre of the turntable used to rotate the urban model. The second, called “model coordinate system” was integral with the turntable, so that when the latter was rotated with respect to the wind direction, the model system was rotated by the
3.2 EnFlo wind tunnel

same angle along the \( z \)-axis. Note that in Ch. 5, in order to distinguish between tunnel and model coordinate system, the former horizontal axes were indicated as “\( x_T, y_T \)”.

Finally, for the part involving the street canyon model (Ch. 6), only the “wind tunnel coordinate system” was employed.

An ultrasonic anemometer was employed in order to provide a reference velocity as input for the closed-loop wind tunnel speed control system; it was placed 5 m from the inlet section, 1 m on the side of the centreline, 1 m from the floor.

A series of 15 vertically stacked heaters at the inlet section allowed the generation of a gradient of temperature that, combined with the floor cooling/heating system, created the different atmospheric types of stabilities.

The temperature immediately downstream of the inlet section heaters was measured by thermistors and sent to the laboratory control system that managed the heaters input power in a closed-loop. Temperature deviation from the nominal values were of the order of \( \pm 0.05^\circ \text{C} \) during the experiments. The laboratory temperature was also kept constant to get a uniform inlet flow and to simplify instrument calibration. For these reasons, water cooled heat exchangers refrigerated the air leaving the test section. The flow uniformity across the inlet was also enhanced by a series of fans placed on the laboratory ceiling and a system of pipes, whose purpose was to mix the air and reduce the natural stratification formed in the laboratory.
3.3 Acquisition system and data analysis

(differences of temperature between floor and ceiling up to 1°C were normally recorded with the fans in action).

The floor could be heated, cooled or left at environment temperature so that, in conjunction with the inlet heaters, a convective, stable or neutral boundary layer could be generated, respectively. To reduce the temperature of the floor, water cooled heat exchangers were employed (only the central 3 m were actually cooled). Fresh water from the laboratory chilled water supply (usually at 10°C) was mixed with the recirculating water in the pipes in order to control the temperature. However, due to a failure of the chilled water supply system, during part of the CBL experiments over the array of buildings (Ch. 5), the laboratory temperature was cooled by means of cold air injected from outside directly into the laboratory and then extracted by means of fans. In this abnormal operating condition, the laboratory temperature was less uniform (differences of temperature between floor and ceiling up to 2.5°C were recorded), but still deemed acceptable.

The equipment for floor heating included a series of 2.0 kW/m² electrically heated mats. They were 2.95 m long and 0.33 m wide. Different arrangement were tested in order to find the one which guaranteed the best lateral uniformity for flow velocity and temperature, as it will be explained in Ch. 4. The temperature of three adjacent panels was measured by a thermistor and used as input for control purpose by the laboratory software. Thermal conductive paste was employed to improve the contact between thermistor and panel. Moreover, 20 mm thick insulating panels were added between the floor and the heater mats in order to increase their temperature uniformity and reduce heat dispersion. An automated traverse system allowed three-dimensional movements of measurement equipment in the wind tunnel (Fig. 3.2). It had a range of about 10 m, 2.0 m and 1.0 m in $x$, $y$ and $z$ respectively (taking into account the cables limitations of measurement instrumentation).

A series of small fans was installed on the traverse, in order to accelerate the air above at the velocity it would have had without any traverse, with the purpose of reducing the blockage. The fans speed was adjusted to provide a vertical flow velocity profile as constant (and close to zero) as possible upstream and beneath the traverse.

3.3 Acquisition system and data analysis

3.3.1 Introduction

Data acquisition, experimental control of the entire facility and some of the data analysis were performed by means of LabVIEW-based software developed by the EnFlo laboratory staff. For the rest of data analysis and post-processing, a MATLAB® code was developed.
Velocity measurements were performed with a laser Doppler anemometry (LDA) system, while a cold-wire temperature probe was employed to measure the fluctuating and mean temperature. A double thermistor rake made of two series of 16 sensors each was employed in the CBL study in order to acquire the temperature field in the section. The rake was held by the traverse 600 mm downstream of the measuring point and the rake arms were, respectively, 580 mm on the left side (towards the negative y-axis and so called “Y-ve”) and 430 mm on the right side (called “Y+ve”). They were separated by a lateral distance of 1010 mm. It spanned a height from 50 mm to 1350 mm (Fig. 3.3) and its acquisition rate was 0.5 Hz. Finally, concentration measurements were performed by means of a fast flame ionisation detector (FFID). The measuring set-up constituted by the LDA, cold-wire and FFID probes allowed for the contemporary sampling of heat and pollutant fluxes. In the literature another technique was developed so far, which substitutes the LDA with a split film probe (a description can be found in Yoshie et al., 2007), hence eliminating the necessity of seeding the flow. However, the presence of a third physical probe in the measuring zone is deemed to increase the blockage and flow disturbance. Moreover, the hot wire needs appropriate calibration corrections in case of non-isothermal flows, which makes it more complex to use. The following sections will describe the employed techniques in more details.

Fig. 3.2 Traverse system
3.3 Acquisition system and data analysis

3.3.2 LDA measurements

An LDA technique was used for fluctuating and mean flow velocity measurements, allowing single-point sampling of two-velocity components. A COHERENT Genesis MX-STM laser with a 40 MHz frequency-shifted Bragg cell was employed. The green light had a wavelength equal to 513.6 nm while the blue was 488 nm. They were conveyed by means of a Dantec Dynamics 27 mm fiber-flow probe with a focal length of 160 or 300 mm. The resulting measuring volume had a diameter of 0.049 mm and was 1.051 mm long. A Dantec Dynamics F60 flow processor was used as burst spectrum analyser (BSA). The target acquisition frequency was 100 Hz for all the experiments, but variable depending on the seeding rate. The LDA technique, in fact, requires the presence of seeding particles. A sugar solution aerosol was employed, whose particles had nominal size of 1 µm in diameter. An ultrasonic mist generator placed above the wind tunnel generated the aerosol which filled the laboratory. The seeding rate was regulated according to the difference between the desired and measured LDA sampling rate.

For the spectral analysis of the LDA measurements, due to the non-uniform sample time, a re-sampling had to be performed. Farr (2014) found that the “sample and hold” method (where the closest sampled value to the re-sampling instants of time is selected) gave the best agreement with hot-wire anemometry in particular at higher frequencies, while the interpolation method (in which the measured samples are linearly interpolated in order to find the value for the re-sampling instants of time) produced the effect of a low-pass filter (Hancock and
3.3 Acquisition system and data analysis

Pascheke, 2014). For this reason the “sample and hold” method was chosen for all the spectral analysis.

### 3.3.3 Cold-wire measurements

To measure fluctuating and mean temperature in the measuring volume a high frequency cold-wire anemometer was employed. In order to calibrate the cold-wire, a thermistor was placed at the same height, but about 15 mm on the side. The cold-wire was a Dantec Dynamics (55P11) miniature wire probe, at which an analogue second order Butterworth low-pass filter was applied with a cut-off frequency of 250 Hz and a constant sampling rate of 1000 Hz. The large sampling frequency (compared to the LDA one) was dictated by the necessity to couple each time the velocity samples (with variable rate) to the closest temperature sample for the heat fluxes computation. The cold-wire was placed downstream of the LDA measuring volume to calculate heat fluxes. The separation between LDA measuring volume and cold-wire was needed to reduce the blockage on the velocity, but at the same time it produces a de-synchronisation of velocity and temperature measurements at a frequency depending on the separation magnitude and the flow velocity (hence acting as a low-pass filter). Such filtering can be considered acceptable if the energy associated with turbulent fluctuation for both temperature and velocity at larger frequencies is small compared to the resolved scales. Heist and Castro (1998) present a method for the use of a cold-wire in conjunction with an LDA and suggest a distance of 3 mm for the displacement between the two measurement volumes, as compromise between the reduction of probe interference and velocity/temperature correlation. In the present work distances variable from 4 to 5 mm were employed. Further details will be provided in the following sections, in which the particular measuring set-ups used for the different phases of the work will be described.

In all the CBL measurements a second thermistor was placed on the traverse 430 mm above the first one to measure the temperature in the region above 1 m where the traverse cannot reach. The same was done also for the experiments on the street canyon model (where only NBL and SBL were tested).

### 3.3.4 FFID measurements

A fast flame ionisation detector system (FFID) was employed for concentration measurements. FFID basic operating principles are described below, but more details can be found in Cheng et al. (1998).

In the employed set-up, flame ions are collected by an electrode negatively based at 150-200 V with respect to the burner, located below the electrode. A series of complex
3.3 Acquisition system and data analysis

reactions takes place throughout the measurement, whose general process can be represented by \( CH + O = CHO^+ + e^- \). For a given hydrocarbon, the current collected by the electrode is proportional to the hydrocarbon molar concentration and the sample volume flow rate through the detector. For the FFID technique, ethane or propane are usually employed as tracer gases (propane in our case). The pointwise sampling is directly made into the flame avoiding mixing process with the fuel, thus minimizing the transit time. In order to provide a constant mass flow to the FFID, a “ballast chamber” is employed, which maintains a nearly constant pressure (also known as a constant-pressure chamber). Tracer samples are sucked through a small diameter transfer tube (0.3 mm in this case), connected to a larger tube in the ballast chamber.

Calibration of the instrument is necessary and it is performed by introducing a mixture of gases with a series of known compositions into the sampling tube. The calibration was performed regularly during the experiments, roughly once every two hours. Measurements of the background propane concentration in the wind tunnel were regularly performed (every 20 minutes) as well, and the value was then subtracted to the measured concentration for each point. The temporal delay in the response of the FFID depends mainly on the length of the sampling tube and is a critical parameter if synchronization with the LDA is of interest. Further details on the measurement of this parameter will be given in the following sections for each set-up. The sampling rate was set equal to 1000 Hz for the same reason presented for the cold-wire (see previous paragraph).

The propane used as tracer was released in a mixture with air. The percentage of propane in the mixture was adjusted depending on the case, in order to avoid the saturation of the measurement. However, for safety reasons a maximum concentration of propane in the air of 1.8% was never exceeded.

3.3.5 MATLAB® post-processing code

A MATLAB® code was developed to analyse and post-process the wind tunnel data using TAB datafiles as input (produced by the Labview software of the lab). The code is suitable for both a first rapid data analysis and high-quality vectorial graph generation for publications. Its main features are:

- rapid generation of bi-dimensional graphs, including profiles and contour plots
- elevated graph customization capability, including \( \LaTeX \) language labels, plot of single and multiple vectorial graphs in a single file, full control of line style, legend, graph dimensions and axes normalisation
3.4 Flow generators

Spires were employed as boundary layer artificial-thickening devices, due to their simplicity and because they were already been extensively used in previous experiments in the EnFlo lab. Irwin’s spires are characterised by a triangular flat front plate, normal to the flow, with a splitter triangular plate on the downwind side. They are normally placed in a spanwise row immediately after the inlet section, as in Fig. 3.4.

![Fig. 3.4 Spires and roughness elements scheme (from Irwin, 1981)](image)

The design process for neutral stratification proposed by Irwin (1981) is based on a momentum balance and is centred around achieving the correct mean velocity profile, supported
3.4 Flow generators

by the experimental evidence that “once the correct mean velocity profile has been achieved, the turbulence intensity and scale tend to fall into line in comparison with full-scale data when using the spire-roughness technique” (Irwin, 1981). Hence, it starts by assigning a value to the desired boundary layer height \( \delta \) and power law coefficient \( \alpha \) (see Eq. 2.11). The height of the spire \( h_{sp} \) is then calculated with the empirical expression

\[
h_{sp} = \frac{1.39 \delta}{1 + \alpha/2}
\]  

(3.1)

while the base-to-height ratio \( b_{sp}/h_{sp} \) is obtained from the following expression, which was derived by assuming a spire lateral spacing of \( h_{sp}/2 \)

\[
b_{sp}/h_{sp} = 0.5 \frac{\psi H_{wt}/\delta}{1 + \psi} \left(1 + \frac{\alpha}{2}\right)
\]

(3.2)

where \( H_{wt} \) is the test section height and

\[
\psi = \beta \left[ \frac{2}{1 + 2\alpha} + \beta - \frac{1.13\alpha}{1 + \alpha} \left(1 + \frac{\alpha}{2}\right) \right] (1 - \beta)^{-2}
\]

(3.3)

\[
\beta = \frac{\delta}{H_{wt}} \frac{\alpha}{1 + \alpha}
\]

(3.4)

Neutral boundary layer spires

A set of five Irwin’s spires had extensively been used in the EnFlo laboratory for the generation of urban-like NBLs. For this reason it was decided to employ the same set in the present work for the neutral case. They were 1260 mm high, 170 mm wide at the base, spaced laterally 630 mm (Fig. 3.6) and combined with rectangularly-shaped roughness elements to control and maintain the surface friction and drag, as shown in Fig. 3.5. The roughness elements were 80 mm wide and 20 mm high, placed on the floor in a staggered arrangement with both streamwise and lateral pitches of 240 mm (Fig. 3.7). Such set of spires was employed also for the generation of the CBL. In fact, as it will be shown in Ch. 4, the BL they produced in unstable heating conditions was deemed acceptable, and the focus of the optimisation was shifted more on the temperature settings and heater mats arrangement.

Stable boundary layer spires

The design of the spires for SBL simulation started by considering the outcome of previous attempts found in the literature. Spires as tall as the test section were employed by Hancock and Pascheke (2014) for both neutral and stable BLs simulation, even though designed by
3.4 Flow generators

Fig. 3.5 Spires and roughness elements employed for NBL and CBL simulations

Fig. 3.6 Spires schematic diagram for NBL simulation
3.4 Flow generators

means of a trial-and-error process for the neutral case only. The design process is detailed by Pascheke and Hancock (2009), where as reference for vertical profiles of horizontal and vertical velocity standard deviation, the empirical ESDU (2001)’s expressions were employed. However, as discussed by Hancock and Pascheke (2014), the spires were found to generate excessive turbulence intensity above the stable layer, owing to the height of the generators, hence suggesting the use of shorter spires in stable cases. Further studies by the same author (Hancock and Hayden, 2018) made use of a 40% down-scaling version of the same spires, showing a better turbulence intensity above the layer (reduced to 1.2% from the 4% found with the full-size spires).

The Irwin’s procedure was employed here as first attempt to design spires for the SBL, starting by choosing appropriate values for $\delta$ and $\alpha$. For the stable stratification case a shallower BL was required for scaling issues: in the real atmosphere a SBL tends to be shallower than a NBL or a CBL. Moreover, a shallower BL would allow to move the measurement traverse to locations outside the BL (being the measuring traverse system limited to a maximum height of about 1 m). For this purposes a value of 800 mm was chosen as starting point for $\delta$. Moreover, as first attempt $\alpha$ was chosen equal to 0.18. The resulting spire dimensions from the application of Eqs. 3.1 and 3.2 were $h_{sp} = 1020$ mm and $b_{sp} = 121$ mm. The tip was cut for safety reasons and to prevent damages, so that the spire was 4 mm wide at the top with final $h_{sp}$ of 986 mm. With a lateral spacing of 500 mm, seven spires were necessary for the given inlet section width. In order to limit the number of variables the roughness elements pattern was the same as the

Fig. 3.7 Roughness elements arrangement and dimension schematic diagram
neutral case (with the further advantage of a faster reconfiguration between neutral and stable set-ups). Such set-up is shown in Figs. 3.8 and 3.9.

An extended and systematic parametric analysis of the spire geometry and arrangement with stable stratification, similar to what attempted by Pascheke and Hancock (2009) for a neutral case, would have been advisable. However, it would have required too much time (considering also the added degree of freedom of the thermal settings with respect to a simpler NBL) and hence it was deemed not feasible in the given wind tunnel time. Nevertheless, some short tests were attempted trying to identify the effect of varying lateral distance between spires, spires number and dimensions. The investigated cases are listed below

- lateral spacing reduced to 461 mm
- 8 spires spaced 406 mm
- 7 spires with \( h_{sp} = 1000 \) mm and \( b_{sp} = 151 \) mm (made by cardboard).

In all cases, the thermal settings were maintained constant. The modifications of the lateral and vertical profiles obtained with such modified arrangements were small or irrelevant compared to the starting configuration, so that the latter was chosen for the rest of the experiments. The results obtained with this configuration are presented in Ch. 4.
3.5 Urban models

3.5.1 Array of buildings

A critical decision in the experimental campaign design was the choice of the urban model. As starting point, the choice has been oriented towards regular idealised geometries, rather than complex reproductions of real parts of cities. In fact, the former allowed an easier assessment of the stratification effect, without the added layer of complexity of other features (like roof shapes or different building heights). Among the idealised geometries, arrays of cubes (with height $H$ equal to the cube-to-cube spacing) are traditionally used for this kind of studies (see e.g. Uehara et al., 2000 or Kanda and Yamao, 2016). Nevertheless, the reduced length of the building walls would be inadequate for the development of a proper street-canyon flow, which form the basis of street-network dispersion models (as recognised by Castro et al., 2017).

The compromise solution of adopting $H \times 2H \times H$ blocks ($H = 70$ mm) with $H$ spacing was found to be ideal for the work targets. In fact, such configuration represents a significant departure from the classical cube array, introducing a geometrical asymmetry which makes it more typical of street canyons in real urban regions (Castro et al., 2017), but at the same time it remains an organised and regular geometry. Moreover, it was previously employed in the DIPLOS project (www.diplos.org) and the wooden building blocks, as well as the neutral dataset and the expertise produced within that project, were already available in the laboratory. Finally, this geometry had never been used in previous experimental studies with thermal stratification, as it was shown in Ch. 2. Such an array configuration can be viewed as a step between the classical cube arrays and more complex models, chosen to allow eventual
comparisons of dispersion behaviour with that predicted by existing network models (e.g. Soulhac et al., 2011).

In Fig. 3.10a a photo and a schematic diagram of the employed urban array model are displayed. Two wind directions were taken into account, 0° and 45°, with the former characterised by the incoming flow perpendicular to the longer sides of the buildings, and the second obtained by an anticlockwise rotation of the model. Two source locations were considered, one in the centre of the long edge, S1, the other in the centre of the short edge, S3, of the building. The sources were located at the ground level, with circular geometry and diameter 22 mm (a photo is shown in Fig. 3.10b). The holes were filled with ceramic beads and the mixture emission velocity was maintained equal to 0.03$U_{REF}$ in order to guarantee a passive and uniform emission.

The mixture gas was released at ambient temperature from the model ground. In the CBL experiments, where the ground was heated up to 60°C, there was the worry that the gas, which is released at a lower temperature, would have lost its passive behaviour. To help verify this point the device depicted in Fig. 3.11 was built. The gas flowed inside the gas heater, which was heated by electrical devices, and, after passing through an insulated tube, reached the source pipe (electrically heated as well). A thermistor at the outlet section of the pipe was used to monitor the gas temperature. A test was done in both NBL and CBL sampling the tracer inside and above the canopy with different tracer gas temperature but the concentration results did not show any significant difference, and the points (not shown) were all inside the normal measuring scatter. It is probable that due to the very small gas emission flow rate (0.70 to 0.87 litre/minute), the gas dispersed its heat quickly after the release. For this reason (apart for the mentioned test) the source heating device was not used throughout the dataset measurements.

The model was formed by about 350 blocks, aligned in a pattern of 14 × 24 rows (referring to the 0° configuration). The frontal area density $\lambda_f$ (defined in Sec. 2.4.2) was 0.33 and 0.35 for the 0° and 45° configuration, respectively. The plan area density $\lambda_p$ was 0.33 for both the angles. The test section model blockage was below 3%.

Since the wind tunnel turntable was not large enough to hold the entire model, in Castro et al. (2017) the building blocks were placed upon a thin aluminium circular plate whose diameter was slightly smaller than the wind tunnel width. The plate was then rigidly connected to the underneath turntable by means of screws, and the latter was then used to rotate the model to the desired angle. However, for the purposes of this work such solution was not deemed ideal, since the presence of the plate and the air gaps between the plate and wind tunnel floor would have reduced the heat flux and made it less uniform. Hence, the decision of laying down the buildings directly on the floor was taken. In order to align them, two series of lines with different colours were plotted on the floor, representing the contours of the buildings at
Fig. 3.10 Urban array model and schematic diagram of the source region (a), the black point is source S1, red point S3. Pollutant source with measuring probes (b).
3.5 Urban models

the two angles of $0^\circ$ and $45^\circ$. To increase the accuracy of the reference lines, a marker pen was connected to the traverse system and the latter used to precisely draw the lines (as shown in Fig. 3.12). The buildings were then aligned manually with the reference lines. The same method of line drawing and manual building alignment was also used by Castro et al. (2017), who quantified the positional error in any horizontal plane in typically 2 mm (so less than 3% of $H$). Finally, the surface temperature uniformity was verified with an infrared camera. Fig. 3.13 shows a picture of a part of the array acquired when the floor was heated at $60^\circ C$. The floor temperature uniformity appears remarkable with the averaged temperature inside the square at the centre of the picture exactly equal to $60.0^\circ C$. The building roof temperature, instead, is around $35^\circ C$.

Due to time constraints, $0^\circ$ measurements were only performed with the SBL set-up and S3 source, while both SBL and CBL are available for the $45^\circ$ (and source S1) case. Moreover, for the same reason only UV velocity components were sampled in the $0^\circ$ measurements. Of the two, $45^\circ$ was deemed more interesting, since in real scenarios the free stream wind very seldom is perfectly aligned with the streets. Moreover, the $0^\circ$ set-up was found to be prone to plume axis asymmetry due to imperfections in the model and wind tunnel flow (Castro et al., 2017), which becomes irrelevant in the other wind direction. For all these considerations, only the $45^\circ$ dataset will be object of discussion in the present thesis, while the $0^\circ$ one served, mainly, as validation for LES simulations, carried out at the University of Southampton (Sessa et al., 2018).
3.5 Urban models

**Fig. 3.12** Marker pen connected to the traverse system and used to precisely draw the model reference lines.

**Fig. 3.13** Infrared image of the heated model (nominal floor temperature 60°C).
3.5 Urban models

3.5.2 Street canyon and local heating

An urban array like the one presented in the previous paragraph was not ideal for a study of local stratification, in which building walls are heated/cooled. In fact, the building dimensions were too small, meaning that the resulting local stratification (with $Ri_H$ proportional to the heated/cooled surface extension) would have been too weak (or required excessive temperature differences). Moreover, a local stratification study necessarily requires a detailed investigation of the region around the heated wall, possibly with high spatial resolution measurements. The modest dimensions of the streets inside the array model, compared with the measuring probe dimension employed, did not allow such measurements and, in addition, made any probe or model positioning inaccuracy or misalignment more relevant. Hence, larger building walls and simpler geometries were advisable in order to reduce the complexity of the problem.

The analysis of the literature (see Ch. 2) showed that a widely used geometry for computation studies of local stratification was the bi-dimensional street canyon. This made such a model ideal in terms of comparing the results with literature data. At the same time, a bi-dimensional geometry made possible to limit the investigation to a single plane (the street canyon central cross-section), hence reducing the measuring time and complexity. The decision was taken to choose an isolated bi-dimensional street canyon with aspect ratio 1 as baseline. In fact, while multiple street canyons upstream would have helped ensuring a developed boundary layer, at the same time the incoming stratification level would have been weakened by the increased roughness. Moreover, the complexity of manufacturing and aligning the model would have been increased.

Once the shape of the model was chosen, the dimensions had to be defined. They were a compromise between the necessity of minimising the blockage and providing at the same time sufficiently large wall surfaces for heat exchange when dealing with local heating. A building height of 166 mm was considered a good compromise on this regard. With a street canyon length of 2.5 m the test section blockage was estimated in 7.9%. Such value is not small, but it made possible to achieve relatively large Richardson numbers with feasible flow speeds and surface temperatures not exceeding $120^\circ C$ (details on this regard will be given in Ch. 6). The street canyon length $L_{SC}$ was larger than 10 times $H$, hence according to Moonen et al. (2011) boundary effects should be negligible.

Different heating configurations were planned to be investigated, no local heating, windward wall heated, leeward wall heated, ground heated, all the three surfaces heated. Moreover, the surfaces that were not heated had to be cooled to avoid their unintended (and not uniform) increase in temperature under the effect of the heated surfaces. For this reason the buildings were designed as wooden boxes, in which an electrical heater mat (similar to the one used on the wind tunnel floor for CBL simulation but with double the power, to be able to reach larger
temperatures) was glued to one side. To the opposite side, instead, a system of rectangular aluminium pipes with water flowing inside provided the cooling. The cooled water was the same used to cool the wind tunnel floor. The heating/cooling configuration was modified simply by rotating the buildings. In Fig. 3.14 a drawing and a photo of the model set-up are shown.

The buildings were divided into two identical parts, joined together in the centre. This was done for two purposes; firstly, to reduce the weight of each part of the model (that had to be moved frequently to change heating configuration); secondly, to have a more versatile model, that could be used in the future also for studies, e.g., with intersections. For the same reason, the height of the building was chosen exactly equal to a half the width of wind tunnel floor heater mats. In this way, if a case with street canyon ground heating and aspect ratio ($H/W$) 0.5 (or less) has to be simulated, the street canyon floor mats can be replaced by the former.

All the experiments were repeated with neutral and stable approaching flow in order to evaluate the combined effect of incoming and local stratification. The source and tracer gas system was the same as used with the array of buildings. The source was placed at the centre of the street canyon. It should be noted that, while the flow could be approximated as bi-dimensional in the street canyon (as it will be shown in Ch. 6), the same is not true for the plume, which is generated by a point source. On this regard, a line source system (see e.g. Meroney et al., 1996) spanning the street canyon length would have been advisable, but it was
3.6 Measuring set-ups and error estimation

3.6.1 Boundary layer generation measurements

Set-up

For the boundary layer characterisation two measuring set-up arrangements were employed. One (Fig. 3.15a) included the LDA probe mounted horizontally and coupled with the cold-wire to measure both the streamwise and vertical components of velocity and heat fluxes. The second (Fig. 3.15b), with only the LDA probe mounted vertically, was meant to acquire the spanwise component of the velocity (and the streamwise one). The LDA focal length was 160 mm for part of the measurements, increased later to 300 mm (by changing the probe lense) to increase the probe distance from the measuring volume and hence reduce any possible flow disturbance (significant differences in the measured flow quantities were not found, though).

The cold-wire was placed about 4 mm downstream of the LDA measuring volume to calculate heat fluxes. This value was chosen in order to reduce the blockage effect of the...
cold-wire on the measured flow velocity without significantly affecting the correlation between velocity and temperature (see Hancock and Hayden, 2018; Heist and Castro, 1998). The cold-wire blockage was found to reduce the \( u \)-component of velocity by less than 1\% by comparing a profile with and without the cold-wire. Moreover, for a mean convection speed of 0.4 m/s (the lowest measured in the dataset on the boundary layer) such separation would correspond to a frequency still comparable with the LDA sampling rate. A thermistor was held about 10 mm on the side of the cold-wire to both measure the mean temperature and calibrate the cold-wire itself.

The sampling time for the measurements was 3 minutes both in the SBL and NBL tests, while it was increased up to 5 minutes for the CBL. In the latter, an even longer period was advised based on the scatter between sets of profiles, but this would have increased the experimental duration too much. Instead, some of the profiles were acquired twice (as two sets of 2.5 minutes each) and the data averaged together to reduce the scatter.

**Error estimation**

The measurement error estimation was made based on the standard error (\( StErr \)) quantification. The standard error was estimated by means of the following formulas for mean, variances and covariances of the generic quantities \( q_1 \) and \( q_2 \)

\[
StErr_{\bar{q}_1} = \sqrt{\frac{\bar{q}_1'^2}{N}}
\]
\[
StErr_{q_1^2} = \sqrt{\frac{\bar{q}_1'^4 - q_1'^2}{N}}
\]
\[
StErr_{q_1q_2} = \sqrt{\frac{q_1'^2q_2'^2 - q_1q_2^2}{N}}
\]

in which \( N \) is the number of independent samples evaluated as

\[
N = \frac{T_{total}}{T_0}
\]

\( T_{total} \) is the total time trace length while \( T_0 \) is the timescale obtained by integrating the area under the auto/cross-correlation coefficient.

For the SBL data shown in Ch. 4 the standard error (reported as \( \pm \) percentage of the considered quantities with an interval of confidence of 66\%) on \( \bar{U} \) and \( \bar{\Theta} \) was less than 1\%, around 5\% for the variances and 15\% for the covariances. For the NBL, similar values were
obtained, except the streamwise velocity variance for which the standard error was closer to 10%. For the CBL the standard error on $U$ and $\Theta$ was still within 1%, but the error on the variances and covariances was larger (10% for the former, 18% for the latter).

### 3.6.2 Building array measurements

#### Set-up

As in the previously described set-up, two configurations were employed. The first one to measure the streamwise and spanwise component ($U$ and $V$, respectively), the second one for the streamwise and vertical ($U$ and $W$). In both cases the probe was vertically positioned, pointing down. In the second configuration a mirror was added to deflect the laser beams and allow the $W$-component to be measured (Fig. 3.16a). In both configurations the FFID and cold-wire probes were positioned downstream of the LDA measuring volume to sample concentrations and temperature, as well as pollutant and heat fluxes. A magnified picture of the support arrangement is shown in Fig. 3.16b, while Fig. 3.17a shows a plan view of the measurement set-up.

In Fig. 3.17b another configuration is also shown: due to an unintentional displacement of the FFID probe from its desired location, some of the SBL and CBL measurements were performed with such set-up before the misalignment was discovered and fixed. The increased
3.6 Measuring set-ups and error estimation

Fig. 3.17 Planview of the measurement set-up: a) normal set-up, b) abnormal set-up (due to unintended probe movement).

Displacement between LDA and CW reduced the low-pass filter frequency, but the value was still deemed acceptable. In fact, a repetition of the experiment for some points in the CBL with the corrected set-up did not show any significant difference in the flux values.

The cold-wire calibration was performed by using a thermistor placed at the same height, but about 15 mm to the side. Only points outside the roughness sub-layer upstream of the model were considered for the calibration, since there lateral gradients of temperature were smaller.

For what concerns the FFID delay time with respect to the synchronization with the LDA, it depends mostly upon the sampling tube (about 250 mm in length, 0.30 and 0.56 mm as internal and external diameter, respectively). To estimate the delay, tracer gas in the form of an air jet was released from a small tube placed slightly upstream of the probe. The delay time occurred from the LDA detection of the air jet and the first FFID concentration measurement was the desired quantity. For this series of experiments the delay time existing between the two systems was found equal to 17.5 ms. Moreover, Maré (2003) reported that for FFID systems with sampling tube in this range of length the expected frequency response is in the order of 100 Hz.

Fig. 3.18 shows two calibration devices used during the measurements: the beam power meter (employed to measure the power of each LDA laser beam) and FFID calibration tube. When the FFID had to be calibrated, the FFID probe was inserted in the calibration tube, then
known concentrations of tracer gas were released and the voltage output of the FFID recorded. A second order polynomial curve was then employed to fit the various calibration points. This procedure was repeated at least every two hours during the measurements, to account for possible calibration drifts.

For each measurement point an acquisition time of 2.5 minutes was chosen, based on previous works (Castro et al., 2017) even though for the CBL case the scatter in the data suggested longer time.

In any wind tunnel facility, traverse system and model arrangement there are imperfections. In case of measurements over a large volume, as in the present case, such imperfections may become more relevant. For example, the wind tunnel floor is not perfectly flat, and this affects the height of the buildings with respect to the probe location. At the same time, the building blocks may be not perfectly aligned or the traverse be not completely rigid. All these issues can modify the measuring location with respect to the closest buildings. To mitigate such problem, local offsets were specified to the traverse in various points of the model. The offset were evaluated case to case by measuring the location of the probe with respect to the closest buildings against the location in which it was supposed to be. They were particularly useful for the vertical profiles.
Velocity correction

The $UW$ set-up previously described was found to detect mean $W$ velocities deviating from the expected zero value above the RSL. Fig. 3.19 shows $W$ acquired upstream of the model in neutral stratification. Both the set-ups with and without the FFID/CW are shown and both are affected by the deviation, even though the latter is larger with the FFID/CW in place. On the basis of this it is possible to speculate that the deviation may be a result of an LDA/Mirror misalignment which causes part of the $U$ component to be detected as $W$. This hypothesis is reinforced by noting that applying a rotation to the measured velocities of an angle $\alpha_{corr}$, so that

$$\bar{W}_{corrected} = \bar{W}_{measured} + \bar{U} \sin(\alpha_{corr})$$

the expected zero trend is obtained. The value of $\alpha_{corr}$ to correct $\bar{W}$ in the LDA only set-up was 2.2°, which increased to 3.5° when also the FFID/CW were added to the set-up. The fact that the introduction of the FFID/CW made the issue worse might be explained as a blockage of the probe which forced the flow to slightly deviate toward down. Despite this, no significant effects were found on the streamwise velocity component. Various attempts have been performed to improve the LDA alignment, but they did not bring to a solution of the issue, hence the measurements were performed with the described set-up and the value of mean $\bar{W}$ corrected in post-processing with Eq. 3.5.

Error estimation

The standard error for first and second order statistics was evaluated for each measuring point and the average error for each quantity is reported in Tab. 3.1. Depending on the location of the measurement some quantities show mean values close to zero, hence very large percentage standard errors. For this reason, values larger than 100% have been filtered from the average computation. Moreover, only points located below $z/H = 1.5$ were considered in the computation. The table shows that the standard error tends to become larger varying from stable to neutral to unstable stratification, as the fluctuations increase. The lateral and vertical component of the velocity have larger error compared to the streamwise, since the former quantities have normally smaller mean than the latter. Largest errors are found for the variance and covariance of the concentration (up to $\pm 25\%$).
Fig. 3.19 Correction of the mean vertical velocity with and without the FFID/CW for the set-up used in the urban array experiment. Profiles acquired at $x_T = -2470$ mm, $y_T = 0$ mm in neutral stratification.

Table 3.1 Standard error table for the building array experiments. Values are reported as percentage of the mean. Errors larger than ±100% have been filtered out by the average. Only points located below $z/H = 1.5$ were considered.

<table>
<thead>
<tr>
<th></th>
<th>$\bar{U}$</th>
<th>$\bar{V}$</th>
<th>$\bar{W}$</th>
<th>$\bar{\Theta}$</th>
<th>$\bar{C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable</td>
<td>1.7</td>
<td>12.7</td>
<td>9.7</td>
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</table>
3.6 Measuring set-ups and error estimation

3.6.3 Street canyon measurements

Set-up

For the experiments in the street canyon only one measurement set-up was employed, shown in Fig. 3.20. It made use of the LDA probe with the mirror to measure the UW components of velocity and FFID and cold-wire for concentration and temperature, like the one previously employed over the urban array (see Fig. 3.16). However, in this case a focal length of 300 mm was used for the LDA, to allow data acquisition in the bottom of the street canyon, whose building height was 166 mm. An even larger focal length would have been advisable, in order to increase the distance between the LDA probe and traverse from the street canyon top. The distance between the mirror and the LDA measuring volume has also been increased to 35 mm.

The procedure to evaluate the FFID delay time has been improved since the previous experimental session. It still employed the same small tube device, but now the delay is estimated as the time giving the maximum cross-correlation between the concentration sampled downstream of the jet and the velocity measured by the LDA. This made possible to automate the procedure and more frequently evaluate the delay. Throughout the experimental campaign the delay time varied from 15 to 30 ms, likely as effect of the deposition of sugar particles in the FFID sampling tube. Nevertheless, sensitivity tests on the pollutant fluxes (performed by computing the same flux data with different delay times) showed a weak dependency of the flux values from this delay.
Fig. 3.21 Correction of the mean vertical velocity with and without the FFID/CW for the set-up used in the street canyon experiments. Profiles acquired at $x_T = -2470$ mm, $y_T = 0$ mm in neutral stratification.

**Velocity correction**

As also found in the previous set-up (see Sec. 3.6.2), the LDA measurements presented a deviation from the expected values for mean $W$, while no issues were observed on the variance and on the $U$ component. Fig. 3.21 shows the profile acquired upstream of the model with and without the FFID and cold-wire. Conversely from the previous experiment, here the only contribution to the $W$ deviation is due to the presence of the FFID/CW, while the set-up with LDA/mirror only shows a reasonable zero trend for $W$, proving that it was correctly aligned. By employing the correction in Eq. 3.5 with $2.7^\circ$ as $\alpha_{corr}$ the mean $W$ values appears reasonably corrected.

Another aspect which created concern was the behaviour of the FFID/CW probe in a reverse-flow region (like the one in the bottom half of the street canyon). In fact, in such condition the FFID/CW probe was located upstream of the LDA and, hence, the wake might have affected the velocity sampling. Nevertheless, a measuring test done in the street canyon cross-section with and without the FFID/CW did not reveal any effect on $U$, while the correction proposed for $W$ was proved to work also in the canopy (as shown in Fig. 3.22 for a vertical profile in the centre of the street canyon).
3.6 Measuring set-ups and error estimation

Fig. 3.22 Effect of the FID/CW presence on the vertical profiles of mean streamwise and vertical velocity at $x/H = 0$. Also the corrected profile is shown.

**Error estimation**

The standard error for first and second order statistics was evaluated also in this experimental campaign. On average in the entire dataset, the standard error for the first order statistics of velocity and concentration was below $\pm 10\%$. For the temperature and velocity variance it was about 7\%, while for the concentration variance it was larger (23\%). Finally, for the covariances of velocity and temperature it was of the order of 20\%, again larger for the concentration covariances (30\%). The high value observed for mean velocities, compared to the variance, is mainly due to the fact that in many points velocities are very close to zero. For this reason, points with error larger than 150\% have been filtered out in the average calculations.
Chapter 4

Generation of the stratified boundary layers

4.1 Introduction

The main aim of this initial part of the work was to develop a methodology for generating SBLs and CBLs in the EnFlo wind tunnel suitable for high roughness surface conditions, starting from the application and evaluation of what had already been done in the past. Such stratified boundary layers had been later employed as approaching flow for the urban models (see results in Chs. 5 and 6). Reference NBLs were also simulated in order to assess the effect of stratification. In the following sections, the simulation of NBLs, SBLs and CBLs will be described starting with an explanation about the method used to extrapolate the surface quantities. For both SBLs and CBLs, the main temperature control parameters for the simulation will be discussed. Then the BLs will be analysed in more details by comparing the results with data obtained in reference NBLs, with lower roughness and in field measurements. Also the issue of the repeatability of the same stable stratification at different Reynolds numbers is addressed. Finally, spectral analysis (see Appx. B for an introduction) will be applied to the simulated boundary layers.

Most of the results presented in this chapter have been published in Marucci et al. (2018).

4.2 Estimation of surface properties

In order to estimate $L$, the values of $\overline{u'w'}$ and $\overline{w'\theta'}$ at the surface have to be extrapolated from the values in the SL. The same can be said for the profiles of mean streamwise velocity and temperature, used to estimate the roughness lengths. However, in an urban boundary layer
due to the high level of roughness typically a roughness sub-layer (RSL) develops, in which the measured quantities are not independent from the position relative to local obstacles (here represented by the rectangular roughness elements). The same surface elements shape and arrangement employed here were investigated (among others) by Cheng and Castro (2002b) in neutral stratification, for which they found a RSL height equal to $5H_R$ (where $H_R$ is here intended as the height of the roughness element). Above such layer they identified an inertial sub-layer (ISL), defined after Oke (1987) as the region where the vertical variation of shear stress was less than 10% (also called constant-flux layer), that extended up to $10H_R$. In their work two methods were investigated to estimate $u^*$ and $z_0$: the first attempted to use only the points in the ISL where the measured values are expected to be independent from the position, while the second method included also the points in the RSL, but spatially averaged among different locations. In order to evaluate the best solution, both methods were verified here for SBL, NBL and CBL; the results are shown in Fig. 4.1 for a location about 12 m from the inlet. The velocities and shear stresses have been normalised by the reference velocity $U_{\text{REF}}$, measured with a sonic anemometer 5 m from the inlet at a height of 1 m. It is here stressed that with such normalization the velocity graph is not necessarily expected to level at 1 (as evident in Fig. 4.1a, where larger values are experienced above $z/H_R \approx 22$). The black points are the values obtained scanning the region downstream of a roughness element with a grid of 20 measuring locations (as shown in the map in Fig. 4.2), repeated for 4 heights ($2.5H_R, 5H_R, 7.5H_R, 10H_R$).

For the SBL (a-d in the figure) the data acquired at $2.5H_R$ shows a clear dependence from the roughness, effect which is widely reduced at $5H_R$, suggesting a similar height for the RSL. However, a constant-flux layer is not clearly identifiable in the region above (the same can be said for the NBL). On this aspect, Cheng et al. (2007) pointed out that a genuine constant-flux layer may not be expected in a wind tunnel with a non-zero pressure gradient as it is the one used here. Their explanation started considering the time and space averaged momentum equation in the stream-wise direction for ideal steady 2D flow over a rough wall

$$\rho \left( \frac{\partial U}{\partial x} + \frac{\partial W}{\partial z} \right) + \frac{dP}{dx} + \rho \left( \frac{\partial \langle u'^2 \rangle}{\partial x} + \frac{\partial \langle u'w' \rangle}{\partial z} \right) = -\rho \frac{\partial \langle u'w' \rangle}{\partial z} \tag{4.1}$$

They estimated each term from measurements over a staggered and uniform array of cubes. The first and second terms on the left-hand side were found negligible near the surface. The axial pressure gradient was determined by measuring the free stream velocity at different fetches over the roughness and found to be the major contributor on the left-hand side and roughly balancing the estimated shear stress gradient near the wall (together with other terms). This was claimed to be the reason for the not constant shear stress behaviour in many wind
4.3 Neutral boundary layer simulation

tunnel measurements. In the present study, for the neutral reference case the pressure gradient \( \frac{1}{\rho} \frac{dP}{dx} \) estimated by the free stream velocity (\( \frac{1}{2} \frac{\partial u'^2}{\partial x} \)) was found to be around 0.005 m/s\(^2\) while \(-\frac{\partial \langle u'w' \rangle}{\partial z}\) was estimated to be about 0.0015 m/s\(^2\) in the region from \(5H_R\) to \(10H_R\) were a constant flux layer was supposed to be. Even though the other terms of the equation were not calculated, the value of the pressure gradient seems large enough to produce the vertical gradient in the shear stress in the inertial layer.

Despite this, the mean values of \( \overline{u'w'} \) and \( \overline{w'\theta'} \) for each height (red circles in Fig. 4.1c and d), that are representative of the spatially averaged profile, show a fairly linear trend above \(5H_R\), which extends down to the floor. This result suggests that a linear fitting in the region above the RSL may be in this case a suitable method to estimate the shear stress and heat flux values at the surface. Such result is confirmed by the analysis of the vertical profiles, one of which is reported in the figure (blue squares), which also shows that the linearity extends considerably above \(10H_R\). For the mean velocity and temperature the variability in the RSL is lower, and both methods brought generally to a similar solution, having the care not to consider the lower points in case they are too far from the trend of the above region. Similar results were obtained for the NBL (not shown) but with more variability due to the larger turbulence.

For the CBL, the points present a higher level of scatter, clearly shown by the two repetitions of the same vertical profile in Fig. 4.1e-h. The scatter of the measurements makes less evident the local effect of the roughness. Nevertheless, the shear stress profile exhibits an approximately constant flux region which extends from the bottom up to about \(25H_R\). A similar trend is shown by the heat flux, but in this case accompanied by a slight reduction below \(5H_R\). Despite this difference, from the analysis of all the vertical profiles, the most robust method to estimate both \( \overline{u'w'} \rangle_0 \) and \( \overline{w'\theta'} \rangle_0 \) appeared to be including all the points of the constant flux region. Finally, for the mean temperature and velocity profiles in the CBL, similar considerations to those for the SBL can be made.

In the following, all the presented parameters are calculated from the average of at least three vertical profiles measured at the centreline and at a distance from the inlet of 12.5, 14 and 15.5 m, in order to have a streamwise average in the region were the boundary layer is reasonably more developed. For part of the CBL data, each profile was also repeated twice to reduce the scatter (only the average of the two repetitions will be shown in the following graphs).

4.3 Neutral boundary layer simulation

As previously reported in Sec. 3.4, the NBL has not been subject to optimisation, due to the large database of cases in which it was already employed in the EnFlo laboratory. However, a
4.3 Neutral boundary layer simulation

Fig. 4.1 Roughness element scan for $Ri_\delta = 0.14$ (a-d) and $-0.5$ (e-h). The scan positions are reported in the scheme in Fig. 4.2.
series of profiles in the developed region (at the centreline of $x = 12.5$, 13.9 and 15.4 m) has been acquired and the results are shown in Figs. 4.3 and 4.4. The height of the boundary layer obtained with the present set-up is about 1 m, as reported in Tab. 4.1. The friction velocity $u_*$ has been evaluated from a linear fitting of the bottom part of the Reynolds shear stress profiles at the three locations considered (see Fig. 4.3f). The value is 0.065, normalised by the reference velocity $U_{REF}$. The aerodynamic roughness length $z_0$ was calculated from a non-linear fitting of the mean velocity profile with the logarithmic law (Eq. 2.10). $u_*$ is constant and equal to the value previously mentioned, while the von Karman constant $k$ was taken equal to 0.40 (Högström, 1988). The value obtained is 2.0 mm, calculated considering the three $x$-locations together. It is equivalent to 0.4 m at full-scale (1/200 scaling ratio), a reasonable value for an UBL (Stull, 1988). The logarithmic fitting is shown in Fig. 4.3a and b, and even though strictly applicable only in the surface layer, it is plotted over the full height of the measurements.

Various opinions exist regarding the minimum value of the roughness Reynolds number $Re_*=u_*/v$ that should be assumed in order to guarantee a fully turbulent flow and the independence of the experiment from the Reynolds number. Snyder (1972) suggested a minimum value of 2.5, while Snyder and Castro (2002) found that a sharp-edged roughness element (as the ones used here) was already aerodynamically rough with values greater than 1. In the present case $Re_*$ happened to be about 17.5, so the flow was well within the fully-rough-wall regime. The Reynolds number based on the boundary layer height $\delta$ ($Re_*=U_\delta/\nu$) was equal to about $1.33 \times 10^5$. The power law fitting (Eq. 2.11) is plotted over the first half of the boundary layer in Fig. 4.3a; the coefficient $\alpha$ which better fits the experimental data is 0.24, where $z_R=0.2\delta$.

The mean velocity and turbulent quantity profiles at the three locations show no significant variations with $x$, ensuring sufficient longitudinal uniformity in the analysed region. The standard deviations for the three components of velocity near the surface, normalised by the
4.3 Neutral boundary layer simulation

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<td>$Re_\delta (x10^5)$</td>
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Table 4.1 Main scale parameter values for NBL case

friction velocity, show values proportional with those reported by Arya (2001), even though consistently lower.

In Fig. 4.4 the turbulent intensities for the three components of velocity are compared with the profiles obtained from ESDU (2001), by setting a $z_0$ of either 0.1 or 0.01 m and a reference velocity of 5 m/s (considered at a height of 10 m in the parametrisation, with values referred to full-scale). The corrective factors for the velocity in ESDU (2001) were obtained by a polynomial fitting of the provided factors from 10 to 40 m/s. The measured profiles for the streamwise and vertical component seem to fit quite well the reference for $z_0 = 0.1$ m in the bottom part of the layer (up to a height of about 300-400 mm). In the upper part the reduction is more accentuated in the present results. However, it should be noted that the reported ESDU profile would represent the first 200 m of a taller NBL, while in the simulation 200 m represents the full-scale boundary layer height. So the observed trend is as expected. A better control of the turbulent intensity profiles was found to be possible with spires extended up to the full height of the test section, as by Hancock and Pascheke (2014), for example. However, as stated earlier, unlike the stable/unstable stratification the NBL was not subject to optimisation.

Fig. 4.5 shows lateral profiles of mean streamwise velocity normalised by the reference velocity, streamwise and vertical turbulent intensities and Reynolds shear stress normalised by the friction velocity for $z = 300$ mm. The lateral, and also longitudinal, uniformity appears good with lateral variations of the velocity within 4-5%, around 6% for the variance and 10% for $u'w'$. Finally, the standard error with an interval of confidence of 66% was around ±1% for the mean velocity, about 5% for variances and up to 18% for $u'w'$. 

Fig. 4.3 Profiles of mean streamwise velocity, standard deviations of velocity and Reynolds shear stress normalised by friction velocity for the NBL. Continuous red in a), b) and broken black line in a) are respectively logarithmic and power law fitting. Lines in c), d) and e) are values near the surface from Arya (2001). Line in f) is a linear fitting to the surface used to evaluate the friction velocity.
4.3 Neutral boundary layer simulation

![Figure 4.4](image1)

Fig. 4.4 Profiles of turbulent intensities for the NBL. Solid and broken lines are from ESDU (2001) for \( z_0 = 0.1 \) and 0.01 m, respectively, at full-scale.

![Figure 4.5](image2)

Fig. 4.5 NBL lateral profiles of mean streamwise velocity, streamwise and vertical turbulent intensities and Reynolds shear stress normalised by friction velocity at \( z = 300 \) mm.
4.4 Stable boundary layer simulation

4.4.1 Temperature controls

The three main thermal parameters to be set in order to simulate a SBL in the EnFlo wind tunnel are the maximum temperature difference $\Delta \Theta_{\text{MAX}}$ between floor and free stream flow set at the inlet $\Theta_{\infty}$, the length of uncooled floor between the inlet and cooled part, and the imposed temperature profile at the inlet section up to the BL height. A fourth temperature parameter would be the gradient of temperature imposed above the BL, if an overlying inversion were considered. However only zero-strength overlying inversion cases were analysed here in order to reduce the number of parameters.

In the present study, different values for $\Delta \Theta_{\text{MAX}}$ were employed, ranging from 6 to 16°C (note that since $\Delta \Theta_{\text{MAX}}$ is considered to be an input parameter, the floor temperature used in its calculation is the desired one, set as temperature of the cooling water, and not the one actually sampled with the thermistors fixed to the floor, which tends to be slightly larger). The desired $Ri_{\delta}$ was also obtained modifying the flow velocity and so allowing the air to be cooled by the floor for a different amount of time.

The second parameter to be considered is the length of uncooled floor after the inlet. Previous studies conducted in the EnFlo laboratory for offshore BLs (Hancock and Hayden, 2018) found a dependency of the shear stress $\overline{u'w'}$ profile from this parameter. Investigating different uncooled floor lengths, the best result in terms of longitudinal uniformity among different locations was found with 5 m for both the offshore BL and the high-roughness case presented here (results not shown). More in general, the length of uncooled floor has to be chosen accordingly to the inlet temperature profile.

Finally, a proper inlet temperature gradient has to be considered. The easiest solution would be to impose a uniform inlet temperature and allow the stability to grow thanks to the cooling effect of the floor. However, Hancock and Hayden (2018) found that with this configuration the upper part of the layer remained unaffected by the non-neutral stratification, with a mean temperature constant with height, while temperature fluctuation and heat fluxes approached zero at lower heights than the Reynolds shear stress. This behaviour was likely caused by the advection downstream of the uniform temperature at the inlet and enhanced by the reduced level of turbulence. On the other hand, also a near constant inlet temperature gradient does not seem to be the best choice. This option was investigated by Ohya and Uchida (2003) and Hancock and Pascheke (2014) and the resulting BL presented decreasing temperature fluctuations with height $z$, followed by a rise in the middle region which was attributed by the authors to a too large gradient of mean temperature in the same region. More promising is the approach experimented by Hancock and Hayden (2018), presented in Ch. 2. The idea was to
impose the measured profile in a naturally-growing SBL (where “naturally-growing” is referred to a BL created just by friction with the cooled floor, without any flow generator or roughness element) as inlet temperature profile, starting from an initial uniform profile. The acquired temperature profile was stretched to fit the desired $\Delta \Theta_{\text{MAX}}$ and BL height $\delta$ and applied to the inlet section with flow generators and roughness elements in place again. The resulting profile is shown in Fig. 4.6a and hence referred to as “Natural”.

However, a direct application of such an initial condition (not shown here) created an undesired large peak in the middle region of the temperature fluctuation graph, not observed in field measurements (see e.g. Caughey et al., 1979). Therefore, the original gradient was reduced applying corrective factors until the best solution was found. The other cases in Fig. 4.6 represent respectively a reduction of a factor 2/5, 3/10, 1/5 of the “natural” one; the uniform temperature case is also shown. They were acquired after just 1.5 m of floor cooling, and so still in the “developing region” of the flow. The most significant effect of varying the inlet gradient is on the temperature fluctuation; in fact, even though the temperature standard deviation profiles show the same trend in the bottom part (Fig. 4.6c) a peak is present in the middle region for the 2/5 case (and it would be even worse approaching the “natural” gradient). The peak is quite reduced for the 3/10 case and disappears for the 1/5 and the uniform profile. However, as compromise, the 3/10-reduced version of the inlet temperature profile was chosen as upstream condition for the following experiments.
4.4 Stable boundary layer simulation

### Table 4.2

Main scale parameters for \( Ri_\delta = 0.14 \) case obtained with different \( Re_\delta \)

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<td>10.8</td>
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</tr>
<tr>
<td>( u_\text{s}/U_{\text{REF}} )</td>
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<td>0.053</td>
<td>0.053</td>
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<tr>
<td>( z_0 ) (mm)</td>
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<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>( z_{0h} ) (mm)</td>
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<td>0.007</td>
<td>0.013</td>
</tr>
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<td>( \theta_0 ) (K)</td>
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<td>0.24</td>
<td>0.16</td>
</tr>
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<td>( \delta/L )</td>
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<td>0.63</td>
<td>0.65</td>
</tr>
<tr>
<td>( Ri_\delta )</td>
<td>0.14</td>
<td>0.14</td>
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#### 4.4.2 Reproducibility of stratification at different Reynolds numbers

The wind velocity is normally not a critical parameter when simulating NBLs: with only a lower value limitation dictated by the requirement of Reynolds number independence, the range of usable velocities is mostly limited by the wind tunnel capabilities. On the other hand, when simulating thermally stratified BLs any small change in velocity produces a large effect on the stratification, being \( Ri_\delta \propto U^{-2} \). Lower velocity values become desirable, in particular, when larger \( Ri_\delta \) are requested, but the temperature difference parameter must be kept within a certain limit.

The purpose here is to investigate the similitude of artificially thickened SBLs obtained from different velocities but matching the same \( Ri_\delta \) by means of adjusting \( \Delta \Theta_{\text{MAX}} \) accordingly. The reference velocity \( (U_{\text{REF}}) \) was set to 1.0, 1.25 and 1.5 m/s, correspondent to \( Re_\delta \) from \( 6.1 \times 10^4 \) to \( 9.2 \times 10^4 \). The stratification level was kept nominally constant by adjusting the \( \Delta \Theta_{\text{MAX}} \) at the inlet (as shown in Tab. 4.2) in order to match a \( Ri_\delta \) of 0.14 in all three cases. Note that as reference temperature \( \theta_0 \) for all the calculations and normalizations the temperature measured with a thermistor at \( z \approx 2 \) mm was taken (the latter height approximately equal to the aerodynamic roughness length, as it will be shown).

Fig. 4.7 shows the non-dimensional vertical profiles of mean streamwise velocity, Reynolds shear stress, mean temperature, vertical kinematic heat flux, gradient Richardson number, Brunt-Väisälä frequency (calculated as \( N_{BV} = \sqrt{\gamma / \Theta} \left( \partial \Theta / \partial z \right) \)), streamwise and vertical velocity length scales. The latter were computed from the numerical integration of the autocorrelation coefficient, assuming the Taylor’s hypothesis of “frozen turbulence”. All the graphs indicate a fairly good agreement among the profiles of the three BLs. Also the values of \( \delta/L \) in Tab. 4.2 appear to scale very well (with \( \delta \approx 850 \) mm for all three cases), confirming that the stratification remained unchanged. To be noted that, even though in Fig. 4.7 only one profile at \( x = 12.5 \) m...
for each case is shown, the values in the table were estimated from the average of profiles at three different locations (as explained in Ch. 3).

In order to estimate the aerodynamic and thermal roughness lengths a non-linear least-squares fitting of Eqs. 2.14 and 2.15 with the profiles of mean velocity and temperature was needed. The expressions for the $\phi_m$ and $\phi_h$ forms that better fit the experimental data are

$$\phi_m = 1 + 8\zeta$$

$$\phi_h = 1 + 16\zeta$$

They are similar to the one found by Hancock and Hayden (2018). On this regard, the quality of the fitting for the $\phi_m$ and $\phi_h$ is shown in Fig. 4.10. The substitution of Eqs. 4.2 and 4.3 into Eqs. 2.14 and 2.15 leads to

$$U(z) = \frac{u_*}{k} \left[ \ln \left( \frac{z}{z_0} \right) + 8 \frac{z - z_0}{L} \right]$$

$$\Theta(z) = \Theta_0 + \frac{\theta_*}{k} \left[ \ln \left( \frac{z}{z_0h} \right) + 16 \frac{z - z_0h}{L} \right]$$

in which the displacement height was set equal to zero (here and for all the cases analysed in this chapter), as indicated also by Cheng and Castro (2002b) for the same roughness. Letting it varying freely led in some cases to inconsistent values without an effective improvement of the fit. The obtained values, despite being the result of different approximations and dependent by the methodology chosen so far, are consistent each other, since they do not differ too much in the three BLs. The $Ri$ profile for the three cases coincides quite well with Eq. 2.19 for the same height for which the fitting is verified between the log-law and the velocity profile. For the integral length scales in Fig. 4.7g and h a comparison with field data is provided as well, by means of the empirical relations $\Lambda_u = 0.082z/Ri$ and $\Lambda_w = 0.015z/Ri$ from Kaimal (1973) (in which $Ri$ was calculated using Eq. 2.19).

Finally, Fig. 4.8 shows the power spectral density graph of streamwise velocity for the three cases considered here against the non-dimensional frequency $n = fz/U$ (where $f$ is the dimensional one). The maximum peak frequency and the general shape is similar for all cases, while the slower case exhibits a steeper reduction at the higher frequencies of the inertial subrange, also compared to the $-2/3$ reference line. This behaviour is expected and compatible with a reduction of the Reynolds number. Difference that, however, does not preclude the similitude of mean and turbulent quantities already commented.
4.4 Stable boundary layer simulation

Fig. 4.7 Profiles of mean streamwise velocity, Reynolds shear stress, mean temperature, vertical kinematic heat flux, gradient Richardson number, Brunt-Väisälä frequency, streamwise and vertical velocity integral length scales for different Reynolds numbers but same bulk Richardson number ($Ri_{\delta} = 0.14$). Black lines are, respectively, (a) Eq. 4.4, (c) Eq. 4.5, (e) Eq. 2.19, while (g) and (h) are from Kaimal (1973).
4.4 Stable boundary layer simulation

Fig. 4.8 Power spectral density of streamwise velocity for different Reynolds numbers but same bulk Richardson number (\(Ri_\delta = 0.14\)). \(z = 190\) mm. Black line is \(-2/3\) slope reference.

The conclusion drawn from this data is the confirmation that for an artificially thickened BL, the same level of stability (in terms of ratio \(\delta/L\) and similitude of non-dimensional mean and turbulent profiles) can be obtained for different velocities by matching the \(Ri_\delta\). Moreover, the reduction in \(Re\) does not seem to affect mean and turbulent quantities. This result is also supported by the fact that the roughness Reynolds number \(Re_* = u_*z_0/\nu\) (used to evaluate whether the surface is fully rough) is for the slowest case still greater than 8, and thus larger than the minimum limit of 1 indicated by Snyder and Castro (2002) for sharp-edged roughness elements in a NBL.

4.4.3 Comparison with NBL, different stratifications and surface roughness

A SBL characterised by \(Ri_\delta = 0.21\) (obtained imposing \(\Delta\Theta_{\text{MAX}} = 16^\circ\)C and \(U_{\text{REF}} = 1.25\) m/s) is compared with a NBL developing from the same spires.

Fig. 4.9 shows the stable (S) profiles at three streamwise locations compared with a neutral (N) one, for which (for clarity) only the average profile at the same three locations is plotted. For the latter, the measured points differ from the average profile less than \(\pm0.5\%\) on \(U\) mean and less than \(\pm5\%\) for the other quantities shown (except for the vertical length scale which differs up to \(18\%\)).

In Fig. 4.9 the mean velocity reaches a maximum and the Reynolds shear stress profile approaches zero for approximately \(z = 850\) mm, which suggests a \(\delta\) value of the same amount (equivalent in full-scale to a BL 170 m deep). Such a value is equal for stable and neutral
Fig. 4.9 Profiles of mean streamwise velocity, Reynolds shear stresses and integral length scales for a SBL with $Ri_\delta = 0.21$ and the reference NBL. The NBL profile is obtained as average of the ones acquired at the same three locations of the SBL.
4.4 Stable boundary layer simulation

Fig. 4.10 Surface-layer similarity functions $\phi_m$ (a) and $\phi_h$ (b) for the SBL. Red lines in (a) and (b) are Eqs. 4.2 and 4.3, respectively.

stratifications. This allows to speculate that the combination of chosen spires and inlet temperature profile overcomes the effect of stability to reduce $\delta$. Also the general shape of the mean velocity profile is fairly similar between the two stratifications, but with the SBL characterised, as expected, by lower velocities at the bottom and higher at the top compared to the NBL (which determine an increment of the power law coefficient $\alpha$ in Eq. 2.11 from 0.27 to 0.37). The aerodynamic roughness length is also almost the same between the two cases ($z_0 = 2.3$ mm for SBL and 2.2 for NBL). The small effect of the stratification on the mean velocity profile leads to the conclusion that such profile is mostly controlled by the spires (as also observed by Hancock and Hayden, 2018).

The reduction of turbulence due to stratification involves the entire BL and it is evident for the variances and the covariance of the velocity which appear up to 50% smaller. Same reduction is also experienced by the integral length scales, while the $u_*$ is about 30% lower (from $u_*/U_{REF} = 0.065$ to 0.047).

Fig. 4.11 presents a comparison between non-dimensional profiles of the two stable and one neutral BLs already introduced plus a more stable one obtained with the same $\Delta\Theta_{\text{MAX}} = 16^\circ\text{C}$ but reducing the velocity to $U_{\text{REF}} = 1.0$ m/s. A fifth case is also added, generated with the same settings of the second, but with a reduced roughness density (in the case the roughness elements rows were 720 mm apart) and characterised by a $z_0$ four times smaller. The main parameters of the five cases are summarised in Tab. 4.3. All the profiles shown are the result of averaging from three different locations (as for the NBL in Fig. 4.9). The longitudinal variability of the profiles ranges from a minimum of $\pm$2% for the temperature variance at $Ri_\delta$ 0.14 to $\pm$15%
Fig. 4.11 Profiles of non-dimensionalised streamwise and vertical velocity variance, Reynolds shear stress, temperature variance, streamwise and vertical kinematic heat flux for different level of stability and roughness. Black points are field data from Caughey et al. (1979).
Table 4.3 Main scale parameters for reference neutral and three different stability cases obtained with different velocities, plus one lower roughness case

<table>
<thead>
<tr>
<th>$Ri_δ$</th>
<th>0</th>
<th>0.14</th>
<th>0.21</th>
<th>0.33</th>
<th>0.21 (LR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{REF}$ (m/s)</td>
<td>1.25</td>
<td>1.50</td>
<td>1.25</td>
<td>1.00</td>
<td>1.25</td>
</tr>
<tr>
<td>$ΔΘ_{MAX}$ ($^{\circ}$C)</td>
<td>0</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>$u_*/U_{REF}$</td>
<td>0.065</td>
<td>0.053</td>
<td>0.047</td>
<td>0.040</td>
<td>0.042</td>
</tr>
<tr>
<td>$z_0$ (mm)</td>
<td>2.2</td>
<td>2.4</td>
<td>2.3</td>
<td>2.4</td>
<td>0.6</td>
</tr>
<tr>
<td>$θ_*$ (K)</td>
<td>-</td>
<td>0.35</td>
<td>0.34</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>$δ/L$</td>
<td>0</td>
<td>0.64</td>
<td>1.13</td>
<td>2.18</td>
<td>1.27</td>
</tr>
</tbody>
</table>

for the covariances when $Ri_δ 0.33$ (with the majority of the profiles below 10%). In general, the variability increased with $Ri_δ$. Moreover, in the lower-roughness case this variability was found to be larger than the higher-roughness case with similar stability.

Among the three high-roughness stable cases, the largest differences in turbulent properties appear in the lower half of the BL. This behaviour is explainable by the fact that the cooling time is increased with a reduced velocity. This causes a larger reduction of turbulence in the bottom part, but the reduced vertical displacement due to the stratification prevents the modification farther away from the floor. This behaviour makes the Reynolds shear stress of the stable cases deviate from the almost-linear trend of the reference NBL. In the bottom half of the BL, the lower roughness case is much more similar to the $Ri_δ = 0.33$ case with high roughness than to the high-roughness case with the same Richardson number ($Ri_δ = 0.21$). This trend is particularly evident in the $u′w′$ graph. The results suggest that a reduction of the roughness has the same effect on the turbulence profiles of an increment of the stratification, at least in the bottom part of the BL. The upper part, on the contrary, seems to be less influenced by the roughness and the inlet conditions are predominant in shaping the profiles.

Despite the modifications described, all the profiles scale reasonably well with the surface shear stress. This is in contrast with what shown, e.g., by Ohya (2001), where for $Ri_δ > 0.25$ the turbulence profiles were expected to collapse in the very stable regime. As mentioned in Ch. 2, Williams et al. (2017) indicated an even lower threshold ($Ri_δ > 0.15$) for the rough surface case. A possible explanation of this discrepancy is that the method employed to artificially thicken the BL, being originally developed for NBL, may not be suitable for very SBLs and further work would be necessary to come to a conclusion. On the other hand, Williams et al. (2017) also pointed out that the $Ri_δ$ could be a too crude indication to determine the transition in the stability regime. They quoted Flores and Riley (2011), claiming that the Reynolds number based on $L$ and $u_*$ ($Re_L = Lu_*/ν$) could possibly be a better indicator of the transition, found to happen for values of $Re_L$ lower than 100-130, independently from the surface roughness. For all the presented cases $Re_L$ was greater than 1000, so a very stable regime based on this
criterion should not be expected. In Fig. 4.11 the field data measurements from Caughey et al. (1979) are reported as well. The agreement is reasonably good, in particular for the $Ri_\delta = 0.14$ case.

The final comments are on the lateral uniformity and standard error experienced with stable stratification and reference NBL. The former, looking at lateral profiles performed at a height of 300 mm spanning a length of $\pm 1000$ mm from the centreline, was found to be generally quite good, with a mean velocity variation of the order of $\pm 2\%$, less than 1 for the mean temperature, around 5\% for the variances and 10\% for the covariances, as shown in Fig. 4.12. Similar values were obtained for the reference NBL (now shown).

As already mentioned in Ch. 3, the standard error on mean $U$ and $\Theta$ was less than $\pm 1\%$, around 5\% for the variances and 15\% for the covariances. To be noted that the lateral (as well as the longitudinal) variability are of the order of the standard error. Similar quantities were found for the reference NBL.

## 4.5 Convective boundary layer simulation

### 4.5.1 Floor heating

As already described in Ch. 3, the laboratory employs 2950 mm long rectangular heater panels, so that when placing them transversally on the floor, the last 275 mm on both sides are not heated (the test section being 3500 mm wide). In the past, Perspex panels were placed within the test section to reduce its width, but this remedy was not pursued in this case because the entire wind tunnel width was necessary for the following experiments with the urban model. Therefore, four different heater mats arrangements were considered, the first of which consisted in adjacent panels placed transversally, with 275 mm on both sides unheated. In Fig. 4.14 a lateral profile of temperature acquired with the double thermistor rake shows a reduction of up to 4\% respect to the centreline (2\% in the region $\pm 1$ m). In the other configurations longitudinal panels were added on the sides in order to cover a wider region of the floor\(^1\). The graph shows that the configuration in which the largest part of the test section is heated does not present the best uniformity, with hot spots closer to the walls, while a reasonable compromise is the third configuration in which 110 mm are left unheated (without the complexity of adjusting the longitudinal panels temperature as for configuration 2).

\(^1\)In configuration 2 the longitudinal panel temperature was increased respect to the transversal one until the best uniformity was achieved. In configurations 3 and 4 all the panels were set at the same temperature
Fig. 4.12 Profiles of normalised first and second order statistics for two lateral profiles at $z = 300$ mm. Case $Ri_\delta = 0.21$. Errorbars indicate the standard error for a confidence of 66%.
Fig. 4.13 Plan-view of the four floor heater mats arrangements
4.5 Convective boundary layer simulation

4.5.1 Simulation

Fig. 4.14 Comparison between different floor heater mats arrangements ($x = 14000$ mm, $z = 300$ mm, $U_{\text{REF}} = 1.25$ m/s, $\Delta \Theta_{\text{MAX}} \approx 20^\circ$C). $\Theta_c$ is the temperature in the centreline.

4.5.2 Temperature controls

Similarly to the SBL, in order to simulate a CBL the temperature difference $\Delta \Theta_{\text{MAX}}$ and the flow velocity are the main ways to control the (unstable) stratification strength. The inlet temperature profile and the strength of the inversion layer imposed above the BL are other important parameters to consider, in particular as they were found to somewhat influence the lateral uniformity of the flow and temperature fields.

For the CBL an inlet temperature gradient and a capping inversion layer were considered separately. Conversely from the SBL, using a NBL as starting point (uniform inlet temperature profile) and obtaining a CBL only by means of the heated floor was found acceptable. This approach was employed, for instance, by Fedorovich and Kaiser (1998) and Ohya and Uchida (2004). Conversely, Hancock et al. (2013) suggested to adopt as inlet setting the temperature profile measured in a section downstream (starting from a uniform inlet profile) and iterating until a matching of the shape between the two was achieved. This method was tested in the present study with high-roughness conditions with the purpose of enhancing the longitudinal uniformity and reducing the fetch necessary to obtain a sufficiently developed CBL. However, the improvements were generally difficult to appreciate and hard to separate from the experimental scatter. Moreover, applying a negative inlet gradient was found to worsen the lateral uniformity (at least in the present case). Fig. 4.15 shows the lateral profiles of Reynolds shear stress, temperature variance and mean streamwise velocity for different inlet gradients. Three cases were considered: uniform temperature, “full gradient” from the direct application of the method and half gradient. The turbulence is less laterally uniform in the “full gradient” case.
4.5 Convective boundary layer simulation

\[ \frac{u'w'}{U_{REF}} \]

\[ \frac{\theta'^2}{K^2} \]

\[ U_{REF} = 1.0 \text{ m/s}, \theta_0 = 60^\circ \text{C}, \]

\[ x = 13900 \text{ mm}, \text{ floor configuration 4}. \]

**Fig. 4.15** (a) Vertical profile of inlet temperature. Lateral profiles of Reynolds shear stress (b), temperature variance (c) and mean streamwise velocity (d) at \( z = 300 \text{ mm} \) (\( U_{REF} = 1.0 \text{ m/s}, \theta_0 = 60^\circ \text{C}, \)

in both graphs. While the Reynolds shear stress graph shows comparable results for the half gradient and uniform cases, the latter presents a slightly better uniformity in the central region of the temperature variance plot. Interestingly, the non-uniformity due to the gradient affects only turbulent quantities and heat fluxes, while mean velocity (Fig. 4.15d) and temperature profiles (not shown) seem not to be affected.

A capping inversion is a characteristic part of the CBL. Some previous studies (Fedorovich and Kaiser, 1998; Ohya and Uchida, 2004) paid great attention to the inversion layer and the entrainment. In the present study the focus is mainly on the simulation of the lower part of the CBL, which is most relevant for flow and dispersion studies in the urban environment. For this reason the correct representation of a capping inversion was not deemed essential. Weak linear inversions were applied above 1 m from the inlet and with a maximum gradient of 30°C/m. Inside this range no effects were experienced in the bottom half of the BL. However, a proper
calibrated inversion capping the BL was found to greatly enhance the lateral uniformity. In Fig. 4.16 the lateral profile of temperature in the upper part with no inversion is compared with two cases with inversions (respectively with a 10 and 20°C/m temperature increase). With no inversion, the lateral temperature profile appears colder in the central region compared to the sides. The opposite was found for the 20°C/m inversion. On the other hand, employing the 10°C/m inversion resulted in a better lateral uniformity of the temperature profiles. This fact seems to suggest that a proper inversion can be defined to match the temperature on the sides with the temperature in the central region. The beneficial effect of such an increased-temperature uniformity can be observed, for example, by comparing the vertical profiles of streamwise mean velocity in the centreline with the ones in the sides (Fig. 4.17).

The length of unheated floor after the inlet did not affect the CBL, as it was instead noted in the SBL case. Only 1 and 4 m were tested and no significant improvements were observed by delaying the heating, apart from an undesired reduction of the level of instability. 1 m was the length used for all the results shown.

4.5.3 Mean and turbulent profiles

The strongest CBL case experimented here, obtained with uniform inlet temperature and an inversion of about 10°C/m, is presented in Fig. 4.18 and compared with a reference NBL (the same presented in Sec. 4.3). The main scale parameters are reported in Tab. 4.4.
4.5 Convective boundary layer simulation

Fig. 4.17 Mean velocity profiles with (a) no inversion and (b) inversion 10°C/m at x = 13900 mm. (U_{REF} = 1.0 m/s, \Theta_0 = 60°C).

Table 4.4 Main scale parameters for two different unstable cases obtained with different velocities and temperature settings, plus reference neutral. (\Delta \Theta_{MAX} is indicated without considering the temperature inversion).

<table>
<thead>
<tr>
<th>\quad \quad \quad \quad \quad</th>
<th>N \quad</th>
<th>HR2 \quad</th>
<th>HR1(U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U_{REF} (m/s)</td>
<td>2.0</td>
<td>1.25</td>
<td>1.0</td>
</tr>
<tr>
<td>\Delta \Theta_{MAX} (°C)</td>
<td>0</td>
<td>−23</td>
<td>−36</td>
</tr>
<tr>
<td>\delta (m)</td>
<td>1.0</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>u_*/U_{REF}</td>
<td>0.065</td>
<td>0.084</td>
<td>0.100</td>
</tr>
<tr>
<td>z_0 (mm)</td>
<td>2.0</td>
<td>1.8</td>
<td>2.0</td>
</tr>
<tr>
<td>\theta_0 (K)</td>
<td>-</td>
<td>−0.78</td>
<td>−1.4</td>
</tr>
<tr>
<td>\bar{\theta}_s (K)</td>
<td>-</td>
<td>0.56</td>
<td>0.79</td>
</tr>
<tr>
<td>u_<em>/w_</em></td>
<td>-</td>
<td>0.72</td>
<td>0.56</td>
</tr>
<tr>
<td>\delta/L</td>
<td>0</td>
<td>−1.1</td>
<td>−2.2</td>
</tr>
<tr>
<td>Ri_\delta</td>
<td>0</td>
<td>−0.5</td>
<td>−1.5</td>
</tr>
<tr>
<td>Re_\delta \times 10^4</td>
<td>13.3</td>
<td>8.7</td>
<td>6.9</td>
</tr>
</tbody>
</table>
Fig. 4.18 Profiles of first and second order statistics and similarity functions for a CBL case ($Ri_\delta = -1.5$) and a reference neutral at the centreline. The NBL profile is obtained as average of the ones acquired at the same three locations of the CBL. Black lines in (a) and (e) are Eqs. 4.6 and 4.7, respectively; blue line in (c) is Eq. 4.8; black line with dots in (e) is the inlet temperature profile. Black lines in (g) and (h) are from Eq. 2.17.
The Businger-Dyer expressions for $\phi_m$ and $\phi_h$ (Eq. 2.17) provide a reasonable agreement with the present data. On this regard, the fitting for $\phi_m$ and $\phi_h$ is shown in Fig. 4.18g and h. The substitution of Eq. 2.17 into Eqs. 2.14 and 2.15 leads to

$$U(z) = \frac{u_*}{k} \left[ \ln \left( \frac{z}{z_0} \right) - \ln \left( \frac{(1 + \alpha_1)^2}{(1 + \alpha_0)^2} \right) \right] + 2 \frac{u_*}{k} \left( \tan^{-1}(\alpha_1) - \tan^{-1}(\alpha_0) \right)$$

(4.6)

with $\alpha_1 = (1 - 16z/L)^{1/4}$ and $\alpha_0 = (1 - 16z_0/L)^{1/4}$;

$$\Theta(z) - \Theta_0 = \frac{\theta_*}{k} \left[ \ln \left( \frac{\beta_1 - 1}{\beta_1 + 1} \right) - \ln \left( \frac{\beta_0 - 1}{\beta_0 + 1} \right) \right]$$

(4.7)

with $\beta_1 = (1 - 16z/L)^{1/2}$ and $\beta_0 = (1 - 16z_{0h}/L)^{1/2}$.

The streamwise mean velocity profile is greatly modified by the stratification: Eq. 4.6 readily fits with the bottom region, up to a sharp “knee” at $z \approx 150$ mm, while the region above shows constant velocity, compatible with the trend expected in a mixed-layer. The velocity profile presented in Fig. 4.1e, being a less unstable case ($\text{Ri}_\delta = -0.5$ instead of $-1.5$), had a shape more similar to the NBL. The aerodynamic roughness length does not seem to be affected by the different stratification (being 2.0 mm for both CBL and NBL), while $z_{0h}$ has a value similar to the SBLs previously presented. The mean temperature also follows the similarity in the SL while the inversion appears notably reduced from the value imposed at the inlet, mostly due to mixing from below. Reynolds stresses have much larger values compared to the neutral case ($u_*/U_{\text{REF}}$ is here 0.10 against 0.067). $\overline{uw}$ and $\overline{w^2\theta^2}$ have a similar trend, as already found for the $\text{Ri}_\delta = -0.5$ case in Fig. 4.1, but the region of constant flux values extend now higher. The shape of the $\overline{w^2}$ profile is significantly different, showing an expected rise with $z$ followed by a decrease, instead of a monotonic reduction. Canonical similarity functions (see, e.g., Kaimal and Finnigan, 1994) do not seem to apply for this case, characterised by a low value of $\delta/L$ ($\approx 2.2$). Moreover, the ratio between friction velocity and convection velocity scale $u_*/w_*$ is here equal to 0.55 and, as reviewed by Fedorovich et al. (2001), when such ratio is larger than $\approx 0.35$ longitudinal rolls due to shear start to form, causing turbulence statistics to deviate from the free-convection case. Hancock et al. (2013) proposed a modified version to take into account the effect of the shear also in the ML. Here their relation for $\overline{w^2}$ in the ML is reported.

$$\frac{\overline{w^2}}{u_*^2} = 6.63 \left( 1 + 0.8 \frac{\delta}{L} \right)^{2/3} \left( \frac{z}{\delta} \right)^{2/3} \left( 1 - 0.8 \frac{z}{\delta} \right)^2$$

(4.8)
Eq. 4.8, in particular, is used here to estimate the BL depth $\delta$ by fitting with the $\overline{w'^2}$ profile (Fig. 4.18b): the value of 1.3 m provides a reasonable fitting. To be noted that at the chosen geometric ratio of 1/200 such height would correspond to 260 m on full-scale, which is quite small compared to normal CBL depths. Such a limitation, dictated by the dimensions of the wind-tunnel, is not deemed critical in this case as the urban models have, normally, considerably smaller dimensions at the urban scale of interest.

Fig. 4.19 shows the non-dimensional Reynolds stresses, temperature fluctuation and vertical heat flux. The high-roughness case previously presented (here called HR1) is compared with the one characterised by the same roughness but weaker instability (HR2). The longitudinal variability for the plotted quantities was below $\pm 10\%$, and for the variance of the velocity components for case HR1 was less than $\pm 2\%$, four times lower than case HR2, suggesting that the increment in the mixing given by a larger $Ri_\delta$ is beneficial for the longitudinal uniformity.
The case U5 from Hancock et al. (2013) is also plotted and allows a comparison with a low-roughness case with similar instability (in this run $\delta/L \approx 1.26$ and $u_*/U_{REF} = 0.055$). The case E2 from Ohya and Uchida (2004) is reported as well (characterised by $\delta/L = 3.11$). The $\overline{u'^2}$ graph shows a good agreement between case HR2 and U5, with similar instability but different roughness. The same can be said for the $\overline{w'^2}$ profiles. Again for $\overline{u'^2}/\overline{w'^2}$ case HR1 presents lower values compared with the weaker case HR2. As far as non-dimensional temperature variance and vertical heat flux are concerned, a good agreement is shown between all the presented experimental cases. The resemblance with the data from Ohya and Uchida (2004) is particularly significant, since no spires were used in their experiments.

Comparison with field measurements is provided by means of Caughey and Palmer (1979), Wilczak and Phillips (1986) and Wood et al. (2010). The non-dimensional streamwise velocity variance experiences a degree of variability among the different authors comparable with the one found experimentally. For the vertical velocity variance the best agreement is found with Wilczak and Phillips (1986), while Caughey and Palmer (1979) and Wood et al. (2010) report lower values (the opposite for the temperature variance). Finally, the vertical heat flux differs from the canonical linear trend found in field data. However, the result is close to what found by Ohya and Uchida (2004) for similar instability. To be noted that for stronger instability cases Ohya and Uchida (2004) obtained profiles of $\overline{w'\theta'}$ closer to the canonical linear.

As for the SBL the final comment is on the lateral uniformity and standard error. The spanwise variation of mean quantities was about $\pm 1\%$, around 10% for the variances and 15 for the covariances. Fig. 4.20 shows the lateral profiles and the standard error for the case U1. The standard error on $\overline{U}$ and $\overline{\Theta}$ was about $\pm 1\%$, up to 10% for the variances and up to 18% for the covariances. For the NBL standard error and lateral uniformity see Sec. 4.3.
Fig. 4.20 Profiles of normalised first and second order statistics for two lateral profiles at $z = 300$ mm. Case $Ri_\delta = -1.5$. Errorbars indicate the standard error for a confidence of 66%.
4.6 Turbulence spectral analysis

4.6.1 Neutral boundary layer

Fig. 4.21 shows the power spectral density graphs (in the following called spectra for brevity) for the streamwise and vertical component of the velocity at four \( x \)-locations in the surface layer \( (U_{REF} = 2.0 \text{ m/s}) \). For an introduction to the method and symbols used see Appx. B. The data is compared with the forms given by Kaimal and Finnigan (1994), reported in Eqs. 4.9, 4.11 and it shows a good match, except for the lower frequency region of Fig. 4.21b where the result is slightly higher.

\[
\frac{fS_u(f)}{u^2_*} = \frac{102n}{(1 + 33n)^{5/3}} \quad (4.9) \\
\frac{fS_v(f)}{u^2_*} = \frac{17n}{(1 + 9.5n)^{5/3}} \quad (4.10) \\
\frac{fS_w(f)}{u^2_*} = \frac{2.1n}{(1 + 5.3n)^{5/3}} \quad (4.11)
\]

Fig. 4.21 Normalised NBL power spectral density for \( u \) and \( w \) at \( z = 115 \text{ mm}, z/\delta = 0.115 \). Continuous lines in (a) and (b) are Eqs. 4.9 and 4.11, respectively.

4.6.2 Stable boundary layer

Fig. 4.22 compares the spectra of the three velocity components for the SBL (case \( Ri_\delta = 0.21 \)) in the surface layer. In the inertial subrange the \(-5/3\) slope reference is also provided showing a reasonable agreement. Moreover, for a certain portion of the region the \( v \) and \( w \)-spectra present similar levels that are roughly \( 4/3 \) of the \( u \)-spectrum.
Fig. 4.22 SBL power spectral density presented showing $-5/3$ slope in the inertial subrange and the $4/3$ ratio between the transverse and streamwise velocity components at $x = 12500$ mm and $z = 115$ mm, $z/\delta = 0.135$ ($Ri_\delta = 0.21$).
The $S_w/S_u$ spectral ratio is better displayed in Fig. 4.23 for five different heights spanning the entire BL depth. For $z/\delta = 0.13$ the ratio approaches the $4/3$ value at about $k_1 = 80 \text{ m}^{-1}$, confirming the trend plotted in the previous figure. For smaller values of $k_1$ the ratios approach zero, due to the predominance of $S_u$ over $S_w$, except on the BL top, where it oscillates at around 0.8, without reaching the local-isotropy value in the higher wavenumber region.

![Fig. 4.23 Spectral ratio $S_w/S_u$ at five different heights for case $Ri_\delta = 0.21$, $x = 13950 \text{ mm}$ and $y = 0 \text{ mm}$. Black line is $4/3$ value.](image)

In Fig. 4.24 the spectra of the three velocity components and temperature are shown for three $x$-locations at $z/\delta = 0.135$ again for case $Ri_\delta = 0.21$. For the velocity also the neutral reference of Eqs. 4.9, 4.10 and 4.11 is reported. The effect of stable stratification is a shift of the spectrum peak towards the right hand side, as also reported by Kaimal and Finnigan (1994) in field data, more evident in Fig. 4.24a and b. This corresponds to a reduction of the wavelength associated with the peak (indicated as $\lambda_m$ in the literature). Analysing the frequency-weighted plots it appears more clearly that the decay in the inertial subrange follows only partially the prescribed $-2/3$ slope (see Appx. B on this regard), in particular for the temperature spectra. In fact, the latter starts to diversify from a frequency $n$ of about 2. A possible reason may be the Reynolds number not sufficiently high, causing a reduction in the distance between larger and smaller scales. This aspect has already been highlighted in Fig. 4.8. Another reason could be that the high level of roughness would prevent the establishing of local isotropy in the proximity of the floor. The latter hypothesis is supported by the fact that spectra acquired farther from the floor appear to slightly better follow the $-5/3$ rule, as it will be shown below, where spectra...
above the surface layer will be presented. Another possible reason for the fast decay of the temperature spectra might be found in the cold-wire dynamic response reduction due to the deposition of sugar particles on the wire. At the time this data was collected, this issue had not been taken into account yet, so the wire conditions were not monitored. In any case, this issue is expected to have affected only marginally the first and second order statistics previously shown, according to other tests undertaken in the laboratory, comparing data acquired with an old and a new cold-wire (Hayden, 2018). Finally, the low-pass filter applied to the cold-wire signal did not have any effect on this trend, since the cut-off frequency was larger than the one observed in the spectra (cut-off frequency of 220 Hz, equivalent to about $n = 30$ for the spectra in the figure, against $n = 2$).

Fig. 4.24 Normalised SBL power spectral density for $u$, $v$, $w$ and $\theta$ at $z = 115$ mm, $z/\delta = 0.135$ (case $Ri_\delta = 0.21$). Black lines in a), b) and c) are neutral reference Eqs. 4.9, 4.10 and 4.11, respectively. Red line is $-2/3$ slope reference.

Fig. 4.25 shows the spectra for the three cases with $Ri_\delta = 0.14$, 0.21 and 0.33, obtained with different velocities. The spectrum peak shifting towards the right as stability increases
(already observed comparing with the neutral case in Fig. 4.24) seems confirmed, even though the differences between the cases are not perfectly clear in that region.

![Image of the normalized SBL and reference NBL power spectral density for u, w, and θ at x = 12500 mm and z = 115 mm, z/δ = 0.135 (Riδ = 0, 0.14, 0.21, and 0.33). Black line in a) and b) is Eq. 4.9 and 4.11, respectively. Red line is −2/3 slope reference.]

The surface layer spectra can also be normalised following conventions established by the Monin-Obukhov scaling, as illustrated by Kaimal and Finnigan (1994), so that their shape is invariant respect to the ratio z/L and all the inertial subranges collapse in a single line. For such purpose the frequency has to be normalised with the height and velocity (as previously done), while the spectrum intensity of the velocity needs to be normalised with \( u_* \) and the dissipation rate of turbulent kinetic energy \( \varepsilon \), expressed in non-dimensional form

\[
\phi_\varepsilon = \frac{k z \varepsilon}{u_*^3}
\]

(4.12)
Kaimal and Finnigan (1994) give for the inertial subrange of $u$-spectrum

$$\frac{f S_u(f)}{u_*^2 \phi_e^{2/3}} = \frac{\alpha_1}{(2\pi k)^{2/3}} n^{-2/3}$$  \hspace{1cm} (4.13)

and taking the von Karman constant $k = 0.4$ and the Kolomogorov constant $\alpha_1 = 0.55$, it gives

$$\frac{f S_u(f)}{u_*^2 \phi_e^{2/3}} = 0.3 n^{-2/3}$$  \hspace{1cm} (4.14)

For the other velocity components, in the same manner

$$\frac{f S_v(f)}{u_*^2 \phi_e^{2/3}} = 0.4 n^{-2/3}$$  \hspace{1cm} (4.15)

$$\frac{f S_w(f)}{u_*^2 \phi_e^{2/3}} = 0.4 n^{-2/3}$$  \hspace{1cm} (4.16)

For the temperature spectra a similar formulation can be introduced, in which $\theta_*$ is employed in the place of $u_*$. Kaimal and Finnigan (1994) proposed

$$\frac{f S_\theta(f)}{\theta_*^2 \phi_e \phi_\theta^{-1/3}} \approx 0.43 n^{-2/3}$$  \hspace{1cm} (4.17)

The surface layer spectra for the three stable cases analysed are plotted in Fig. 4.26 with the new normalisation. For $\phi_e$ the expression suggested by Kaimal and Finnigan (1994) has been used

$$\phi_e^{2/3} = \left(1 + 5 \frac{z}{L}\right)^{2/3}$$  \hspace{1cm} (4.18)

For the $u$-spectra the inertial subranges collapse together following the line in Eq. 4.14. The low frequency range shows a systematic and clear reduction of the values reducing $z/L$, together with a shifting towards the right of the peak of maximum energy, again in agreement with field observations. The same can be said for $w$ and $\theta$-spectra, even though for the former the $U_{REF} = 1.0$ m/s spectrum does not collapse perfectly with the line from Eq. 4.16 (as the other two do).

Finally, in Fig. 4.27 the spectra of case $Ri_\delta = 0.21$ ($U_{REF} = 1.25$ m/s) are shown for heights between $z/\delta = 0.13$ to 1.0. Above the surface layer the stable spectra do not follow any similarity, so they are plotted simply normalised by the friction velocity. The energy due to turbulence decreases with the height (Kaimal and Finnigan, 1994). The spectrum at the BL
4.6 Turbulence spectral analysis

![Fig. 4.26](image)

Fig. 4.26 Normalised SBL power spectral density for $u$, $w$ and $\theta$ at $x = 12500$ mm and $z = 115$ mm, $z/\delta = 0.135$. Red lines in a), b) and c) are Eq. 4.14, 4.16 and 4.17, respectively.
top, as anticipated, does not present a $-5/3$-slope range, differently from all the others, which seem to follow the law even better than the surface layer spectra.

![Fig. 4.27 Normalised SBL power spectral density for $u$, $v$, $w$ and $\theta$ at $x = 12500$ mm varying the height ($Ri_{\delta} = 0.21$). Red line is $-5/3$ slope reference.](image)

### 4.6.3 Convective boundary layer

Turbulence isotropy was investigated for the CBL as well, starting from the $4/3$ ratio relationship between $S_w$ and $S_u$. Fig. 4.28 presents $S_w/S_u$ against the wavenumber $k_1$ non-dimensionalised by the BL depth $\delta$, in order to better compare the result with Kaiser and Fedorovich (1998), who show CBL spectra acquired in a thermally-stratified wind tunnel. In the bottom part the ratio is lower than $4/3$, indicating a stronger contribution from $S_u$ and horizontal motion, with the value approaching the $4/3$ reference only for a short range of wave numbers. For $z/\delta = 0.14$ the value of the power spectral density of the two velocity components is of the same order, and the vicinity with the $4/3$ line is observed for a wider range. In the two upper locations inside the ML, the ratio approaches the $4/3$-reference from
above, similarly as found by Kaiser and Fedorovich (1998). They attributed the high anisotropy at low wave numbers in the ML to the dominance of buoyancy forces, creating a vertical motion. The elevated amount of scatter in the ratio does not allow a precise estimation of the point at which the measured spectra ratio starts to be closer to the local-isotropy value (Kaiser indicated a value of 10).

\[ \frac{z}{\delta} = 0.04, 0.14, 0.45, 0.75 \]

\[ k_1 \delta = \frac{2\pi f \delta}{\theta U} \]

\[ \frac{S_w}{S_u} \]

\[ k_1 \delta = 2\pi f \delta / U \]

**Fig. 4.28** Spectral ratio \( S_w / S_u \) at four different heights for case HR1, \( x = 13900 \) mm and \( y = 0 \) mm. Green line is 4/3 value.

In Fig. 4.29 the spectra for CBL (case HR1) are plotted for different lateral locations from −1 to 1 m inside the surface layer, normalised by friction velocity and temperature. Their shape is reasonably similar, confirming the lateral uniformity obtained also for the spectra. The velocity spectra show a linear part which follows the \(-2/3\) reference from about \( n = 1 \). Conversely, the temperature spectra present a slope comparable to \(-2/3\) in the range between \( n = 0.3 \) and 2, starting to reduce quickly after that.

A spectrum for the neutral case is also displayed in the figure, together with Eqs. 4.9 and 4.11, which are reference forms of the neutral case (already plotted in Fig. 4.21). The \( u \)-spectra do not seem to be modified by buoyancy: they maintain a similar shape. On the contrary, the \( w \)-spectra show a higher level of energy at lower frequencies, region identified by Kaiser and Fedorovich (1998) as controlled by buoyancy. Consequently, the peak of maximum energy in the graph is also shifted towards the left compared to the neutral case.
4.6 Turbulence spectral analysis

\[ n = \frac{f_z}{\bar{U}} \]

\[ n = \frac{f_z}{\bar{U}} \]

\[ n = \frac{f_z}{\bar{U}} \]

**Fig. 4.29** Normalised CBL and reference NBL power spectral density for \( u, w \) and \( \theta \) at \( x = 13900 \) mm and \( z = 136 \) mm, \( z/\delta = 0.10 \) (case HR1, N) for different \( y \). Black line in a) and b) is Eq. 4.9 and 4.11, respectively. Red line is \(-2/3\) slope reference
As for the SBL, also the surface layer spectra of the CBL can be normalised by $\phi_e^{2/3}$ in order to collapse the inertial subrange. In this case the following form for $\phi_e^{2/3}$ was used (from Kaimal and Finnigan, 1994)

$$\phi_e^{2/3} = 1 + 0.5 \left( \frac{z}{|L|} \right)^{2/3} \quad (4.19)$$

Fig. 4.30 displays three normalised spectra for case HR1 and HR2 at $z = 136$ mm at the centreline. For both velocities and temperatures, the spectra of the two cases superimpose perfectly on each other. For the $w$-component a shift of the peak frequency towards the left was expected with increasing $z/|L|$ (Kaimal and Finnigan, 1994), however this is not observed in Fig. 4.30b, differently from the SBL case. A comparison with the red lines from Eq. 4.14, 4.16 and 4.17 shows that the intensity of the normalised spectra is too low.

This discrepancy, which was absent for the SBL cases presented in Fig. 4.26, was found to be related to $\phi_e^{2/3}$. For this purpose, Fig. 4.31 shows the values of $\phi_e^{2/3}$ directly calculated...
from the measured $\varepsilon$ (see Sec. 4.6.4) for the cases with $Ri_\delta = 0.21$ and $-1.5$ compared with Eqs. 4.18 and 4.19, respectively. While for the SBL the approximation for the first 10% of boundary layer appears reasonable, the CBL shows a completely different trend in the bottom part: a reduction with the height instead of the expected increase. Using the measured $\phi_e^{2/3}$ in place of Eq. 4.19, both the normalised velocity spectra for the two cases perfectly coincide with the reference, as shown in Fig. 4.32.

For the temperature, the substitution of $\phi_e^{2/3}$ is not enough to make the spectra superimpose with the reference line. The other two parameters used for the normalization are $\phi_h$ and $\theta_*$. The first one proved to represent a good fitting of the experimental data in the surface layer (see Fig. 4.18h). Applying a reduction of 40% to $(\overline{w\theta})_0$ and consequently to $\theta_*$ was found to make the two spectra coincide with the reference. However, the clear trend of the vertical heat flux in the bottom half of the BL (see Fig. 4.18f) excludes the possibility that such a high overestimation of the surface value would be possible. Further work might be necessary to clarify this aspect.

Finally, the spectra in the ML are presented. Here $|L|, u_*$ and $\theta_*$ are replaced by $\delta, w_*$ and $\overline{\theta}$, as scaling parameters for length, velocity and temperature, respectively. As highlighted by Kaimal and Finnigan (1994), the spectra should not change for a given $(\overline{w\theta})_0$ and $\delta$, since none of them are expected to change with height. In Fig. 4.33 the spectra for five different heights for case HR1 are displayed. For the $x$-axis $n_\delta = f \delta / U$ has replaced $n = f z / U$. For all the spectra the shape is approximately maintained constant along the ML. A quite good $-2/3$ slope is also observed in the inertial subrange. If the intensity of the velocity spectra is roughly constant with height (with a more pronounced reduction only for the upper location), the temperature spectra presents a decrease, according to what already shown for the temperature variance profile.
4.6 Turbulence spectral analysis

\[ n = \frac{f_z}{\theta U} \]

\[ n = \frac{f_z}{\theta U} \]

\[ n = \frac{f_z}{\theta U} \]

\( z/|L| \)

0.20 HR1

0.11 HR2

Fig. 4.32 Normalised CBL power spectral density for \( u, w \) and \( \theta \) at \( x = 13900 \) mm and \( z = 136 \) mm for case HR1 and HR2. \( \phi_\epsilon^{2/3} \) obtained from measured data and \( (\bar{w}\theta)_0 \) reduced of 40\%. Red lines in a), b) and c) are Eq. 4.14, 4.16 and 4.17, respectively.
Fig. 4.33 Mixed layer normalised CBL power spectral density for $u$, $w$ and $\theta$ at $x = 13900$ mm for case HR2. Black lines are $-2/3$ slope reference.
4.6 Turbulence spectral analysis

4.6.4 Dissipation rates of turbulent kinetic energy and temperature fluctuations

The dissipation rates for the CBL and SBL experiments have been calculated following the procedure by Fedorovich and Kaiser (1998). The expressions from Kolmogorov’s inertial subrange theory

\[ F_u(k) = \alpha_1 \varepsilon^{2/3} k^{-5/3} \]  
\[ F_w(k) = \frac{4}{3} \alpha_1 \varepsilon^{2/3} k^{-5/3} \]

have been fitted to the inertial subrange part of the velocity spectra employing the least square method. The \( \varepsilon \) obtained for the \( u \) and \( w \)-component of velocity should be coincident in an isotropic flow.

The same procedure was also applied to the temperature spectra to obtain the temperature fluctuation destruction rate \( \varepsilon_T \), fitting the equation from Obukhov (1949)

\[ F_\theta(k) = \beta \varepsilon_T \varepsilon^{-1/3} k^{-5/3} \]

in which \( \beta \) was taken equal to 0.8. The \( \varepsilon \) values needed for the fitting were chosen equal to the average between \( \varepsilon_u \) and \( \varepsilon_w \).

Fig. 4.34 shows dissipation rates of turbulent kinetic energy and temperature for CBL case HR1 and HR2 together with field data from Caughey and Palmer (1979). The values of \( \varepsilon_u \) and \( \varepsilon_w \) do not differ too much each other, confirming in a certain manner the reliability of the method employed. The measured non-dimensional \( \varepsilon \) present larger values compared to the field data, in particular close to the ground, possibly due to the high shear and weak instability. To be noted that case HR1 (more unstable) experiences lower non-dimensional \( \varepsilon \) than HR2 together with a less steep reduction in the ML. \( \varepsilon_T \) shows values similar to the field data close to the ground, but they are followed by a steep reduction which deviates from the reference in the upper half of the BL. However, also Fedorovich and Kaiser (1998) found large differences in the upper portion between different studies and noted how bigger \( \varepsilon_T \) values are experienced in case of strong capping inversions (that has not been simulated here).

Fig. 4.35 reports dissipation rates for the SBL (case \( Ri_\delta = 0.21 \)), compared with field data from Caughey (1982). In this case both the non-dimensional \( \varepsilon \) and \( \varepsilon_T \) show lower value compared to the reference, in particular for \( \varepsilon_T \), but with a similar trend.
4.6 Turbulence spectral analysis

Fig. 4.34 Dissipation rates of turbulent kinetic energy and temperature for CBL case HR1 and HR2 at $x = 13900$ mm, $y = 0$ mm. Black points are field data from Caughey and Palmer (1979).

Fig. 4.35 Dissipation rates of turbulent kinetic energy and temperature for SBL at $x = 13950$ mm, $y = 0$ mm. Black points are field data from Caughey (1982).
Chapter 5

Effects of non-neutral boundary layers on flow and dispersion in an urban array

5.1 Introduction

This chapter will discuss the results from the second part of the project. The stratified boundary layers presented in the previous chapter are here employed as approaching flow to an urban model made up by an array of rectangular buildings. Firstly, the method used to evaluate the surface properties will be introduced. Then, a description of the BL flow above and inside the canopy will be given, highlighting the differences between the different types of stratification and the reference neutral flow. Three stable stratification levels and two unstable have been considered. Finally, findings about the effects of non-neutral stratification on pollutant concentration and mass fluxes from a ground level point source release will be presented and discussed.

5.2 Estimation of surface properties

An approach for the estimation of surface quantities in stratified UBLs was already considered in the previous chapter (see Sec. 4.2). It assumed that the spatially averaged profiles for the Reynolds shear stress and vertical heat flux were approximately linear in both the roughness sub-layer (RSL) and the region immediately above. With this hypothesis (experimentally observed in that case) the value at the surface for both quantities may be obtained by means of a linear fitting of the data above the RSL alone, without the necessity of a strict spatial averaging of the profiles, being the quantities in that region independent of the local effect of the roughness. The application of this method is a necessity in the present case, as the
data acquired do not have a resolution high enough for a proper spatial averaging. A different approach was employed by Castro et al. (2017) for the determination of the friction velocity in a NBL over the same urban array of buildings tested here. They calculated the friction velocity by increasing the shear stress obtained just above the canopy by a factor of 1.3, following Cheng and Castro (2002a). Using two wind directions (0 and 45°), they obtained $u_*/U_{REF}$ equal to 0.0748 and 0.0891, respectively. Fig. 5.1 shows the results from the application of both methods for the NBL case and a 45° wind direction, employing $5 \times 1260$ mm spires. Four vertical profiles are available, even though only one for the entire BL depth. A linear fitting was attempted in the region between $1.5H$ and $4H$ leading to the value at the surface correspondent to a friction velocity $u_*/U_{REF}$ of 0.081. Such interval extends from part of the RSL (ending at about $z/H = 2$, according to Castro et al., 2017) up to the region above. To be noted that a constant flux layer is not discernible, as expected, likely due to the non-zero pressure gradient (see Sec. 4.2). As support of this argumentation, Kanda and Yamao (2016) was able to obtain a constant flux layer over an array of cubic buildings, but employing a wind tunnel with adjustable ceiling height and shape to generate a zero-pressure gradient boundary layer (for the particular wind tunnel design see Ogawa et al., 1981). Nevertheless, a reasonably good linear trend, similar to what was found in Ch. 4 for the approaching flow, is appreciable, suggesting the applicability of the same method also in this case. On the other hand, multiplying the averaged value of the shear stress at $z/H = 1.25$ for 1.3 leads to a friction velocity of 0.087, slightly higher than the value obtained with the linear fitting, but closer to the 0.089 reported by Castro et al. (2017). Following these considerations and because of the quite good agreement obtained with both approaches, the linear fitting method was deemed more practical in this case, also considering that no multiplicative factors are available for the vertical heat flux.

As far as the displacement height ($d$) is concerned, Castro et al. (2017) suggested the values of $0.62H$ and $0.59H$, for wind directions 0 and 45°, respectively. Such values were obtained from LES and DNS simulations assuming $d$ as the height at which the surface drag appears to act (Jackson, 1981). They claimed that calculating $d$ together with $z_0$ by means of fitting the log-law with the streamwise wind profile and fixing the von-Karman constant $k$ would lead to larger values of $d$ and unrealistically smaller values of $z_0$. However, the latter approach was applied in the present study, as it is the most widely used approach and led to consistent results, with values of $z_0$ comparable with Castro et al. (2017). Finally, the same approach was considered for the thermal roughness length $z_{0h}$ calculation, in which the temperature measured at a height of 10 mm at the centre of the model was used as reference $\Theta_0$. Two cases were considered, one in which the displacement height for the temperature profile $d_h$ was maintained equal to $d$, and the other in which it was a free fitting parameter. In all cases $k$ was set constant and equal to 0.40.
5.2 Estimation of surface properties

\[ \frac{u'w'}{U_{REF}} \]

\[ \frac{z}{H} \]

Fig. 5.1 Reynolds shear stress at surface extrapolation for NBL case with 5 × 1260 mm spires and wind direction 45° over urban model.
5.3 Effects of stratification on the boundary layer

5.3.1 Stable boundary layer

Simulated SBL characteristics

In order to generate the two weaker stable approaching flows, the same wind tunnel settings as detailed in the previous chapter were employed, characterized by a non-uniform inlet
5.3 Effects of stratification on the boundary layer

Fig. 5.3 Example of determination of $u_*, (w'\theta')_0, z_0, d, z_{0h}$ and $d_h$ for a CBL case ($Ri^{app}_\delta = -1.5$). Red lines in c) and d) are Eqs. 4.6 and 4.7, respectively.
5.3 Effects of stratification on the boundary layer

Table 5.1 SBL cases parameters, “Lower roughness” case acquired with roughness elements only, “Higher roughness” case with the urban array at wind direction 45°. (*measured from 0° case, **extrapolated value - no measure available)

<table>
<thead>
<tr>
<th></th>
<th>Lower roughness</th>
<th>Higher roughness</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>$\Delta \Theta_{MAX}$</td>
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<td>0</td>
</tr>
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<tr>
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<td>850</td>
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<td>-</td>
</tr>
<tr>
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<td>0</td>
</tr>
<tr>
<td>($w/\Theta_0^*)_0$ (mKs$^{-1}$)</td>
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<td>0</td>
</tr>
<tr>
<td>$\theta_*$ ($^\circ$C)</td>
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<td>-</td>
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<td>-0.006</td>
</tr>
<tr>
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<td>-</td>
</tr>
<tr>
<td>$z_{0h}$ (mm) [d$_h$ fitted]</td>
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<td>-</td>
</tr>
<tr>
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</tr>
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<tr>
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<td>76.09</td>
</tr>
</tbody>
</table>

temperature profile, a reference velocity $U_{REF}$ of 1.25 m/s and a $\Delta \Theta_{MAX} = 16^\circ$C (defined in the previous chapter as the difference between the demanded floor temperature and the free-stream flow set at the inlet). The values indicated in Tab. 5.1 (labelled as “Lower roughness”), were obtained averaging three profiles at different longitudinal positions in the centreline within the region where the model would be located (similarly to what was done in the previous chapter). The strongest simulated SBL was obtained reducing the velocity to 1.15 m/s and increasing $\Delta \Theta_{MAX}$ to 17.8$^\circ$C. The combined effect of velocity reduction and $\Delta \Theta_{MAX}$ increment was considered the best compromise between the need of maintaining a sufficiently high Reynolds number while preventing an overheating of the LDA probe. Unfortunately, no measurements were performed with this stratification level before placing the model. It should be noted that $R_{i_0}^{app}$ is the nominal (or desired) bulk Richardson number of the approaching flow, which sometimes differs slightly from the one actually measured.

A comparison from the lower roughness values in Tab. 5.1 and the ones over the urban array (called “Higher roughness”) allows to understand how the scaling parameters vary as consequence of the increased roughness. Firstly, it is possible to note how the friction velocity
is gradually reduced by applying a stable stratification both in the lower and higher roughness case. However, while the reduction experienced after the application of $Ri_\delta = 0.14$ is about 19% in both cases, when $Ri_\delta = 0.21$ the friction velocity is only 22% lower than the NBL above the canopy, compared to a 28% reduction experienced when the urban array is not in place. Moreover, a further increase in stability produce just an additional 2% reduction. This suggests that while certainly stratification affects the flow above the canopy, an increment in roughness tends to reduce the sensitivity of the friction velocity to stratification variations (in terms of $Ri_\delta$).

As far as the aerodynamic roughness length $z_0$ is concerned, while in the lower roughness case no significant stratification effects were observed, with the urban array a reduction between 27 and 35% was measured. At the same time, the displacement height $d$ (assumed equal to zero in the former) shows a slight gradual increase with increasing stratification (up to 12% larger) to a value around $0.7H$ (similar to what found by Jackson, 1981 for cubes and other geometries). On the other hand, Uehara et al. (2000) did not find any significant effect after applying stable stratification (incidentally, not even in the CBL case), despite having comparable values for $z_0$ and $d$. It should be noted that in their case only one vertical profile was considered.

The boundary layer depth $\delta$ seems not to be affected by the presence of the model, as can be observed from the Reynolds shear stress plot in Fig. 5.4. The reference temperature $\Theta_0$ in the presence of the model was considered to be the temperature measured with a thermistor at $z = 10$ mm inside the canopy, close to the tracer source. It is important to note that such reference temperature is different from the one used to calculate the Richardson number and Monin-Obukhov length in the lower roughness case (in that case the temperature at a height $z = z_0 \approx 2$ mm is used). The $\Delta\Theta$ calculated with such reference value, combined with a slight increment of the velocity due to the blockage above the model (the latter being less than 3%), brings to a reduction of the measured $Ri_\delta$ between 10 and 14%. Conversely, the modification in the Monin-Obukhov length $L$ is clearly larger, with an increment up to 80% due to the increased roughness, which causes a reduction of the surface stability. In the table, the value of $Ri_H$ is also shown, for which the averaged values of velocity and temperature measured at roof level are considered (it should be noted that only a limited number of samples are available at roof level and the values in that region are very dependent upon position). It is interesting to note that above the array $Ri_\delta \approx Ri_H$, meaning that the velocity reduction at canopy top, respect to the BL top, compensates for the lower temperature difference and reference length in the calculation. The same is not true for the other case, where the lower roughness causes a larger increment of velocity closer to the ground.

Finally, the thermal roughness length $z_{0h}$ was evaluated in two ways (as also detailed in the previous paragraph). In the first case, the displacement height $d_h$ was kept constant and
equal to the one obtained from the velocity profile \((d)\), in the second it was a free parameter in the fitting process together with \(z_{0h}\). Interestingly, both methods bring to a similar result, with differences in displacement height of less than 15% and a \(z_{0h}\) of the same order of magnitude, comparable with the one measured in the lower roughness case.

**SBL flow above the canopy**

The BL above the canopy is here presented in the form of a series of vertical profiles acquired at different locations within the model, as clearly indicated in the schematic diagram at the bottom of Fig. 5.4. All the measuring locations were in the second half of the array where, according to the work done in the DIPLOS project (Castro et al., 2017), the NBL would be fully developed. Regarding the SBL development, clear modifications take place above the array compared to the approaching flow (measured at \(x_T/H = -35\), about 1.5 m upstream of the model), while in the second half of the array the values in the first 25-30\% of the BL do not differ too much at the various locations. Nevertheless, a clear outcome on the development of the SBL over the array cannot be stated as only one full vertical profile was taken.

The mean streamwise velocity appears slower than the approaching flow for the bottom quarter of the BL (due to the increased drag), faster above (for the conservation of momentum). Consequently, the power law coefficient \(\alpha\) increases, as better shown in Fig. 5.5, varying from 0.40 to 0.60. Curiously, the value of \(\alpha\) above the array in neutral stratification is again 0.40, suggesting that for this parameter, the applied stable stratification has an effect similar to the increment in roughness under neutral conditions.

The Reynolds shear stresses above \(3H\) appear only slightly modified by the presence of the building array, suggesting a similar depth of the internal boundary layer developing above the canopy. Below, on the other hand, a dramatic increase is experienced, peaking at roof level. Interestingly, above \(3H\) the turbulence over the array appears slightly reduced compared to the approaching flow, despite the fact that the reduction in stability due to the higher roughness would suggest an increment.

As far as the mean temperature is concerned, the measured values over the array are lower than in the approaching flow up to \(5H\), unchanged above. The temperature gradient extends clearly into the canopy (with a larger gradient than above). The temperature variance profile, on the other hand, extends its similarity region down to \(2.5H\), below which the fluctuations are heavily damped. A damping in the temperature fluctuations in this region can also be observed in the results of Uehara et al. (2000) and Kanda and Yamao (2016). The streamwise and vertical heat fluxes appear less sensitive to the increase of roughness compared to the other quantities.

Fig. 5.6 presents a comparison between the three different stable stratification cases and the reference neutral at one location. The Reynolds stresses are non-dimensionalised by the friction
5.3 Effects of stratification on the boundary layer

The approaching profile is sampled at \( x_T/H = -35 \), about 1.5 m upstream of the model.

**Fig. 5.4** Vertical profiles of first and second order statistics for velocity and temperature for \( \text{Re}_f^{\text{app}} = 0.21 \).
5.3 Effects of stratification on the boundary layer

Fig. 5.5 Power law mean velocity fitting for NBL and SBL above the array and approaching flow.
velocity, while in the quantity involving the temperature fluctuation the friction temperature $\theta_*$
is introduced. In the mean velocity graph it is possible to appreciate how the slope varies with
stability layer strength: the values are gradually larger above $2.5H$ and lower below, causing an
increment of the $\alpha$ coefficient.

For the Reynolds stresses, the turbulence reduction due to stratification causes the profile
to change shape, becoming more curved, and thus deviating from the neutral case (as already
observed in the previous chapter for roughness conditions similar to the approaching flow).
The mean temperature profile appears almost unchanged in shape when varying stratification
(by means of changing the $\Delta \Theta$). The temperature variance graphs show a peak at around $2.5H$,
slightly reducing in height with increasing stratification and followed below by an almost linear
reduction. The heat flux graphs have a similar behaviour, but with a small region of constant
flux above the canopy and a more marked peak at roof level, even though these quantities
depend heavily on location in the roughness sub-layer.

As reference the field data from Caughey et al. (1979) are also plotted (Fig. 5.6). For the
Reynolds stresses, their trend is quite linear with height, causing the SBL data to deviate as
stratification increases (due to the already mentioned increment in the curvature of the profile).
Not surprisingly the NBL, looking more linear, seems to fit better the field data. The largest
difference seems to be for the vertical velocity fluctuations, likely caused by a very high value
of the friction velocity due to the large roughness imposed. The agreement is clearly better for
the thermal quantities, which appear to follow the trend, at least above $2.5H$. It is interesting to
note that for a cubic array of blocks under stratified and neutral conditions Uehara et al. (2000)
found a height of the internal boundary layer of $2.5H$, as in the present case.

Also the integral length scales for the streamwise and vertical velocity are reported (Fig. 5.7),
computed as detailed in Ch. 4. For what concern the streamwise velocity length scale, for the
neutral case the graph shows large scatter, with the profile increasing up to about $7H (0.5\delta)$
and then reducing. The amount of the length scale at the peak is also around $7H$, hence closer
to what indicated by Robins (1979) and Shirakata et al. (2002) ($\approx 0.3\delta$) respect to what found
by Kanda and Yamao (2016) ($\approx 1.1\delta$). The vertical velocity length scale, differently, increases
almost monotonically with the height above the canopy, but remaining confined to lower values
(up to $1.5H$). In the stable cases all the length scales preserve the same trend as in the neutral,
but with gradually smaller length values.

**SBL flow inside the canopy**

Fig. 5.8a-c shows the Reynolds stresses inside the canopy on the streets facing the short-edge
of the buildings. Despite the high level of turbulence mechanically produced by the building
blocks, a clear and gradual reduction due to stratification is perfectly appreciable with values
Fig. 5.6 Vertical profiles of first and second order statistics for velocity and temperature varying the level of stability at $x/H = 1, y/H = -6$. Black points are field data from Caughey et al. (1979).
5.3 Effects of stratification on the boundary layer

Fig. 5.7 Vertical profiles of integral length scales for SBL cases at $x/H = 1$, $y/H = -6$

up to four times lower than the neutral case. In Fig. 5.8d-f the same quantities are presented, but non-dimensionalised by the friction velocity. They do not seem to scale perfectly according to this parameter, with the SBL values systematically smaller than the NBL ones (as it was indeed above the canopy, too).

In terms of flow channelling, the chosen urban array model was found to produce a street canyon type flow (Castro et al., 2017), even though the ratio between long and short edge of the building was only 2. This means that the velocity in the street facing the long edge of the buildings is expected to approximately align with the road centreline, hence deviating from the mean flow direction above the canopy. Such trend is clearly visible in Fig. 5.9, where vectors of horizontal velocity are plotted at $z/H = 0.5$. The channelling appears well developed already in the NBL, while the addition of stable stratification (contrary to the initial expectations) does not seem to increase this trend. Nevertheless, the main effect of the stratification on the mean velocity inside the canopy is a general reduction of the magnitude, as already noted by other authors, see e.g. Uehara et al. (2000), Li et al. (2016), Kanda and Yamao (2016). The former explained this behaviour by the fact that cavity eddies developing inside the street canyon would be weakened by SBL (the opposite for CBL) with a reduced downward flow which, for larger Richardson numbers (not investigated here), would result in nearly zero velocity inside the canyons. Half building height above the canopy, instead, the flow is already perfectly aligned with the free-stream direction.
5.3 Effects of stratification on the boundary layer

Fig. 5.8 Reynolds stresses inside the canopy ($z/H = 0.5$) varying the stable stratification. Quantities are non-dimensionalised by both the reference (a-c) and friction (d-f) velocity.
5.3 Effects of stratification on the boundary layer

5.3.2 Convective boundary layer

Simulated CBL characteristics

Tab. 5.2 reports the main parameters for the CBL simulations. A uniform temperature profile was set at the inlet, capped by a linear inversion of roughly 10° C/m starting from 1 m upwards (as detailed in Ch. 4). Comparing the values reported in Tab. 5.1 and 5.2, there are some differences in the reference NBL mainly due to the different spires employed. Comparing the NBL results with the ones in Castro et al. (2017) obtained with a similar set-up (including the same spires) and wind orientation, it is possible to observe how the value of the friction velocity is unchanged \( \frac{u_*}{U_{REF}} = 0.081 \), while the aerodynamic roughness length is larger here \( \frac{z_0}{\delta} = 2.7 \text{ mm} \) in their case). It should be noted, though, that Castro et al. (2017) calculated \( \frac{z_0}{\delta} \) in a different manner (setting a fixed value for \( d \) from CFD and varying \( z_0 \) and \( k \)).

The effect of a CBL on the friction velocity is analogous to an increment in roughness. In fact, the value of \( u_* \) over the array with a NBL (0.081) is similar to the one in the lower roughness with \( \frac{Ri_{app}}{\delta} = -0.5 \) (0.088) and the same can be said comparing \( \frac{Ri_{app}}{\delta} = -0.5 \) over the array (0.105) with the case with the strongest instability but lower roughness (0.101). Moreover, as it was found for the SBL, the effect of increment in friction velocity consequent to the application of the stratification is less marked over the array (with an increase of 45% respect to the NBL case) than in the lower roughness case (where the increment was more consistent, 50%).

Fig. 5.9 Planar view of mean horizontal velocity vectors inside \((z/H = 0.5, \text{ left})\) and above \((z/H = 1.5, \text{ right})\) the canopy for SBL and NBL.
Table 5.2 CBL cases parameters, wind direction 45°.

<table>
<thead>
<tr>
<th></th>
<th>Lower roughness</th>
<th>Higher roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Ri_{\delta}^\text{app}$</td>
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</tr>
<tr>
<td>$\Delta \Theta_{\text{MAX}}$</td>
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<td>0</td>
</tr>
<tr>
<td>$U_{\text{REF}}$ (m/s)</td>
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<td>1.25</td>
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<td>$u_*/U_{\text{REF}}$</td>
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<td>$z_0$ (mm)</td>
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<td>$d$ (mm)</td>
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</tr>
<tr>
<td>$\delta$ (mm)</td>
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<td>1000</td>
</tr>
<tr>
<td>$\Theta_0$ (°C)</td>
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<td>-24.6</td>
</tr>
<tr>
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</tr>
<tr>
<td>$(w'\theta')_0$ (mKs$^{-1}$)</td>
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<td>0.079</td>
</tr>
<tr>
<td>$\theta_*$ (°C)</td>
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<td>-0.60</td>
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<tr>
<td>$w_*/U_{\text{REF}}$</td>
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<td>0.115</td>
</tr>
<tr>
<td>$z_{0h}$ (mm)</td>
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<tr>
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<td>52.3</td>
</tr>
<tr>
<td>$z_{0h}$ (mm)</td>
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<td>0.0050</td>
</tr>
<tr>
<td>$L$ (mm)</td>
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<td>-2340</td>
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<td>$\delta/L$</td>
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<td>0.92</td>
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<td>$Ri_{\delta}$</td>
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<td>$Re_*$</td>
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<td>$Re_{\delta} \times 10^3$</td>
<td>88.5</td>
<td>87.8</td>
</tr>
</tbody>
</table>

5.3 Effects of stratification on the boundary layer
5.3 Effects of stratification on the boundary layer

Regarding the effect of the unstable stratification on $z_0$ and $d$, it can be noted that the former experiences an increase up to 50% from the NBL, regardless the level of instability, while the latter appears reduced by roughly one half. The boundary layer depth was kept the same above the array as in the case without, since Eq. 4.8 (from Hancock et al., 2013), used to determine $\delta$ in the approaching flow, does not seem to fit the $\sqrt{\overline{w^2}}$ profile over the array. Moreover, the value of $\delta$ over the array cannot be too different from the one in the lower roughness case due to height constrains of the wind tunnel ceiling.

The vertical heat flux over the array appears reduced, also as consequence of the wooden buildings not being heated. The values of thermal roughness length are all very close to each other (same order of magnitude), and so are the displacement heights $d_h$ determined from the temperature profile. The increment in friction velocity combined with the reduction of vertical heat flux causes an increase in the values of Monin-Obukhov length over the array which are doubled compared to the approaching flow. A similar behaviour is also found for the $u_\ast/w_\ast$ ratio and $Ri_\delta$ indicating a clear reduction of the instability level, even though, as found in the SBL cases, the different reference temperature and the model blockage might be a factor for the Richardson number. The values of $Ri_H$ in the unstable cases are lower than the respective $Ri_\delta$, also as a consequence of the fact that the difference between $\delta$ and $H$ is much larger for the CBLs compared to the SBLs, in which the two Richardson numbers were found comparable.

CBL flow above the canopy

In Fig. 5.10 the vertical profiles for the lower and higher roughness cases are compared for the stronger stratification. Unlike the treatment of the SBL case in Fig. 5.4, in which the lower roughness was represented by profiles acquired upstream of the model at $x_T/H = -35$, here the average of two profiles acquired at $x_T/H = 1.4$ and 22.4 without the model in place are considered. The reason for this difference is that at $x_T/H = -35$ the CBL is still not sufficiently developed, and so it would not represent a fair comparison.

This is the only case in the dataset for which all the profiles extend throughout all the traverse range (from $z = 25$ mm to 945 mm). As a general observation, the various profiles above the array show a good degree of similarity, meaning that the flow reached an equilibrium with the roughness underneath and is not evolving longitudinally too much.

On the other hand, differences are clearly observable on the BL with and without the model. The flow slows down as an effect of the increased roughness for heights up to $4H$, while above that no differences are found on the velocities. Since for the conservation of mass flux has to remain constant, there should be a further acceleration in the region above 1 m, but no measurements were performed at such heights. As an effect of the reduction in velocity,
the mean temperature is higher in the canopy and immediately above, while the temperature fluctuations are unchanged.

Streamwise velocity variance is larger above the canopy up to about $7H$ while no significant differences are experienced by the vertical component in the same region, despite the increase in roughness, meaning that, as expected, the mixed layer does not scale with the friction velocity. The Reynolds shear stress is slightly increased over the array (as also indicated by the friction velocity). The opposite happens for the vertical heat flux which, despite the larger temperature gradient, appears reduced. As already mentioned, a possible reason is the fact that the wooden buildings are colder than the heated panels. On the other hand, the streamwise temperature flux is slightly increased over the array.

Fig. 5.11 compares results from different stratification levels at one location. The axes are non-dimensionalised by the friction velocity and temperature. As the unstable stratification increases a mixed layer develops above the roughness sub-layer, with almost constant velocity above $z/H = 3$ in the most unstable case. For the $Ri_{\delta}^{app} = -0.5$ case a velocity profile that is of intermediate shape between the NBL and the $Ri_{\delta}^{app} = -1.5$ cases is observed. A similar consideration can be made for the mean temperature profile. The streamwise velocity variance appears to scale appropriately with the friction velocity up to $5H$, while above this the unstable stratification causes an increase in fluctuations. The threshold appears to be lower for the vertical velocity variance, where the vertical profile starts to be different immediately above the canopy. Observation of the Reynolds shear stress reveals that a region of strictly constant flux above the canopy never develops, as also observed by Cheng and Castro (2002a). On the other hand, vertical heat fluxes present a constant region up to about 8-10$H$. Finally, streamwise heat fluxes and temperature fluctuations scales reasonably well with friction temperature.

The integral length scales for the streamwise and vertical velocity are reported in Fig. 5.12. For the streamwise length scale the $Ri_{\delta}^{app} = -0.5$ case shows quite a similar trend compared to the neutral case, with only slightly larger values above $z/H = 5$. Conversely, the case $Ri_{\delta}^{app} = -1.5$ shows slightly smaller values compared to the neutral one. This apparently opposite trend is very likely just due to the large scatter. It should be noted that also Boppana et al. (2014) found only a very small reduction in the streamwise velocity length scale after the application of CBL. On the other hand, in the vertical component of the velocity the length scales increase with the instability level, as expected, due to the larger vertical structure and boundary layer depth. Peaks of $\Lambda_w$ are, respectively, $0.14\delta$, $0.3\delta$ and $0.36\delta$ for the three cases considered. The differences in the vertical velocity length scale are much larger than in the streamwise one. On this aspect, by comparing experiments with and without spires, Kanda and Yamao (2016) found that $\Lambda_w$ is very dependent on the turbulence generator, more than on the applied stratification.
Fig. 5.10 Vertical profiles of first and second order statistics for velocity and temperature for $Ri_{\delta}^{app} = -1.5$. The data without the urban array are obtained as average of two profiles at $x_T/H = 1.4$ and 22.4, $y_T/H = 0$ in wind tunnel coordinates.
5.3 Effects of stratification on the boundary layer

Fig. 5.11 Vertical profiles of first and second order statistics for velocity and temperature varying the level of instability at $x/H = 1$, $y/H = -6$. 

\[
\frac{U}{U_{REF}} \quad \frac{\Theta - \Theta_0}{\Theta_0 - \Theta_0}
\]

\[
\frac{\partial}{\partial} \frac{u'u'}{u^2} \quad \frac{\theta'^2}{\theta^2} \quad \frac{w'\theta'/(u, \theta_*)}{u^2} \quad \frac{w'\theta'/(u, \theta_*)}{\theta^2}
\]
5.3 Effects of stratification on the boundary layer

Finally, velocity and temperature variances as well as vertical heat fluxes are shown in Fig. 5.13 normalised by the mixed layer scaling velocity and temperature. They are compared with data from literature, like in Fig. 4.19 where data without an urban model was considered. Profiles above the canopy do not differ much from the ones without model, as already noted in Fig. 5.10, hence similar comments to the ones provided in the previous chapter for Fig. 4.19 are valid here as well. In addition, experimental profiles by Kanda and Yamao (2016) are also considered (they refer to a CBL case characterised by $Ri_\delta = -0.27$ and $\delta/L = -0.61$). The trend they show for all the turbulent quantities is remarkably similar to the one found here, in particular for the vertical heat flux. Kanda and Yamao (2016) commented on the difference between the heat flux profile measure in the laboratory and the linear trend from field measurements, attributing the discrepancy to the usage of fences and spires, which introduce larger energetic eddies. Conversely, in the SBL cases, the larger eddies are suppressed. Also the low values of $\delta/L$ may play a role (as indicated in Ch. 4).

CBL flow inside the canopy

Fig. 5.14 shows the Reynolds stresses inside the canopy. The effect of unstable stratification is here a clear increase in the magnitude of the streamwise and vertical velocity variance. For $\overline{u'w'}$ the scatter between the points at different locations but same position respect to local buildings in the CBL cases suggests a high level of unsteadiness, for which a longer measuring time would be preferable. Fig. 5.14d-f presents the same graphs non-dimensionalised by the friction velocity.
5.3 Effects of stratification on the boundary layer

Fig. 5.13 Profiles of non-dimensional Reynolds stresses, temperature variance and vertical kinematic heat flux at $x/H = 1$, $y/H = -6$. Data is compared with Caughey and Palmer (1979), Ohya and Uchida (2004) (case E2), Wilczak and Phillips (1986), Wood et al. (2010) and Kanda and Yamao (2016).
5.3 Effects of stratification on the boundary layer

Fig. 5.14 Reynolds stresses inside the canopy ($z/H = 0.5$) varying the unstable stratification. Quantities are non-dimensionalised by both the reference (a-c) and friction (d-f) velocity.
5.4 Effects of the stratification on the dispersion

5.4.1 Plume characteristics

Stable stratification

In Fig. 5.15 contour plots of pollutant mean concentration are shown for the NBL and a SBL case \((Ri^\text{app} = 0.21)\) both inside \((z/H = 0.5)\) and above \((z/H = 1.5)\) the canopy from a ground level source release at \(x/H = -1\) and \(y/H = -1.5\). It can be noted how the plume central axis (evaluated as detailed in the Appx. F) does not seem to be affected by the applied stable stratification inside the canopy. In fact, the axis appears to deviate from the free-stream wind direction by about \(14.7^\circ\) in both cases, due to the street canyon channelling effect. This is even more evident in the first \(2H\) downstream of the source, where the plume axis is almost coincident with the street canyon centreline. Above the canopy, the plume axis still presents a deflection from the free-stream wind direction, despite the fact the flow field is already completely aligned (as shown in Fig. 5.9). The angles are slightly different, though (\(8.6^\circ\) for NBL and \(10.8^\circ\) for SBL). This can be seen as a result of the fact that the pollutant concentrations in the canopy remain larger further away from the source in case of stable stratification.

The plume width does not appear significantly affected by the applied stratification inside the canopy, with just a small reduction, and similar statement can be made for the plume above. This can be better appreciated from the lateral profiles of mean concentration shown in Fig. 5.16, where the values for two other levels of stability are plotted as well.

In order to quantify the effect on the width of the plume, a fitting was attempted with a Gaussian distribution (see Sec. 2.4.1). The following curve

\[
\bar{C} = Ae^{-\frac{(y_{\text{plume}} - \mu)^2}{2\sigma_h^2}}
\]

in which \(A\), \(\mu\) and \(\sigma_h\) are free fitting parameters, was fitted (by means of a non-linear least squares method) to profiles extrapolated from the contour plots, perpendicular to the axis of the plume indicated in Fig. 5.15. On this aspect, two axes were defined, \(x_{\text{plume}}\) which coincides with the plume axis, and \(y_{\text{plume}}\), perpendicular to the former, as shown in Fig. 5.17. In Fig. 5.18 the values obtained for \(\sigma_h\) (representative of the plume width along \(y_{\text{plume}}\)) are displayed for the neutral reference and the \(Ri^\text{app} = 0.21\) cases for five \(x_{\text{plume}}\) locations (the origin of the plume reference system was chosen so that \(x_{\text{plume}}\) represented the distance of the lateral profiles from the source). The trend of \(\sigma_h\) shows that inside the canopy the plume width is only very slightly reduced by the stable stratification, and only far from the source. Above, instead, a difference (but still very small) is discernible throughout the plume.
Fig. 5.15 Contour plots of non-dimensional mean concentration for NBL and SBL inside and above the canopy for wind direction 45°. Black line is plume centreline, violet line is free-stream wind direction.
5.4 Effects of the stratification on the dispersion

\[ \frac{\bar{C}_U}{R_{2pp}^2} = -3 \]
\[ \frac{\bar{C}_U}{R_{2pp}^2} = -9 \]
\[ \frac{\bar{C}_U}{R_{2pp}^2} = -21 \]

Fig. 5.16 Lateral profiles of mean concentration inside and above the canopy for four levels of stability.
5.4 Effects of the stratification on the dispersion

Fig. 5.17 Plume axes reference system.

Fig. 5.18 $\sigma_y$ for SBL and NBL varying the distance from the source at $z/H$ of 0.5 (a) and 1.5 (b). The Gaussian fitting for each profile is shown in Fig. E.2.
The mean concentration values, on the contrary, show a clear effect of the different stratification levels. In all the graphs shown in Fig. 5.16, the concentration – both inside and immediately above the canopy – appears larger in the SBL and increasing with $Ri_\delta$ up to about twice as large. The only exception is in the upper region closer to the source, in which the trend is inverted. This behaviour is expected and due to the reduced vertical displacement of the flow under a SBL.

Similarly, the plume depth is smaller under stable stratification, as shown in Fig. 5.19. It is also possible to note how all the SBL cases seem to behave similarly above $1.5H$, showing the same plume depth reduction of up to 30% compared to the NBL. Within the canopy, the concentration level appears constant with height, at least down to the lowest measured position ($0.5H$).

The $\sigma_z$ plot (Fig. 5.20), obtained as $\sigma_h$ by replacing the $y_{plume}$ with the $z$ axis, confirms that the plume depth is very similar in the three considered stability cases, starting to differ only after $10H$ from the source. It is possible to note that the values of $\sigma_z$ appeared to be more sensitive to the stable stratification than $\sigma_h$. This is in agreement with what observed by Briggs (1973) in field experiments over urban roughness. On the contrary, Kanda and Yamao (2016) found an opposite behaviour, with the plume depth almost unaffected and the width sensibly reduced by the application of stable stratification. They were not able to explain such a peculiar behaviour.

The lateral concentration fluctuation profiles at 0.5 and $1.5H$ (not shown) have a similar trend to the mean concentration, varying with stratification in the same manner. The behaviour of the vertical profile, though, is different up to $z/H = 2$, as shown in Fig. 5.21, where the fluctuations present an increase to a maximum above the canopy, followed by a reduction further above. Nevertheless, the amplification or reduction of the variance values following the stratification is similar to what experienced by the mean concentrations. To be noted that in the profile closer to the source ($x/H = -1$, $y/H = -3$) the fluctuation is two orders of magnitude larger than the next location, with a trend similar to the mean concentrations.
5.4 Effects of the stratification on the dispersion

Fig. 5.19 Vertical profiles of mean concentration approximately along the plume axis for four levels of stability.
5.4 Effects of the stratification on the dispersion

Fig. 5.20 $\sigma_z$ for SBL and NBL varying the distance from the source. The Gaussian fitting for each profile is shown in Fig. F.1.

Unstable stratification

Fig. 5.22 shows contour plots of pollutant mean concentration for the NBL and a CBL case ($R_i^{app} = -1.5$) both inside ($z/H = 0.5$) and above ($z/H = 1.5$) the canopy from a ground level source release at $x/H = -1$ and $y/H = -1.5$. Conversely from the considered SBL cases, the plume central axis here appears modified by the unstable stratification also inside the canopy, with an angle increment of 20% respect to the wind direction. The same percentage increase is found for the region above the canopy.

When comparing the mean concentration values the unstable stratification effect appears opposite to what measured for the SBL. In this case, the concentration levels are reduced almost everywhere (up to three times), as a consequence of the increased vertical exchange. This fact is better appreciable in Fig. 5.23, where the lateral profiles of the two cases are shown, together with a case of intermediate instability. The results for the latter lays between the NBL and the stronger instability case. Fig. 5.24 displays the computed values of $\sigma_h$, representative of the plume width. The trend shows here a clearer increase inside the canopy (after $9H$), compared to the SBL. Above the canopy a difference is discernible throughout the plume, as it was for the SBL. The results for the intermediate instability case lay again between the NBL and the strongest instability.

The plume depth starts differing from $x/H = 1$, as discernible in Fig. 5.25, where vertical profiles of mean concentration are shown for different locations. It appears deeper, indicating that the pollutant tracer is able to penetrate deeper into the BL above the canopy, reaching a height of more than $7H$ at the farthest measured location, even though with very low concentra-
Fig. 5.21 Vertical profiles of concentration variance approximately along the plume axis for four levels of stability.
Fig. 5.22 Contour plots of non-dimensional mean concentration for NBL and CBL inside and above the canopy for wind direction $45^\circ$. Black line is plume centreline, violet line is free-stream wind direction.
5.4 Effects of the stratification on the dispersion

Fig. 5.23 Lateral profiles of mean concentration inside and above the canopy for three levels of instability.
5.4 Effects of the stratification on the dispersion

Fig. 5.24 $\sigma_h$ for CBL and NBL varying the distance from the source at $z/H$ of 0.5 (a) and 1.5 (b). The Gaussian fitting for each profile is shown in Fig. F.2.

Concentration values. Such a trend is expected, since the enhanced vertical exchange due to the buoyancy forces contributes to clean the air inside the canopy, facilitating the exchange with the region above. The $\sigma_z$ plot in Fig. 5.26 confirms this behaviour, with the parameter showing a clear and progressive increment after the application of unstable stratification, more evident than the variation in the plume width. Again this result is in accordance with Briggs (1973) and in contrast with Kanda and Yamao (2016).

The concentration variance (Fig. 5.27) seems to behave like described for the stable cases, varying according to the mean concentration levels.

5.4.2 Vertical pollutant fluxes

Fig. 5.28 shows the graphs of vertical velocity variance, mean concentration, vertical turbulent and total pollutant fluxes with varying stable stratification levels at a location at the centre of an intersection. Inside the canopy the turbulent fluxes are close to zero (and slightly negative), while the total ones experience a peak at about $0.5H$ (the lowest measured position), meaning that the mean pollutant fluxes are predominant there. In general, the total vertical fluxes follow the trend of the mean concentration profile, also when different levels of stratification are involved. Despite this, the turbulent fluxes experience a steep peak at roof level (or slightly above), reaching values similar to the mean fluxes. This is an important aspect because the roof level is critical in the exchange between the canopy and the upper region. Moreover, the total pollutant flux at roof level is not seen to be affected by the stratification (at least at the centre of the intersection). The fact that the total fluxes inside the canopy are larger in the stratified case
5.4 Effects of the stratification on the dispersion

Fig. 5.25 Vertical profiles of mean concentration approximately along the plume axis for three levels of instability.
5.4 Effects of the stratification on the dispersion

Fig. 5.26 $\sigma_z$ for CBL and NBL varying the distance from the source. The Gaussian fitting for each profile is shown in Fig. F.1.

despite the reduced vertical turbulence is indicative of the predominance of the mean fluxes over the turbulent ones. Above the canopy, however, both the total and turbulent flux appear to be reduced by stratification.

In the CBL case, as previously mentioned, the vertical velocity fluctuations are enhanced everywhere. On the other hand, the concentration levels are reduced inside and above the canopy until a point (that in the case of Fig. 5.29 is at about $2H$) after which the concentration starts being larger than the NBL, hence making the plume deeper. In this situation, the vertical turbulent pollutant flux appears generally increased inside the canopy and above $1.5H$. In the region immediately above the roof level, instead, a steep gradient seems to advantage the neutral case. That said, inside the canopy the turbulent flux remains irrelevant compared to the mean values except, again, at roof level and above, where they have the same order of magnitude.

An interesting point to analyse is the similitude between vertical turbulent pollutant fluxes and concentration gradient

$$K_z \frac{\partial C}{\partial z} = -\bar{w}'c'$$  \hspace{1cm} (5.2)

where $K_z$ is a constant of proportionality (as introduced in Sec. 2.4.1). In fact, such behaviour was demonstrated by Dezso-Weidinger et al. (2003), confirmed by Carpentieri et al. (2012) for neutral stratification and it is normally used in models to compute vertical turbulent pollutant fluxes. Nevertheless, its validity in the SBL and CBL cases was still questioned. In Fig. 5.30 profiles of vertical turbulent pollutant fluxes are plotted and compared with the concentration
Fig. 5.27 Vertical profiles of concentration variance approximately along the plume axis for three levels of instability.
5.4 Effects of the stratification on the dispersion

![Graphs](image)

**Fig. 5.28** Vertical profiles of vertical velocity variance, mean concentration, turbulent and total vertical pollutant flux varying the stable stratification at the centre of an intersection \((x/H = 1, y/H = -6)\).
5.4 Effects of the stratification on the dispersion

Fig. 5.29 Vertical profiles of vertical velocity variance, mean concentration, turbulent and total vertical pollutant flux varying the unstable stratification at the centre of an intersection ($x/H = 1$, $y/H = -6$).
gradient profiles obtained from a Gaussian fit of the mean concentration. The proportionality in this case is evident, though the constant of proportionality seems to vary. In particular, it tends to increase with unstable stratification and decrease with stable, ranging from 0.009 to 0.06. A variability depending on the location and mechanical turbulence was found by Carpentieri et al. (2012) and it is confirmed here (the constant reaching a value of 0.14 in case of stronger stratification, see Tab. 5.3).

In Fig. 5.31 the values of the mean $K_z$ from Tab. 5.3 are plotted against $Ri_\delta$ and $\delta/L$. A parametrisation is attempted by means of a polynomial fitting of the second order (also shown in the figure)

$$K_z (\delta/L) = 0.0202 (\delta/L)^2 - 0.0425 (\delta/L) + 0.0306 \quad (5.3)$$

$$K_z (Ri_\delta) = -0.0064 Ri_\delta^2 - 0.0839 Ri_\delta + 0.0294 \quad (5.4)$$

### 5.4.3 Joint probability density function of vertical velocity and concentration fluctuations

The effects of stratification on the joint probability density distribution of vertical velocity and concentration fluctuations are now analysed. Five different heights along a vertical profile at the centre of an intersection ($x/H = 1, y/H = -6$) are considered, both inside and above the canopy up to $z/H = 1.5$ for three levels of stratification. The number of bins and their range was kept the same for all cases. For a description of the technique and quadrant subdivision see Appx. C.
5.4 Effects of the stratification on the dispersion

\[ R_i^{\text{app}} = 0 \]

\[ R_i^{\text{app}} = 0.14 \]

\[ R_i^{\text{app}} = 0.21 \]

\[ R_i^{\text{app}} = 0.29 \]

\[ R_i^{\text{app}} = 0.5 \]

\[ R_i^{\text{app}} = 1.5 \]

**Fig. 5.30** Vertical profiles of vertical turbulent pollutant fluxes \((x/H = 1, y/H = -6)\) with varying stratification (a-d obtained with the SBL set-up, e-g with the CBL one). The red triangles are the vertical turbulent pollutant flux, while the blue line is the gradient of dimensionless concentration over \(z/H\) obtained by a Gaussian fit of the mean concentration vertical profile (see Fig. F.1).
5.4 Effects of the stratification on the dispersion

Fig. 5.31 Relation between the mean of $K_z$ at three locations and $Ri_\delta$ or $\delta/L$. Dotted lines are obtained by fitting the experimental data with a polynomial curve.

From Fig. 5.32 it is possible to observe how the graphs for the NBL and SBL are very similar. On the other hand, a trend is observable, with the higher values of concentration fluctuations slightly more probable in SBL than in the NBL. On the CBL the contours appear narrower with the concentration fluctuations concentrated in a smaller range with higher probability. Despite these differences in the concentration fluctuation range, the vertical velocity fluctuations span a similar range for the three cases (appropriately non-dimensionalised by the friction velocity). Moreover, at a height of $1.5H$ the most probable event seems the entrainment of clean air from above (sweeps) for all the stability cases.
5.4 Effects of the stratification on the dispersion

\[
\begin{align*}
\text{SBL} - R_{ib}^{APP} &= 0.21 \\
\text{NBL} - R_{ib}^{APP} &= 0 \\
\text{CBL} - R_{ib}^{APP} &= -1.5
\end{align*}
\]

Fig. 5.32 Joint probability density distribution for three stability levels at the centre of the intersection \((x/H = 1, y/H = -6)\). \(c'_* = c'U_{REF}H^2/Q\).
Chapter 6

Local heating effects

6.1 Introduction

In this chapter the results of the simulation of neutral and stable approaching flow in combination with local wall and ground heating for a bi-dimensional street canyon with unity aspect ratio will be presented. Firstly, the approaching flows to the model will be briefly described. Then, consideration on the Reynolds number independence will be given. Results are hence presented, focusing on the velocity and TKE field, mean temperature and heat flux, mean concentration, pollutant fluxes and common ventilation coefficients. The dispersion is investigated by releasing a passive tracer from a ground point source in the centre of the canyon. Also a quadrant analysis will be considered (see Appx. C), in which the fluctuations of two quantities at single locations are decomposed into four quadrants. Three pairs of parameters will be taken into account, namely the interactions between the vertical velocity fluctuations and the fluctuations of streamwise velocity, temperature and concentration. For the terminology associated to each quadrant see the scheme in Fig. C.1.

Most of the results presented in this chapter have been published in Marucci and Carpentieri (2019).

6.2 Approaching flow

Two different types of approaching flows were studied, a neutral and a stable boundary layer. The scaling characteristics of the two boundary layers are reported in Tab. 6.1. The reference velocity $U_{REF}$ was chosen equal to 0.65 m/s. This quite low velocity was necessary to obtain appreciable local stratification effects within the canyon. The boundary layer depth was approximately equal to 5 times the model height. $\Delta \Theta$ is the difference between the air...
temperature at the boundary layer top ($\Theta_\delta$) and the wind tunnel floor temperature ($\Theta_0$). Three non-dimensional numbers are given to quantify the approaching flow stability level (already introduced in the previous chapters but in the following repeated for clarity). The ratio $\delta/L$ and the bulk Richardson number, evaluated at the boundary layer top, $Ri_\delta$, and at model top, $Ri_H$

$$Ri_\delta = \frac{g (\Theta_\delta - \Theta_0) \delta}{\Theta_0 U^2_\delta}, \quad Ri_H = \frac{g (\Theta_H - \Theta_0) H}{\Theta_0 U^2_H}$$

(6.1)

Finally, for the same two heights also two Reynolds numbers are evaluated ($Re_\delta$ and $Re_H$), while the roughness Reynolds number is $Re_* = z_0 u_* / \nu$ (the kinematic viscosity $\nu$ is the one at floor temperature for all three).

Vertical profiles of first and second order statistics of velocity and temperature are displayed in Fig. 6.1 for three locations along the wind tunnel centreline, acquired without the street canyon model. The most evident effect of the stable stratification on the approaching flow is the large dampening in the turbulence, well represented by the friction velocity reduction of almost 50%. Conversely, the mean velocity profile is only slightly modified, according to what already observed in Ch. 4, to which refer for further comments.

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1$\Theta_0$ in this chapter was measured by averaging the measurements from a series of five thermistors attached to the cooled wind tunnel floor every 2 m. Temperature variations within $\pm 0.3^\circ C$ were observed but deemed acceptable.
Fig. 6.1 First and second order statistics for the approaching flow. Black lines are NBL while blue are SBL.
6.3 Reynolds number effect

Reynolds number independence is a key feature of fluid dynamics experiments to guarantee that normalised velocities are representative of the full-scale flow field. The necessity to work with small velocities to obtain reasonable buoyancy effects with reasonable wall temperatures in local stratification studies means that Reynolds independence might be difficult to satisfy. In order to assess the Reynolds number effect for the chosen velocity the isothermal case was repeated with different reference speeds (varying from 0.5 to 1.25 m/s). Fig. 6.2 shows a vertical profile of the mean velocities and TKE. The TKE is evaluated as \( \frac{3}{4} u'^2 + \frac{3}{4} w'^2 \), assuming that the lateral component \( v'^2 \) (not measured) behaves like the average of the other two (Allegrini et al., 2013). The measurements show that \( U \) is rather insensitive to the Reynolds number in that range, while \( W \) experiences a slight reduction above the canopy for the two lower velocities considered. The same can be said for the TKE which, in the \( U_{REF} = 0.65 \) m/s case, sees an average reduction of 5% above the canopy and 9% within it, compared to the 1.25 m/s case. These can be considered small and the \( U_{REF} = 0.65 \) m/s case can reasonably be taken as representative for a full-scale flow. Fig. 6.3 shows the velocity vectors for the 1.25 and 0.65 cases. The most critical part is represented by the canyon lower-right corner (also visualised in the magnified window). Here the lower velocity case appears to differ the most, but the region affected is also quite limited in space, so that it does not seem to affect a large portion of the flow field.

Finally, it is worth mentioning that in all the cases presented here, \( Re_H \) is always larger than 3400, which is the critical value indicated by Hoydysh (1974) to have independence from viscous effects in the street canyon flow pattern. The result is also supported by the fact that \( Re_* \) (used to evaluate whether the surface is fully rough) is, for the slowest case, still greater than 1, which is the minimum value indicated by Snyder and Castro (2002) for sharp-edged roughness elements in a NBL. It should be stressed that the comparisons and criteria employed here are for an isothermal case, while it is still under debate their extension to non-isothermal cases (as very recently pointed out by Chew et al., 2018).

6.4 List of cases and scaling quantities

Five local heating configurations were investigated during the experiments: no heating (NH), windward wall heated (WH), leeward wall heated (LH), ground heated (GH) and all the three cavity surfaces heated (AH). The measurements were repeated with neutral and stable approaching boundary layers (indicated as SNH, SWH, SLH, SGH and SAH, respectively for
Fig. 6.2 Mean streamwise, vertical velocity and TKE for different reference velocities, equivalent to \( Re_H 10000, 8000, 6000, 5200, 4000. \) \( x/H = -0.3. \)
the five cases highlighted above) to investigate the combined effects of approaching flow and local stratification.

Tab. 6.2 lists the local scaling quantities for the different experimental cases, which will be used to normalise the graphs in the following sections.

\( U_{2H} \) and \( \Theta_{2H} \) are, respectively, the mean streamwise velocity and temperature measured at \( x/H = 0, \ z/H = 2 \). They will also be used to normalise the respective quantities in the following graphs, so that a comparison with the literature (widely using a similar scaling) is possible. \( \Theta_{GROUND} \) is the temperature of the ground measured inside the street canyon, while \( \Theta_{HOT} \) is the temperature of the heated canyon surface(s). A local Richardson number is defined...
to quantify the local stratification in case the canyon wall or ground heating is applied. It is defined as

$$Ri_{Local} = \frac{g(\Theta_{2H} - \Theta_{HOT})H}{\Theta_{2H}U_{2H}^2}$$  (6.2)

Because of the lower $\Theta_{HOT}$ temperature for the [S]GH and [S]AH cases (due to the heat transfer with the wind tunnel floor) the $Ri_{Local}$ is smaller than for the other cases ([S]WH and [S]LH). For this reason only a qualitative comparison between the latter cases and the differential wall heating ones is possible.

The lateral variability of flow quantities was also investigated in order to assess the bi-dimensionality. Two lateral profiles at $x/H = -0.3$, $z/H = 0.2$ and $x/H = 0.3$, $z/H = 0.9$ have been measured in the range $y/H = \pm 3$ for each case. On average, the streamwise velocity variability was in the range $\pm 18\%$ compared to the mean value and $\pm 10\%$ for the vertical component. The temperature was laterally quite uniform ($\pm 1\%$). Velocity and temperature variances were within $15\%$, more variability for the covariances ($\pm 50$ and $30\%$ for velocity and temperature, respectively). Overall, the uniformity in the investigated range was deemed satisfactory. Finally, it is worth mentioning that for all the contour graphs and spatially-averaged statistics displayed in the following paragraphs, experimental data have been interpolated by using the “natural neighbour method” (Sibson, 1981) on a grid with resolution $H/100$.

### 6.5 Flow and temperature field

#### 6.5.1 Flow and turbulence

Fig. 6.4 shows the contours of normalised mean velocity, as well as streamlines. Also vertical profiles for $x/H = 0$ and longitudinal profiles at $z/H = 0.5$ are presented for the various configurations. For the contours graphs and spatially averaged statistics displayed here and in the following figures, experimental data has been interpolated on a grid of resolution $H/100$ with the “natural neighbour interpolation” method (Sibson, 1981). The flow structure inside the canyon with incoming NBL when no local heating was applied is characterised by a single-vortex pattern whose centre is located at $x/H = 0$ and approximately at a height of $z/H = 0.6$. Conversely from what other authors observed (e.g., Allegrini et al., 2013, Li et al., 2016, Park et al., 2012), no secondary vortices are present close to the bottom corners, but this may be due to the lower resolution of the measurement grid (the closest measuring point to the surfaces is $0.1H$ from them). The above structure is retained with only minor modifications in the LH and GH case as well. Conversely, in the WH case a second counter-rotating vortex arises, generated by the buoyancy forces produced by the heated wall, which opposes the
Fig. 6.4 Contours and vectors of mean velocity, white lines are streamlines. The red lines represent the heated surfaces in each case ([S]NH left, [S]WH centre up, [S]LH right up, [S]GH centre down, [S]AH right down). The line plots on the right show the vertical profiles of mean streamwise velocity at $x/H = 0$ and the longitudinal profiles of mean vertical velocity at $z/H = 0.5$; NBL = continuous lines, SBL = dashed lines.
Fig. 6.5 Contours of TKE. The red lines represent the heated surfaces in each case ([S]NH left, [S]WH centre up, [S]LH right up, [S]GH centre down, [S]AH right down). The line plots on the right show the vertical profiles of longitudinally-averaged TKE at $x/H = 0$ and the longitudinal profiles of vertically-averaged TKE at $z/H = 0.5$; NBL = continuous lines, SBL = dashed lines.
descending motion of the air into the canyon, hence slowing down the velocity (as better shown by the profiles on the right-hand side of the figure, in which the vertical velocity closer to the windward wall appears to become even positive). A similar behaviour was observed by several authors (e.g. Sini et al., 1996, Allegrini et al., 2013, Cai, 2012b), hence a consensus seems to have been established. The centre of the main vortex appears shifted toward the upper corner of the leeward building (differently from Cai, 2012b, in which the centre was moved towards the windward wall upper corner) and, on average, the mean velocity within the canyon is 50% lower than in the NH case. It should also be noted that the streamlines in the WH case do not appear completely closed. A winding flow of this type was also observed by Park et al. (2012) and Kovar-Panskus et al. (2002). Park et al. (2012) commented that this phenomenon can appear when the mechanical and thermal forcings act together but in the opposing way. Another factor might be the presence of three-dimensional flows. In this regard, Allegrini (2018), investigating a case of three-dimensional street canyon subject to ground heating, found important modifications on the velocity along the canyon axis due to buoyancy. Future measurements of lateral velocity components might help in clarifying this issue. Park et al. (2012) and Kovar-Panskus et al. (2002) do not comment further about this aspect. The windward wall heating is also responsible for some modifications in the flow pattern for the AH case, even though of minor extent. The latter, in fact, appears slightly distorted at the bottom windward corner, due to the buoyancy arising from the heated wall. Excluding the WH case, in all others cases, buoyancy forces act to accelerate the flow, thus resulting in a 37%, 29% and 23% average increment of the velocity within the canyon for cases LH, GH and AH, respectively.

The application of the incoming SBL has an evident effect on reducing the mean velocity, mainly in the bottom half of the canyon. Li et al. (2016) simulated a similar level of stability for the approaching flow in bi-dimensional street canyons and they too found similar conclusions. However, in their case this effect was more accentuated, leading to the formation of real stagnation regions closer to the ground. In our measurements the reduction is more modest, but it should be stressed that the geometry here is not exactly the same as in Li et al. (2016). In the SWH case, the SBL has the effect of further slowing down the speed, leading to the formation of almost-zero velocity regions within the canopy. Conversely, in the SLH case the SBL exerts a much lower reduction on the mean velocity field. It can be argued that since local heating and stable approaching flow have opposite effects on the mean velocity field, in this particular case the local heating overcomes the incoming stability. On average, the velocities in the canopy are reduced by 16, 34 and just 1% for the SNH, SWH and SLH cases, respectively, compared to the NBL cases. For the SGH case the average velocity value is unchanged, while for the SAH a reduction of 26% is observed. The latter result may be explained by assuming that the
acceleration due to wall heating is more sensitive to thermal stratification above the canopy than just the ground heating. Allegrini et al. (2013) also pointed out how the GH case is the most effective in accelerating the flow in the canopy, hence it should not surprise if it is also the best in opposing the velocity reduction due to the SBL.

The observed TKE fields are reported in Fig. 6.5. A logarithmic scale was deemed necessary, in order to adequately discern also the smallest variations of turbulence in the canopy (the averaged profiles on the right side, however, are in linear axes). In all cases the largest values of TKE are found in the region between $z = H$ and $1.5H$, above the canopy. In the WH case, the main feature is the presence of an increasingly turbulent region close to the heated wall, with the turbulence peaking around the upper windward street-canyon corner and spreading upstream. Allegrini et al. (2013) found the maximum TKE values in the same region, attributing this to the fact that there the cold air enters the canyon, hitting the warmer air, which is rising due to buoyancy at the windward wall. The longitudinally-averaged profile appears to grow almost linearly in the canopy. A similar trend was found also by Park et al. (2012), despite the fact that they presented only profiles at the vertical centreline. In the LH case, the increment in TKE in the canyon is more limited and not located near the heated wall, but closer to the windward wall (as also pointed out by Allegrini et al., 2013). The slight reduction of TKE above the canopy is likely not generated by the leeward wall heating, but rather from the way the model was cooled. In fact, in order to allow the wind tunnel to remotely change from neutral to stable approaching flow, the cooling water used to refrigerate the unheated model surfaces was allowed to flow also in the rest of the wind tunnel floor. Since such water (to regulate the laboratory temperature) was set to 1°C lower than the free-stream one, the generated approaching flow presented a slightly positive temperature gradient, hence resulting in a very weak SBL, instead of a completely neutral one. This procedure was corrected for the other cases, so they do not show this issue. For the GH case, the increment in TKE compared to NH is quite uniform, involving all the locations in the canopy and leading to a 40% larger averaged value. For the AH case the variation is more significant with an increment of 160% in particular close to the windward wall.

When scaled with the reference velocity, the stable stratification generates a strong and generalised reduction of TKE both above and inside the canopy, also in the presence of wall heating. This is estimated in an average decrease inside the canopy of 50 and 46% for the SNH and SWH compared to the NBL cases, while for the SLH, SGH and SAH such reduction was smaller (30%). Despite the different local stratification, above $1.25H$ the TKE profiles collapse very well on each other in the SBL cases, meaning that the wall buoyancy-generated turbulence does not affect the SBL above. To be noted that the TKE reduction inside the canopy is not as large as for the approaching flow (see Figure 6.1), for which the levels where almost four times
6.5 Flow and temperature field

lower after the application of the SBL. This brings to state that the influence of local obstacle and source of heating on the local TKE field is, on average, stronger than the approaching flow stability effect, hence reduction in the incoming flow turbulence levels do not correspond to decrease of TKE in the canyon of the same amount.

6.5.2 Temperature and heat fluxes

Contour plots of mean temperature in the various cases are shown in Fig. 6.6 and 6.7 (except the NH case where there is no temperature variation). Vertical and longitudinal profiles of longitudinally- and vertically-averaged mean temperature are also presented. It should be noted that, since velocity, temperature and concentration measurements took place at the same time, it was chosen to align the LDA with the exact desired measuring location, letting the cold-wire and FFID measuring 5 mm downstream. This measuring offset is taken into account in the graphs of mean temperature and concentration (whose contour plots appear moved 5 mm on the right side), while when fluxes are of concerned, the location of the LDA will be considered. For the SNH case the temperature is normalised as \( \frac{\theta - \theta_{2H}}{\theta_{2H} - \theta_{GROUND}} \). Above the canopy the temperature is clearly vertically stratified, while warmer air is observed sinking closer to the windward wall and raising colder along the leeward one, once being cooled by the floor. Thus, the stratification within the canopy appears to be directed horizontally across the canyon rather than vertically.

In the ground- and wall-heated cases the temperature is normalised as \( \frac{\bar{\theta} - \theta_{2H}}{\theta_{HOT} - \theta_{2H}} \). In the WH and LH cases the warming effect appears to be mostly confined near the heated wall, with the WH case producing a larger increment in temperature compared to the LH case. However, because of the way the different instruments are mounted (as previously mentioned), the temperature measurement grid is closer to the windward wall (0.07\( H \)) than to
Fig. 6.7 Contours of mean temperature. The red lines represent the heated surfaces in each case ([S]WH left up, [S]LH right up, [S]GH left down, [S]AH right down). The line plots on the right show the vertical profiles of longitudinally-averaged mean temperature and the longitudinal profiles of vertically-averaged mean temperature; NBL = continuous lines, SBL = dashed lines.
the leeward wall ($0.13H$). This contributes to the lower maximum temperatures observed for the LH and SLH cases. Keeping this in mind, it is noted that the averaged mean normalised temperature within the canopy is also higher for WH (0.104) than for LH (0.083). As pointed out by Cai (2012b), they are representative of the warming efficiency of the heated wall on the canyon air. Above the canopy, though, the LH case presents larger temperatures compared to WH, meaning that the heating from the leeward wall is dispersed more in the upper region, as expected from the stronger mean vortex flow. For the GH case, the heating is less dispersed above the canopy, as a consequence of the fact that the heated surface is deeper into the canyon. Despite this, the normalised average temperature in the canyon is lower than in the LH case (0.065 for GH, against 0.083 of the LH case), even though a comparison with the same surface temperature would help clarifying if the GH case is really less effective in heating the canopy. Conversely for the AH case, the normalised average temperature is 0.246, larger than all the others as expected, since more heat is provided to the air in the canyon and less is subtracted (being all the three internal surfaces heated).

The application of the incoming stable stratification appears to lower the normalised temperature inside the canopy in all the cases except the SAH, without altering the shape of the longitudinally- and vertically-averaged profiles. This may be caused by the fact that for the SBL case the not-heated walls are refrigerated at a lower temperature than for the NBL ($5^\circ C$ colder since a lower cooling water temperature is needed to stratify the approaching flow). They are expected to extract more heat from the air, then, lowering the canopy temperature more. On the other hand, in the SAH case all the internal surfaces are heated and this effect is not found. It should also be noted that in the AH case the wall temperature is $75^\circ C$, while in the stable case it is only $70^\circ C$ (due to insulation problems with the cooled wind tunnel floor).

Finally, it should be stressed that, due to the temperature gradient extending up to the boundary layer top, in the SBL cases the choice of a higher reference height for the temperature would affect the normalised temperature values, while for the NBL cases the air temperature above $2H$ is constant. Having this in mind, the averaged mean temperature within the canopy for the SWH and SLH cases are found to be 0.072 and 0.067, respectively, closer to each other compared to the two NBL cases, while for SGH and SAH it is 0.021 and 0.265, respectively. The SGH case experiences the larger reduction compared to the GH but this is expected, since the local stratification here ($Ri_{\text{Local}} = -0.56$) is only a half of the two walls heated cases (SWH and SLH, for which $Ri_{\text{Local}} \approx -1.25$) while the approaching BL is stratified at the same level ($Ri_H = 0.13$).

Fig. 6.8 and 6.9 reports the graphs for the turbulent vertical heat flux. In the SNH case the flux is mainly negative, as expected for a SBL without a local source of heating. The maximum region is found in the shear layer immediately above the canopy, where the colder air raising
from the street canyon faces the warmer upper region air. The heat flux in the canopy is larger closer to the exchange surfaces, while a region of slightly positive vertical heat flux is found closer to the leeward wall. Since only the floor surface is cooled, while the building walls are left passive, the colder air raises up facing the slightly warmer leeward wall, which in turns gives rise to the positive heat flux.

The heat flux field is obviously very dependent upon which surface is heated. The LH case is the one which affects less the heat flux distribution within the canopy, since the heated air is immediately released above the canopy and only a small part is re-entrained inside, although this point will be better analyse later through the the quadrant analysis. The flux peaks at the top of the leeward wall and spreads downstream over the canopy in the region of high shear. On the other hand, the WH case affects more the upper half of the canopy, with the heat flux peaking at the windward wall upper corner. Another feature is the presence of a slightly-positive flux region spreading up to the upper leeward building corner. Such flux is likely generated by the hot air trapped into the main vortex. A region of relatively strong negative heat flux is observed in the lower half of the canopy for both the cases. They also highlight a vertical heat flux maximum for the LH at 1.25\(H\), moved down to 1\(H\) for the WH case. It is interesting to note that a similar location for the two maxima (even though only the profile along the centreline was shown) was also found by Park et al. (2012).

In the GH case, closer to the ground the longitudinally-averaged heat flux shows a peak due to the bottom heating in addition to the peak at roof level. In the AH case the largest fluxes are found close to the leeward upper corner, with maxima close to the windward wall and above roof level. In the canopy, on the contrary, in the leeward region fluxes are comparable with the GH case, consistent with the fact that also in this case the leeward wall heating does not
Fig. 6.9 Contours of turbulent vertical heat flux. The red lines represent the heated surfaces in each case ([S]WH left up, [S]LH right up, [S]GH left down, [S]AH right down). The line plots on the right show the vertical profiles of longitudinally-averaged turbulent vertical heat flux and the longitudinal profile of vertically-averaged turbulent vertical heat flux; NBL = continuous lines, SBL = dashed lines.
produce a significant heat flux increment within the canyon. In the AH case heat fluxes are found to spread heavily in the region above the canopy, also upstream of the canyon.

The application of the incoming SBL does not significantly modify the above analysis, but it contributes mainly to reduce the positive heat flux, in particular above the canopy, resulting in a lower extent of the heat plume. One exception is for the SLH case close to the leeward wall, where the SBL intensifies the positive heat flux. This might be due to the fact that the cooling action of the windward wall and the floor (refrigerated at lower temperature compared to NBL) reduced more the temperature of the air approaching the heated wall, thus increasing the $\Delta \Theta$, and in turns the heat exchange. In the SAH case, on the contrary, heat fluxes are mostly increased within the canopy region compared to the AH counterpart. This might be explained by the the same two reasons previously presented for the temperature field behaviour.

### 6.6 Dispersion and ventilation

#### 6.6.1 Pollutant concentration field

Fig. 6.10 shows the mean normalised concentration field in the cross-section for the ten cases investigated in both logarithmic (contour plots on the left) and linear (averaged profiles on the right) scale. The concentration is normalised as $C^* = C U_2 H^2 / Q$ where $Q$ is the pollutant tracer flow rate from the source. The isothermal case is characterised by a large concentration region upstream of the source rising along the leeward wall up to the street canyon top, where some pollutant is re-entrained inside the canopy while other is carried downstream by the mean flow. In the WH case the pollutant transport by means of the main vortex is weakened by the action of the buoyancy force. Moreover, concentration values are increased downstream of the source closer to the ground and along the windward wall, the latter due to pollutant up-drafts. The concentration pattern is very similar to that found by Cai (2012a) (see Fig. 2.8), who simulated a scalar release from the entire street-canyon floor surface with windward wall and roof heating. For the LH case no significant differences are found in the cross-section compared to the NH case, despite the strengthened main vortex. In the GH case, on the other hand, pollutant concentrations appear reduced, in agreement with the findings of Li et al. (2010) and Cheng and Liu (2011b), as sign of a better ventilation. The reduction is mostly located in the highly polluted area along the leeward wall. In the AH case a larger reduction is observed, now also in the windward side region (as well summarised by the longitudinal profile of vertically-averaged concentration on the right-hand side of Fig. 6.10).

The application of the incoming SBL creates a generalised increase of concentration inside the canopy, also shown by the histogram in Fig. 6.11, which reports the values of normalised
Fig. 6.10 Contours of mean concentration. The red lines represent the heated surfaces in each case ([S]NH left, [S]WH centre up, [S]LH right up, [S]GH centre down, [S]AH right down), the black circles represent the pollutant source. The line plots on the right show the vertical profiles of longitudinally-averaged mean concentration and the longitudinal profiles of vertically-averaged mean concentration; NBL = continuous lines, SBL = dashed lines.
6.6 Dispersion and ventilation

![Graph showing normalised canyon cross-section averaged concentrations and standard deviations](image)

**Fig. 6.11** Normalised canyon cross-section averaged concentrations \(\langle C_\ast \rangle\) and normalised canyon cross-section averaged standard deviations of concentration fluctuation \(\langle \sigma_{C_\ast} \rangle\).

canyon cross-section averaged concentrations for all the cases. For SNH the value is increased by about 75% compared to the NH case. Such increment is very close to what found by Li et al. (2016) for a line source with a similar level of stratification. An even larger increment of concentration is experienced by the SWH case, which has a level of pollutant within the canopy that is double compared to the NBL counterpart. Such strong increase is concentrated mostly in the lower half of the canopy, thus more significant at pedestrian level. The increment for the SLH case is more modest, with a 55% increase. Looking at the longitudinal profiles of vertically-averaged concentration, it is possible to observe how, while for the NH and LH case the high level of pollutant close to the leeward wall is even increased by the SBL, for the WH and SWH it is consistently lower. In the latter, the region of larger concentration is moved towards the centre of the canyon, driven by the velocity stagnation region which determines a large level of concentration immediately after the source release. For the SGH case, the increment in average concentration in the canopy compared to the neutral counterpart is 50%, while a lower increase is found for SAH (only 20%), according to the fact that if more heat is provided locally, then a variation of the incoming flow should produce smaller effects.

The standard deviation of the pollutant fluctuations averaged in the cross-section is also reported in Fig. 6.11. For all cases the standard deviation is found to be larger than the mean value, often due to large (but quite sporadic) peaks in the signal (causing also a large positive skewness). This is particularly true for the WH case, where the standard deviation is twice as large as the mean concentration within the canyon. The SBL has the effect of increasing the pollutant fluctuations, but less than the mean concentration, so that for the SLH case they have
roughly the same value. Cai (2012a) also reported fluctuations larger for the windward-heated case compared to the leeward-heated, but not exceeding 50% of the mean concentration within the canopy. The larger value in this case can be explained by the choice of a point source instead of a surface release.

### 6.6.2 Pollutant fluxes

As stated in previous chapters, the vertical pollutant flux can be divided into a turbulent component ($w'c'_v$), and a mean ($\overline{w'c'_v}$), while total fluxes can be given by the sum of the previous two ($\overline{w'c'_v} + \overline{W'c'_v}$), where $W_v$ represents the vertical velocity normalised with $U_{2H}$.

Fig. 6.12 shows the contours of the pollutant fluxes in the cross-section. For the isothermal case $\overline{w'c'_v}$ is only appreciable close to the source and at roof level (where it assumes positive values), while inside the canopy the mean flux controls the vertical pollutant exchange (with positive flux in the upstream half and negative in the downstream region of the street canyon, according to the mean vortex pattern). This result is in line with what observed by Carpentieri et al. (2012, 2018) for more complex geometries. The LH case presents a similar trend, with a larger mean flux due to the increment in the mean velocity field. Conversely, in the WH case turbulent fluxes are comparable to mean fluxes inside the canopy, due to the weakened mean flow. The negative total flux in the downstream half of the canyon almost disappears, since positive turbulent and negative mean flux counterbalance each other. A slightly-positive flux region is observed very close the windward wall, due to updrafts caused by the heated wall. In the GH case (but also in AH) a region of positive $\overline{w'c'_v}$ appears along the leeward wall, which contributes to pollutant ventilation. This is in agreement with what found by Li et al. (2010), and reported in Fig. 2.7.

The application of the incoming stable stratification was found to have small effects on the turbulent pollutant fluxes, which are only slightly altered. In particular, a region of negative flux appears close to the leeward wall for the SNH case, which opposes the pollutant ventilation (as also observed by Li et al., 2016). On the other hand, the large increment of concentration in the canopy almost everywhere overtakes the reduction in the mean velocity, hence the mean flux appears increased for all the cases. This is particularly true for the SLH case, where the averaged velocity reduction was just 1% (see Sec. 6.5.1). In the SWH case, the positive flux region close to the heated wall appears strengthen by the SBL.

It must be stressed that since the pollutant release is not bi-dimensional, the vertical flux may be influenced by a variation in the lateral dispersion. On this aspect, Sessa et al. (2018) comparing the difference between point and linear source dispersion in stable atmosphere pointed out that the effects of stratification on the first configuration are expected to be larger due to a reduced lateral spreading. On the other hand, results from Ch. 5 did not show significant
variation of plume lateral dispersion from a point source in a rectangular array of buildings (but for lower levels of stable stratification). It appears, then, that this aspect deserves further investigation.

### 6.6.3 Exchange rates of pollutant and air

The pollutant exchange rate (PCH) and the air exchange rate (ACH), are computed by integrating the instantaneous vertical pollutant flux and vertical velocity, respectively, along the street canyon width \( W \) at roof level (see Appx. D). Their computation, though, requires the knowledge of instantaneous velocity and concentration fields, while in the present case the field points were not measured simultaneously. Despite this, the time-averaged rates (\( \overline{PCH} \) and \( \overline{ACH} \)) can still be computed as

\[
\begin{align*}
\overline{PCH} &= \int_{W} w(t)c(t)dx = \int_{W} w(t)c(t)dx \\
\overline{ACH} &= \int_{W} w(t)dx = \int_{W} w(t)dx
\end{align*}
\]  

providing that the measuring time is long enough to get statistically representative samples. The two rates can then be decomposed in \( \overline{PCH}^+ \), \( \overline{ACH}^+ \) and \( \overline{PCH}^- \), \( \overline{ACH}^- \) considering only the positive or negative instantaneous velocity samples. The positive rates represent the removal of pollutant/air from the canopy, while the negative the pollutant/air re-entrainment into the canopy. More in detail, in the present case \( \overline{PCH}^+ \) and \( \overline{ACH}^+ \) have been computed imposing equal to zero all the negative velocity instantaneous samples, the opposite for \( \overline{PCH}^- \).

It should be noted that air exchange rates at the canyon top correspond to the actual pollutant removal only by assuming well-mixed conditions within the canopy. However, particularly for a point source, this assumption is not satisfied. For this reason, to get a better insight of the vertical ventilation, the exchange rates are computed at different heights in the canyon (Garau et al., 2018), as displayed in Figs. 6.13 to 6.16.

In an ideal 2D neutral case flow, \( \overline{ACH} \) should be equal to zero and \( \overline{ACH}^+ = \overline{ACH}^- \) at each height in the canyon for the conservation of the mass. However, this is very difficult to achieve in wind tunnel experimentation. In the present case, despite all the efforts in ensuring a bi-dimensional flow, such condition is not perfectly achieved. Analysing the profiles of mean vertical velocity (see Appx. G in this regard) it appears that in the leeward side of the canyon (in particular at roof level) the velocity tends to be larger than in the windward, hence producing a mass unbalance. Reasons for this may be a slightly incorrect alignment of the probes or the model. In particular the latter could produce a lateral flow, not detected by the LDA, which
6.6 Dispersion and ventilation

Fig. 6.12 Contours of normalised vertical turbulent, mean and total pollutant flux. Velocities are normalised as \( (w', \bar{W})/U^2H \), while concentrations as \( (c', \bar{C})/U^2H^2/Q \).
can be responsible of such imbalance. It should be noted, though, that the unbalance is not constant but it depends on the conditions of stratification, the worse case being the SWH. Air density variations due to the heating were found to have a quite small effect on this aspect. The most probable cause is deemed to be the occurrence of lateral flow, possibly stronger in case of windward wall heating, also due to the general velocity reduction experienced in that condition. Despite this issue, comparing the exchange rates among the different cases is still considered to be useful, since the measuring setup and model were the same in all the cases.

In the isothermal case, $\overline{ACH^+}$ presents a maximum approximately at the height of the main vortex centre (as also found by Garau et al., 2018) followed by a decrease up to the canyon top. The LH case shows a similar trend, but with amplified values due to the larger velocity magnitudes. On the other hand, in the WH case $\overline{ACH^+}$ almost monotonically increases with height, but with lower values compared to the other case. The application of the incoming stable stratification has the general effect of decreasing the exchange rate, following the reduction in the mean and fluctuating velocities discussed in Sec. 6.6.1. The observed decrease in the exchange rate is rather limited for the LH case, for which the stable stratification had a smaller impact on the mean and turbulent flow. The GH and AH cases are both characterised by an increment of $\overline{ACH^+}$ compared to the isothermal configuration, more significant for the AH case. With a SBL, the AH case experiences also a larger reduction in the air exchange rate.

$\overline{PCH^+}$ presents a different trend, namely a reduction with height thanks to the larger values of concentration in the bottom region. Despite this, the differential wall heating configurations are still organised with WH, NH and LH in growing order of exchange rate values. For them, the effect of stable stratification is interestingly seen to produce opposite effects compared to $\overline{ACH^+}$. As a matter of fact, on average $\overline{PCH^+}$ is increasing within the canopy, especially for SLH, while the air exchange rate did not show a significant modification in that case. On the other hand, the SWH case does not show significant variations from WH. This discrepancy might be up to the fact that concentrations in SBL were found to increase more than the velocity reduction, hence resulting in a possible increase of $\overline{PCH^+}$ values. The effect is similar to what it was observed in vertical pollutant fluxes (Sec. 6.6.2). As far as the GH and AH cases are concerned, the former shows a value of $\overline{PCH^+}$ comparable with NH, while the latter appears even reduced, despite the fact that $\overline{ACH^+}$ was larger. AH is also the only case for which applying a SBL produces a further reduction. However, it does not appear to be a precise relationship between the value of $\overline{PCH^+}$ and the pollutant concentration in the canopy cross-section. On this aspect, repeating the experiment with a linear emission source would help understanding if a more clear relationship is experimentally achievable.
6.7 Turbulence structure: quadrant analysis

Despite this, $PCH^+$ at roof level are found to be approximately twice as large as $PCH^-$, confirming the results by Liu et al. (2005) and Di Bernardino et al. (2018) for the isothermal case.

6.7 Turbulence structure: quadrant analysis

Figs. 6.17, 6.18 and 6.19 summarise the analysis for the investigated quantities by means of the ratio of ejections over sweeps as well as unorganised over organised motions. Such a visualisation is very compact and convenient, but it does not allow to distinguish the contribution of the inward from the outward interactions. When necessary, then, salient differences will be highlighted in the following description. Moreover, special care should be taken in observing the graphs, since a large value of the ratio might result from a small numerator divided by an extremely small denominator. Nevertheless, in the following comments the predominance of a component on the other is highlighted only when effectively corresponding to a meaningful and genuine difference of magnitude of the component values (by looking at the data for each quadrant). Finally, it should be also noted that the quadrant analysis is meaningful only in case the turbulent contribution surpasses the mean flow. Hence, for the [S]WH is particularly...
6.7 Turbulence structure: quadrant analysis

Fig. 6.14 Vertical profiles of normalised $\overline{ACH^+}$ for the [S]NH, [S]GH and [S]AH cases. Continuous lines represent NBL data while dashed lines are SBL cases.

significant, less for the other cases, characterised by a stronger mean flow. Nevertheless, for completeness all the cases are here considered.

With a neutral approaching flow, ejections and sweeps dominate the momentum transport above the canopy ($z/H > 1.15$) with, respectively, 50% and 30% of the total contributions, as also found by Cheng and Liu (2011a). However, at roof level sweeps are also dominant over ejections, with almost inverted percentages. When the windward wall is heated, sweeps are reduced and ejections are dominant close to the heated corner. An increment of the ejections at roof level was observed also by Park et al. (2012). The LH case is characterised by increased outward interactions closer to the heated wall. Inward interactions, on the other hand, are always accentuated on the lower downstream corner, apart for the windward heated cases, for which their peak is moved towards the canyon centre. Sweeps at roof level are reduced for the GH and AH cases, but they are still the main contributors. Above the canopy, on the contrary, the predominance of ejections is even strengthened by the AH case, thanks to the large amount of heat that spreads in that region (see Fig. 6.9). When the incoming stable stratification is introduced, large ejections above the canopy are confined in the region between $z/H = 1.25$ and 1.5, while above it they become comparable with sweeps. Unorganised motions within the canopy are also reinforced in the SLH case.
Fig. 6.15 Vertical profiles of normalised $\overline{PCH^+}$ (on the right quadrant) and $\overline{PCH^-}$ (on the left) for the [S]NH, [S]WH and [S]LH cases. Continuous lines represent NBL data while dashed lines are SBL cases.
As far as the heat flux is concerned, ejections dominate in the WH case above the canopy, while at roof level sweeps are also determinant on the leeward wall side. In the lower half of the canopy the heat flux is negative (predominantly unorganised motions) due to the cooling from the refrigerated ground and leeward wall. In the LH case, the effect of wall heating is barely seen in the canopy, as already pointed out in Sec. 6.5.2. As a matter of fact, the heat flux is mostly negative, with the exception of a strong sweep region of fresher air at roof level near the windward wall and, of course, ejections very close to the leeward heated wall. Above the canopy ejections of warm air depart from the upstream wall corner. For the LH and AH cases only positive fluxes are present (organised motions), with the predominance of ejections, apart at roof level where sweeps control the turbulent heat exchange. In stable stratification (SNH case), unorganised motions are dominant as outward interactions above the canopy and inward interactions at roof level and along the windward wall. Positive heat flux in the form of sweep is only found close to the leeward wall. The main effect of the stable approaching flow in the wall heated cases is in confining the ejections of hot air closer to the canopy. Moreover, in SWH the stagnant region at the bottom of the canopy is controlled by inward interactions.

The turbulent pollutant flux in the isothermal case was found comparable with the mean only close to the source and at roof level (see Sec. 6.6.2). In the first location ejections are
Fig. 6.17 Ratio of ejection vs sweep (odd columns) and unorganised vs organised motion (even columns) contributions to the vertical momentum flux.
Fig. 6.18 Ratio of ejection vs sweep (odd columns) and unorganised vs organised motion (even columns) contributions to the vertical heat flux.
Fig. 6.19 Ratio of ejection vs sweep (odd columns) and unorganised vs organised motion (even columns) contributions to the vertical turbulent pollutant flux.
dominant, while at roof level and closer to the windward wall sweeps of cleaner air play an important role, in accordance with the findings by Cheng and Liu (2011a) and Li et al. (2016). The application of a stable stratification has the effect of reducing the ejections closer to the source and at the same time strengthening inward interactions in the upper left region (as also shown by Li et al., 2016). In the WH case the turbulent structure appears widely modified, with ejections controlling the turbulent transport everywhere except on the upstream side at roof level, where sweeps play an important role as well. Inward interactions in the canopy are extensively reduced, changing from 20% down to 9% of the total contributions. Conversely, the LH case does not present any significant modification in turbulent pollutant transport compared to the isothermal case. Both the GH and AH cases see a increment of the ejections within the canopy, but not as strong as for WH. The incoming SBL in the SWH case has the effect of slightly enhancing sweeps, while in SLH the main modification is the reduction of the ejections closer to the heated wall. No significant modifications are experienced in the SGH and SAH cases compared to the neutral counterparts.
Chapter 7

Conclusion

7.1 Introduction

In this concluding chapter, firstly a summary of the results is provided in three paragraphs (one for each part of the work). Then the novelty and validity of the study is highlighted and placed in the contest. Finally, some concluding comments, limitations and possible future developments are presented in two dedicated paragraphs.

7.2 Summary of the results

7.2.1 Generation of stratified boundary layers

Experiments involving the simulation of stable and convective boundary layers over a very rough surface have been performed in the EnFlo thermally-stratified wind tunnel. Artificial thickening by means of Irwin’s spires was used to accelerate the formation of a sufficiently deep boundary layer, suitable for urban-like boundary layer flow and dispersion studies. The velocities were sampled by a two-component LDA probe, coupled with a cold-wire sensor to measure also heat fluxes.

For the stable boundary layer, the methodology presented by Hancock and Hayden (2018) for low-roughness offshore surface conditions has been successfully applied to cases with higher-roughness and Richardson number ranging from 0.14 to 0.33 (based on the boundary layer depth). The reproducibility of mean and turbulent profiles at different Reynolds numbers by matching the bulk Richardson number has been verified (although in a limited range of velocities). Different levels of stratification produced modifications in the turbulence profiles of the lower half of the BL, but little or no change in the region above. The same can be said for the effect of the surface roughness, whose reduction was found to produce results similar to
those observed after an increase in the stratification. A case with stronger stability (in terms of bulk Richardson number greater than 0.25) was simulated but the turbulence profiles continued to scale with the lower stability cases, suggesting that the employed spires may not be suitable to simulate such an extreme condition, although further studies are needed. The results were in reasonably good agreement with field measurements (Caughey et al., 1979).

For the simulation of a convective boundary layer, great attention was given to the flow uniformity inside the test section. Two instability levels were considered, equivalent to Richardson numbers of $-0.5$ and $-1.5$. The selection of a non-uniform inlet temperature profile was in this case found not as determinant as for the stable boundary layer to improve the longitudinal uniformity, while the application of a calibrated capping inversion considerably improved the lateral uniformity. The non-dimensional vertical profiles of turbulent quantities and heat fluxes, did not seem to be influenced by roughness (by a comparison with Hancock et al., 2013), suggesting, again, that changes of roughness produce only local effects in the generated boundary layer. Good agreement is also shown with Ohya and Uchida (2004), in which no spires were employed.

An analysis of the spectra for the stable cases in the surface layer showed a relatively small inertial range (in particular for the temperature) which follows only marginally the $-5/3$ rule. This could be due to a not sufficiently high Reynolds number, but considering that above the surface layer the situation is improved, the cause may also be attributed to the highly rough surface. Apart for this, they appear to scale reasonably well when normalised according to the Monin-Obukhov scaling. As far as unstable cases are concerned, the inertial range in the spectra was found to follow more strictly the $-5/3$ rule compared to the stable cases, likely thanks to the increased turbulence due to heating. The effect of buoyancy was mostly visible at the lower frequency of the $w$-spectrum, in the way of an increment of the energy and a shift towards the left of the peak of maximum energy compared to the neutral case (as also observed by Kaiser and Fedorovich, 1998).

### 7.2.2 Effects of stratified approaching flow on an array of buildings

An experimental campaign aimed to investigate the effects of atmospheric stratification on flow and dispersion over an aligned array of rectangular blocks was performed in the EnFlo wind tunnel. A series of three stable and two convective boundary layers was employed, together with reference neutral cases, with Richardson number of the approaching flow ranging from $-1.5$ to $0.29$. For most of the experiments the wind direction was at an angle of $45^\circ$ degrees respect to the array, with only some measurements performed at $0^\circ$ for neutral and stable cases only. A propane tracer was released from a circular point source placed at ground level at the centre of the model. Pollutant concentrations were sampled by a FFID probe, which
combined with a bi-component LDA and a cold-wire placed close to each other, allows the point measurement of mean and fluctuating pollutant, velocity and temperature values, as well as Reynolds shear stresses, heat and pollutant fluxes. Measurements were performed inside and above the canopy, by means of lateral and longitudinal scans of the pollutant plume at 0.5 and 1.5 times the building height, combined with vertical scans along the plume axis. Also, measurements of the undisturbed approaching flow were performed and used to evaluate the effect of the presence of the model.

As far as stable stratification is concerned, results on the flow above and inside the canopy show a clear reduction of the Reynolds stresses (which reflects in a reduction of the friction velocity), despite the high level of roughness. The latter, however, caused an increment of the Monin-Obukhov length up to 80% compared to the approaching flow. The aerodynamic roughness length and displacement height seem affected by stratification, with a reduction up to 35% for the former and an increment up to 12% for the latter. On the other hand, the wind direction of the flow inside and immediately above the canopy are not influenced, even though the mean values appear reduced. A clear reduction of the turbulence within the canopy was observed. Comparisons between the approaching flow and boundary layer over the canopy suggest a height of the internal boundary layer of about $2.5H$, in agreement with what Uehara et al. (2000) found for an array of cubes.

In the convective stratification cases, the friction velocity appears increased by both the effect of roughness and unstable stratification, even though the sum of the two contributions considered singularly is larger than the increment resulting by their combined effect. As it was for the stable case, the increased roughness causes a reduction in the surface stratification, reflected in an increase of the Monin-Obukhov length, which is double over the array compared to the approaching flow. The effect on the aerodynamic roughness length and displacement height are specular to the SBL case, an increase up to 50% of the former and a reduction of the same amount for the latter. The observation of the mean velocity profile suggests a height of the internal layer between 3 and $4H$, invariant along $x$ in the measurement region.

The results of the pollutant dispersion show that the stratification (either stable or unstable) effect on the plume width is significantly lower than the effect on the vertical profiles (as also indicated by Briggs, 1973). Stable stratification did not affect the plume central axis inside the canopy, but in the unstable case the axis appeared to deviate from the neutral case direction. Above the canopy both stratification types caused an increase in the plume deflection angle compared to the neutral case. Measured concentrations in stable stratification were up to two times larger in the canopy compared to the neutral case, the opposite for the convective stratification (which are up to three times lower). Vertical turbulent pollutant fluxes have been found to be only slightly affected by stratification, but without significant changes in the general
trend. Mean pollutant fluxes in the canopy remain predominant close to the source, even though at roof level and above turbulent and mean fluxes have the same order of magnitude. The proportionality between the vertical turbulent fluxes and the vertical mean concentration gradient (base of the K-theory) is confirmed also in the stratified cases.

Finally, a quadrant analysis of the vertical velocity and concentration fluctuations at the centre of the intersection did not show significant differences between different stratifications, even though a complete mapping of the surface would have better clarified the various behaviours.

### 7.2.3 Effects of stratified approaching flow and local heating on a bi-dimensional street canyon

The aim of the third and last part of the work was to investigate buoyancy effects on flow and dispersion characteristics in a bi-dimensional isolated street canyon of unity aspect ratio. Both local heating (by means of heating either the windward, WH, the leeward canyon wall, LH, the ground, GH, or all the three mentioned surfaces, AH) and different approaching flow stratification (neutral and stable) have been considered.

As far as the mean velocity field is concerned, a single-vortex structure was observed in all cases, except when the windward wall was heated. In this case a counter-rotating vortex formed close to the heated wall, resulting in a reduction of the velocities within the canopy. Conversely, heating the leeward wall produced a considerable increment in the vortex speed. Increment that was experienced with a minor extent in the GH and AH cases (noting that the latter two cases are not directly comparable with the former two, since a lower wall temperature was applied). The incoming stable stratification was only found significant in the reduction of the velocities in the lower half of the canopy. In terms of turbulent kinetic energy, the largest values were found above the canopy. Inside the street canyon the WH case produced the greatest increment, in particular (but not only), close to the heated wall region. Conversely, in the LH case no enhancement of turbulence close to the heated wall was measured. The overall biggest increment was observed for the AH case, despite the lower wall surface. Incoming stable stratification was found to produce a large and generalised reduction of turbulence both inside and above the canopy in all the cases when normalised by the reference velocity. Such reduction, though, was only a fraction of the one exerted on the approaching flow, meaning that in the canopy the largest contribution came from the local wall heating.

Analysing heat exchange, the WH case produced larger temperature increments within the canopy than the LH case, for which the heat vacated immediately the canyon, as evidenced by the larger temperature and heat flux above the canopy. In any case, larger temperature increments are confined close to the heated walls. The stable stratification has the effect of
lowering the normalised temperature inside the canopy, as well as the positive vertical heat flux. The only exception is represented by the AH case for which the latter seem increased.

Tracer released from a ground level point source highlighted how the largest modifications in the plume cross-section can be expected when the windward wall is heated. In this case, breaking the updraft close to the leeward wall increases the pollutant level on the windward side. Leeward wall heating was not found to produce significant modifications on the plume shape and concentration levels, while in the GH and AH cases, the concentration was significantly lower. The application of an incoming stable stratification created a generalised increment of pollutant in the canopy, with concentration up to double. From the point of view of the vertical pollutant fluxes, the turbulent component was found comparable with the mean only close the source and at roof level. Conversely, in the WH case with the weakening of the main vortex the two components were comparable each other. The stable stratification did not affect considerably the turbulent exchange, but hence reinforced the mean. Both air and pollutant exchange rates have been computed inside the canopy. The former appeared reduced by the application of stable stratification, as a consequence of the lowered mean and turbulent velocity. The latter, instead, was generally increased, likely as consequence of the enhanced concentration in the stable cases.

Finally, a quadrant analysis was also performed on the vertical fluxes of momentum, heat and pollutant, and various modifications in the turbulence structure caused by buoyancy effects were identified.

7.3 Validity and novelty of the work

One of the things that characterised more this work is the great attention paid to the development of as realistic as possible urban boundary layers. In most of the literature on urban dispersion and stratified flows, instead, the approaching flow to the model is often not carefully designed and barely described by one or more vertical profiles. The usage of spires to artificially thicken and shape the flow is crucial if the development of a tall boundary layer is of interest. Irwin’s spires in combination with non-neutral stratified boundary layers had already been attempted in the literature, but with the exception of the Hancock’s works (see e.g. Hancock and Hayden, 2018 and Hancock et al., 2013) for offshore wind farms, no detailed and systematic studies were present. The technical findings summarised in Sec. 7.2.1, are hence particularly useful for the experimentalists aiming to simulate stratified atmospheric boundary layers, especially if boundary layer depth, lateral and longitudinal uniformity are of interest.

Among the findings, it is of particular value the prove of repeatability of the same boundary layer properties with spires in place at different Reynolds numbers by matching the same bulk
Richardson number. This, in fact, allows more freedom in setting the experimental conditions, especially in case particular constrains are present for either the temperature or the velocity. Another important finding to mention is the beneficial use of a calibrated temperature inversion capping a convective boundary layer to enhance the lateral uniformity and block undesired secondary flow structures, which would reduce the flow bi-dimensionality. Despite the fact that in the field unstable boundary layers may present non-uniformities in space and time, it is opinion of the author that in controlled experiments like the ones attempted in this work, non-uniformities should be avoided if possible, to better represent an idealised (but still realistic) case.

The tested boundary layer stratification levels ranged from weakly stable to weakly unstable. Despite the fact that more extreme conditions may create more dramatic effects on the aerodynamic and dispersion properties, it should be noted that in urban areas extreme stratifications are normally quite uncommon (excluding locations at larger latitudes were very stable conditions may occur even in rural or urban areas). As support of this argument, Fig. 7.1 shows the frequency of the different stratifications observed over London, UK (from Wood et al., 2010). It can be immediately noted that the most frequent cases are the ones characterised by lower stratification, with the region between \(-1 < z'/L < 1\) occurring for about 75% of the times, both during night and day (where the reference height \(z'\) represents the difference between the 190.6 m high measuring tower and the displacement height over the city). Unfortunately, the boundary layer depth for each of these cases was not indicated by Wood et al. (2010), so a comparison with the wind tunnel data is hard, but considering a scaling ratio of 1/200 (as done during this work) the resultant Monin-Obukhov length values at full-scale of the experimental data are of the order of \(\pm 200\) m (hence approximately in the range of \(-1 < z'/L < 1\) compared to the London data, and so covering 75% of the times).

For what concerns the local stratification, the wall temperature difference of up to about 100°C tested experimentally in the street canyon would correspond to just 0.5°C at full-scale (providing that the Richardson number similitude holds), considering the same reference velocity and a scaling ratio of 1/200. Tab. 7.1, referring to the windward and ground heated cases, reports the equivalence of temperature difference at full-scale for different reference velocities (up to 4 m/s). It can be noted that for the largest velocity, the field case would require a temperature difference of about 18°C to match the same stratification as in the experiments (which corresponds to the largest temperature difference detected by Aliabadi et al., 2017 in a real urban canyon).

In case larger stratifications than the ones investigated here (both in terms of approaching flow or local heating) had to be achieved, either larger temperature differences or smaller velocities should be considered. A temperature increment is possible, provided that measuring
7.3 Validity and novelty of the work

Fig. 7.1 Frequency histogram of stability (expressed as \(z'/L\)) in 0.1 bins for daytime and nighttime acquired over the city of London, UK (adapted from Wood et al., 2010). \(z'\) is here equal to 186 m, representing the difference between the height of the measuring tower and the displacement height over the city, which was around 4.6 m.

Table 7.1 Tested local stratification equivalence at full-scale. The windward heated (WH) and ground heated (GH) cases stratification level is taken as representative also for the leeward heated and all surfaces heated cases, respectively. For the definition of the local Richardson number see Eq. 6.2, while \(\Delta \Theta_{HOT} = \Theta_{HOT} - \Theta_{2H}\).

<table>
<thead>
<tr>
<th>Case</th>
<th>Wind Tunnel</th>
<th>Full-scale (1/200)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH</td>
<td>Ri_{Local}</td>
<td>U_{2H} (m/s)</td>
</tr>
<tr>
<td></td>
<td>-1.27</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>0.64</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>18.4</td>
</tr>
<tr>
<td>GH</td>
<td>Ri_{Local}</td>
<td>U_{2H} (m/s)</td>
</tr>
<tr>
<td></td>
<td>-0.56</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>0.64</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>9.0</td>
</tr>
</tbody>
</table>
instruments (like the LDA probe) are sufficiently protected and temperature measuring devices (like thermistors or thermocouples) remain inside their measuring range. A further reduction of the velocity, instead, should be carefully considered to avoid undesired low Reynolds number effects. A change of the geometric scale can also affect the stratification, with the main limitation dictated by the wind tunnel test section dimensions and blockage effect of the model. For what concerns very stable boundary layers, their correct simulation by using spires remains questionable (as already highlighted in Sec. 7.2.1) and further work is needed.

About the experiments over the array of rectangular buildings, the novelties are found in the particular geometry chosen (similar studies were performed only with arrays of cubes at zero wind direction, see e.g. Kanda and Yamao, 2016 or Jiang and Yoshie, 2018), the measuring technique (which, coupling for the first time LDA, cold-wire and FFID allowed to contemporary sample high frequency velocity, temperature and concentration fluctuations, as well as heat and pollutant fluxes) and the completeness of the stratification levels considered (with multiple stable and convective stratifications tested, differently from the available literature). The findings are summarised in Sec. 7.2.2 and the results allowed to characterise the differences in the boundary layers and the pollutant plume (from a ground point source release) inside and above the canopy. In particular, it is worth mentioning the assessment of the proportionality between the vertical mean concentration gradient and the vertical turbulent pollutant fluxes also in stratified cases, with a parametric relation given for the constant of proportionality $K_z$ (even though dependant on the geometry chosen). This parameter is important for the implementation of street network dispersion models (like SIRANE, see Soulhac et al., 2011). A weakness of the chosen technique is represented by the fact that it allows only punctual measurements, which are time consuming in the acquisition phase and do not permit to capture the instantaneous flow field and structure. On this regards, a coupling of the produced experimental data with numerical simulations (better if LES) would be advisable to increase the understanding of the physics. This partially already took place thanks to the collaboration with the University of Southampton (Sessa et al., 2018), even though only for the stable cases at zero degree as wind direction.

Finally, the bi-dimensional street canyon case with local heating, even though already investigated numerically, was not previously studied experimentally (differently from the street cavity, see e.g. Allegrini et al., 2013). In particular, the combination of the stable incoming stratification and local canyon heating represented an absolute novelty, allowing to describe the combined effects on the flow and dispersion properties, with the findings summarised in Sec. 7.2.3. Many of the results confirmed what already shown by numerical simulations, but the fact that they were obtained with an experimental technique gives more validity to both. At
the same time the produced dataset will be undoubtedly very useful for future CFD validations and comparisons.

7.4 Final remarks

The work detailed in this thesis highlighted the importance of taking into account the effects of atmospheric and local stratification when dealing with studies of urban aerodynamics and dispersion. Wind tunnel modelling was employed throughout all the study. Despite nowadays more efforts are put into the numerical simulations, there is still the necessity of physical modelling, also considering the lack of good validation datasets. This work tried to contribute filling this gap in a way as systematic and complete as possible. The study started from the development of the approaching flow, in the attempt to improve the simulation technique and obtain well developed, realistic and laterally uniform stable and unstable boundary layers. Then, the urban dispersion problem was approached at a neighbourhood scale, by sampling the boundary layer and pollutant plume both above the canopy (an idealised array of buildings) and inside. As a consequence of the dimensions and geometry of the model, high-spatial resolution measurements were not attempted here. However, in the last part of the work a simpler geometry (bi-dimensional street canyon) was considered and the attention moved to the microscale region, with a finer mesh sampling, as close as possible to the building walls. Here the local flow patterns were captured and also local wall and ground differential heating was taken into account.

Even though not exhaustive and with some limitations (detailed in the next section) this work helps shedding more light on the effects of stratification and the author hopes it will be of help for the research community. The experimental database produced during the project is unique and of high quality. It can assist in developing, improving and validating numerical models, as well as developing parametrisations for simpler models. The outcomes of the work have been disseminated widely, both nationally and internationally through journal papers, conferences, workshops and meetings, as also detailed in the list of publications. The datasets produced for the results are available at the following links.

- Boundary layer generation (Ch. 4): https://doi.org/10.6084/m9.figshare.5993572.v1
- Building array (Ch. 5): https://doi.org/10.6084/m9.figshare.8320007
- Local heating (Ch. 6): https://doi.org/10.6084/m9.figshare.7804454
7.5 Limitations and future developments

A first limitation was the choice of the levels of stability. Only weak stratification levels were considered. In fact, although for the stable cases Richardson numbers larger than 0.25 were also simulated, they resulted in small surface stability levels (in terms of Monin-Obukhov length) due to the large surface roughness.

Other limitations came from the urban model selection. An idealised array of rectangular blocks and a bi-dimensional street canyon were chosen. Idealised geometry allows to better identify and describe flow patterns (e.g. in the case of the bi-dimensional street canyon the entire flow characteristics were described by means of sampling only the central cross-section). On the other hand, effects of other features (e.g. roof shape or different height buildings, different canyon aspect ratio) were not considered. On this regard, the wall heated street canyon model was design with the buildings made of two identical parts in order to be able in the future to simulate also a case with intersection. In the same model, the building height was chosen as half the dimension of the heater mats available in the lab. In this way cases with different canyon aspect ratio and ground heating can be simulated without the necessity to buy other expensive equipment.

Only two wind directions were considered for the building array tests (and one of them only for very limited cases). On this regard, an heated turntable (as large as the test section) was actually designed and manufactured during the project to further investigate different wind directions with convective boundary layers. The turntable was not used in this project because of time constraints, but it may be useful in future experiments.

Only a single point source was considered. In this way it is simpler to establish source-receptor relationships with a better tracking of the pollutant path. That said, in the building array case, the repetition of the experiment with different source locations would have enhanced the dataset completeness and made possible further comparison. In the bi-dimensional street canyon case, instead, a linear source was definitely preferable, in order to have a 2D plume. It was not attempted to avoid further complication in the experimental set-up, but it would constitute an important improvement for future experiments.

As far as the measuring techniques are concerned, a major limitation is represented by the fact that only point measurements are possible with the chosen set-up. Other techniques, like the particle image velocimetry, can allow an entire section of the flow field to be sampled at the same time (at the cost of other limitations, though). Moreover, the contemporary presence of LDA, cold-wire and FFID enabled to sample pollutant and heat fluxes at the same time and in the same location. Nevertheless, it caused a perturbation of the velocity, that mostly affected the vertical velocity component (even though a correction was applied to compensate for this issue). Moreover, the displacement between the three probes, indispensable to avoid excessive
interference, caused a decoupling of the signal for frequencies depending on the streamwise velocity. Such issue was particularly concerning in case of small velocities, mostly experienced in the street canyon experiments.

A further limitation of the experiments is represented by the difficulties in measuring close to the building walls or wind tunnel floor, as a consequence of the probe dimensions. In the building array case, in particular, lower measurements than the sampled ones were indeed possible, but they were not attempted as a consequence of a not adequate initial arrangement of the measuring traverse. In the street canyon case the bi-dimensionality of the flow was assessed by means of two lateral profiles in the range ±0.5 m. A larger range and more locations would have been advisable for a better evaluation.

Finally, an interesting and still open point is the representativeness of scaled-down laboratory experiments involving heated walls compared to full-size models. On this regard, Chew et al. (2018), after performing CFD simulation at different scales, pointed out that a non-isothermal case may not be Reynolds number independent, even though the isothermal is, and suggested to be careful in extending conclusions obtained with reduced-scale model to the full-scale case. Further studies have to be conducted to address this point, even though the investigation of a meaningful range of Reynolds numbers was proved to be very challenging in case of stratified flow in wind tunnel.
References


References


Appendix A

Meteorology governing equations

Five equations provide the foundation of boundary layer meteorology: the equation of state (I), conservation of mass (II), momentum (III), moisture (IV) and heat (V). They are reported in Eqs. A.1-A.5 using the Einstein summation notation.

\[ I \] \[ P = \rho RT_v \] (A.1)
\[ II \] \[ \frac{\partial u_i}{\partial x_j} = 0 \] (A.2)
\[ III \] \[ \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} - \hat{\delta}_{ij} \beta + f_c \epsilon_{ijk} u_j + \nu \frac{\partial^2 u_i}{\partial x_j^2} \] (A.3)
\[ IV \] \[ \frac{\partial q_T}{\partial t} + u_j \frac{\partial q_T}{\partial x_j} = \nu_q \frac{\partial^2 q}{\partial x_j^2} + \frac{S_{qr}}{\rho} \] (A.4)
\[ V \] \[ \frac{\partial \theta}{\partial t} + u_j \frac{\partial \theta}{\partial x_j} = \nu_\theta \frac{\partial^2 \theta}{\partial x_j^2} - \frac{1}{\rho c_p} \frac{\partial Q^*_j}{\partial x_j} - \frac{L_p E}{\rho c_p} \] (A.5)

\( R \) in the equation of state is the gas constant for dry air (\( R = 287 \text{ Jkg}^{-1}\text{K}^{-1} \)). The hypothesis of incompressibility has been applied (valid for all the turbulent motions smaller than the mesoscale). \( \hat{\delta}_{ij} \) and \( \epsilon_{ijk} \) in the momentum equations (also called Navier-Stokes equations) are the Kronecker delta and the alternating unit tensor, respectively. The Coriolis parameter \( f_c \) is equal to \( (1.45 \times 10^{-4} \text{ s}^{-1}) \sin \phi \), where \( \phi \) is the Earth latitude. For what concerns the equation of moisture, \( q_T = q + q_L \) is the total specific humidity of air, in which \( q \) and \( q_L \) are the water vapour and liquid water specific humidity, respectively. \( \nu_q \) is the molecular diffusivity of water vapour in the air, while \( S_{qr} \) is a net moisture source term for the remaining processes not already included in the equation. Finally, in the heat conservation equation \( \nu_\theta \) is the thermal diffusivity, \( Q^*_j \) is the component of net radiation in the \( j^{th} \) direction. \( L_p \) is the latent heat associated with
the phase change of $E$, where $E$ represents the mass of water vapour per unit volume per unit time being created by a phase change from liquid or solid.

The described system of equations is closed, meaning that the number of unknowns is equal to the number of equations. However, due to its high non-linearity is not possible to be solved analytically.

The so-called Reynolds decomposition consists in splitting the variables of interest in a mean and turbulent part, so that $u_i = \overline{U}_i + u'_i$, $p = \overline{P} + p'$, $\theta = \overline{\Theta} + \theta'$ and $q = \overline{q} + q'$. By substituting in the system of equations we obtain

\begin{align*}
I) \quad \overline{P} &= \rho RT_v \\ 
II) \quad \frac{\partial \overline{U}_j}{\partial x_j} &= 0 \\ 
III) \quad \frac{\partial \overline{U}_i}{\partial t} + \overline{U}_j \frac{\partial \overline{U}_i}{\partial x_j} &= - \frac{1}{\rho} \frac{\partial \overline{P}}{\partial x_i} - \delta_{i3} g + f_i \varepsilon_{ij3} \overline{U}_j + v \frac{\partial^2 \overline{U}_i}{\partial x_j^2} - \frac{\partial (\overline{u}_i \overline{u}_j)}{\partial x_j} \\ 
IV) \quad \frac{\partial \overline{q}}{\partial t} + \overline{U}_j \frac{\partial \overline{q}}{\partial x_j} &= v_q \frac{\partial^2 \overline{q}}{\partial x_j^2} + S_{qT} - \frac{\partial (\overline{u}_j q'_T)}{\partial x_j} \\ 
V) \quad \frac{\partial \overline{\Theta}}{\partial t} + \overline{U}_j \frac{\partial \overline{\Theta}}{\partial x_j} &= v_\theta \frac{\partial^2 \overline{\Theta}}{\partial x_j^2} - \frac{1}{\rho c_p} \frac{\partial \overline{Q}_j}{\partial x_j} - \frac{L_p E}{\rho c_p} - \frac{\partial (\overline{u}_j \overline{\theta}')}{\partial x_j}
\end{align*}

This new system of equations is remarkably similar to the basic conservation equations, except for the addition of a turbulence term at the end of Eqs A.8, A.9 and A.10. The presence of these last terms implies that turbulence must always be considered also when modelling only the mean quantities of the PBL. Moreover, the number of unknowns now exceeds the number of available equations, hence the system is no longer closed. This issue is known as “closure problem of turbulence” and additional equations are needed to relate these terms.
Appendix B

Spectral analysis

Spectral analysis of the turbulence allows to estimate and quantify the contribution to the total energy of the different eddy sizes, each at a different frequency \( f \). Normally, a non-dimensional frequency \( n \) is employed in plotting atmospheric power spectral densities

\[
n = \frac{fz}{\overline{U}} \tag{B.1}
\]

where \( z \) and \( \overline{U} \) are respectively the height and the mean streamwise velocity at the measurement height.

Following the Taylor’s hypothesis of “frozen turbulence”\(^1\), wavelengths can be identified in the spectrum, corresponding to

\[
\lambda = \frac{U}{f} = \frac{z}{n} \tag{B.2}
\]

Generally, the turbulence spectrum is divided into three lateral zones: an “energy-containing range” at lower frequency, where energy is introduced by buoyancy or shear phenomena; the “inertial subrange” in the middle region, which does not depends on how the turbulence was generated and separates the energy containing range and the third one; the “dissipation range” at high frequency, in which vortices are too small to still exist and the spectrum approaches zero.

It can be shown (as reviewed by e.g. Kaimal and Finnigan, 1994, after Kolmogorov, 1941) that the energy density in the inertial subrange should be proportional to the wave number to the power of \(-5/3\) (or equivalently to \(-2/3\) in the \( fS \) spectrum) assuming that the turbulence is isotropic and the \( Re \) sufficiently large. The same law apply for temperature (as illustrated

---

\(^1\)Taylor proposed that in case the turbulent eddy timescale is longer than the time it takes the eddy to be advected past the measuring sensor, turbulence might be considered to be frozen as it advects past the sensor. Hence, the wind speed could be used to translate turbulence measurements as a function of time to a function of space (as reviewed by Stull, 1988).
by Obukhov, 1949 and shown, for instance, by Caughey, 1982 for both stable and convective BL). Moreover, an effect of local isotropy in the inertial subrange is visible in the velocity component spectrum levels: the $v$ and $w$ spectral levels should be $4/3$ times those of $u$. Finally, spectra can be displayed both against a frequency (as previously discussed) and against a wave number $k_1$ defined as

$$k_1 = \frac{2\pi f}{U}$$  \hspace{1cm} (B.3)

so that, taking $u$-spectrum as an example

$$\frac{2\pi}{U} F_u(k_1) = S_u(f)$$  \hspace{1cm} (B.4)
Appendix C

Quadrant analysis

The turbulence structure is often investigated by means of a quadrant analysis (Wallace et al., 1972), in which the fluctuations of two quantities in the same location are decomposed into four quadrants. Such quantity can be constituted by the momentum, pollutant or heat flux. Different terminology has been employed in the literature to identify the events associated with the different quadrants. In this thesis the terminology specified in Fig. C.1 is adopted. Events characterized by a positive fluctuation of both vertical velocity and concentration or temperature are called “ejections” and represent the rise of more polluted/warmer air. On the other hand, negative fluctuations of both the quantities are called “sweeps”, representing the sink of cleaner/colder air. Both the events contribute positively to cleaning/cooling the air inside the canopy. Conversely, a positive (or negative) fluctuation of vertical velocity coupled with a negative (or positive) fluctuation of concentration/temperature represents the rise of cleaner/colder air or the sink of more polluted/warmer air, hence contributing negatively to the ventilation in the street. Ejections and sweeps are often referred as “organised motions” while inward and outward interactions as “unorganised motions”. For what concerns the momentum flux, the same terminology is adopted, but the phenomena are localized in different quadrants, according to Fig. C.1.
**Fig. C.1** Scheme of quadrant division of the events for the vertical turbulent pollutant and heat flux (on the left), momentum flux (on the right).
Liu et al. (2005) introduced two useful parameters for the evaluation of the canopy ventilation in street canyons, the pollutant exchange rate (PCH) and the air exchange rate (ACH), computed by integrating at roof level the instantaneous vertical pollutant flux and vertical velocity, respectively.

\[
PCH(t) = \int_{b} w(t)c(t)dx \tag{D.1}
\]

\[
ACH(t) = \int_{b} w(t)dx \tag{D.2}
\]

The two rates can then be decomposed in \( PCH^+, ACH^+ \) and \( PCH^-, ACH^- \) considering only the positive or negative instantaneous velocity samples. The positive rates represent the removal of pollutant/air from the canopy, while the negative the pollutant/air re-entrainment into the canopy.
Appendix E

Pasquill-Gifford stability classes

Pasquill (1961) proposed a method to classify the stability of the atmosphere based on simple observations. The system takes into account the effects of shear and buoyancy on turbulence generation through measurements of the wind speed at 10 m, the incoming solar radiation and cloudiness. Six Pasquill-Gifford classes are defined, from A to F, where A is the most unstable and F the most stable. The conditions for each category are summarised in Tab. E.1.

<table>
<thead>
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<th>Surface wind speed (m/s)</th>
<th>Insolation</th>
<th>Night</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strong</td>
<td>Moderate</td>
</tr>
<tr>
<td>&lt;2</td>
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<td>A-B</td>
</tr>
<tr>
<td>2-3</td>
<td>A-B</td>
<td>B</td>
</tr>
<tr>
<td>3-5</td>
<td>B</td>
<td>B-C</td>
</tr>
<tr>
<td>5-6</td>
<td>C</td>
<td>C-D</td>
</tr>
<tr>
<td>&gt;6</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>
Appendix F

Gaussian fit of mean concentration profiles over the array of buildings

Vertical profiles of mean concentration for all the stratifications at five different locations are plotted in Fig. F.1, fitted with Gaussian curves. The fitting was performed by means of a non-linear least squares method (as also detailed in Sec. 5.4). Fig. F.2 shows the lateral profiles of mean concentration inside ($z/H = 0.5$) and above the canopy ($z/H = 1.5$). They were obtained by interpolating the contour plot grid points values in the $y_{plume}$ direction at five different distances from the source. The plume axes are defined in Fig. 5.17. Such lateral profiles were employed to find the plume axis, as the one that determined the smallest averaged $\mu$ parameter (see Eq. 5.1) for the distances considered.
Fig. F.1 Vertical profiles of mean concentration fitted with Gaussian curves (continuous lines). Stables cases are on the left column, unstable on the right.
Fig. F.2 Lateral profiles of mean concentration fitted with Gaussian curves (continuous lines). Left column is inside the canopy, right one above the canopy.
Appendix G

Longitudinal profiles of mean vertical velocity in the canyon cross-section

Longitudinal profiles of mean vertical velocity for all the cases at three heights in the canopy are plotted in Fig. G.1. It appears that the stable stratification always results in a reduction of the vertical velocity, even though the amount is dependent on the condition of local stratification.
Fig. G.1 Longitudinal profiles of mean vertical velocity for all the cases at three heights in the canopy.