Numerical study of outdoor ventilation efficiency of simplified urban configurations with equal and unequal street widths

de Coo, L.B.

Award date:
2013

Link to publication

Disclaimer
This document contains a student thesis (bachelor's or master's), as authored by a student at Eindhoven University of Technology. Student theses are made available in the TU/e repository upon obtaining the required degree. The grade received is not published on the document as presented in the repository. The required complexity or quality of research of student theses may vary by program, and the required minimum study period may vary in duration.

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
Final master project

Numerical study of outdoor ventilation efficiency of simplified urban configurations with equal and unequal street widths

L.B. de Coo

Eindhoven, 2013
Personal information and supervisory committee

Author
L.B. de Coo

Date
November 2013

Personal information
Document type: Master project
Project title: Numerical study of outdoor ventilation efficiency of simplified urban configurations with equal and unequal street widths

Date: 21\textsuperscript{th} November 2013
Student name: L.B. de Coo
E-mail address: l.b.d.coo@student.tue.nl
Student number: 0720858

Study program related information
Master: Architecture, Building & Planning (ABP)
Specialty: Building Physics and Services

Supervisory committee
Chairman: prof.dr.ir. B.J.E. Blocken
E-mail address: b.j.e.blocken@tue.nl

Supervisor: ir. R. Ramponi
E-mail address: r.ramponi@tue.nl

Supervisor: ir. W.D. Janssen
E-mail address: w.d.janssen@tue.nl
Acknowledgements

This report is the completion of my graduation research carried out at the department of Built Environment, Eindhoven University of Technology, for the master track of Building Physics and Services.

This report discusses on the effect of a central main street on the outdoor ventilation efficiency in the surrounding area on simplified urban configurations with equal and unequal street widths.

I would like to express my appreciation to everyone who contributed to the final product of this research, especially to:

- prof.dr.ir. B.J.E. Blocken for his inspirational lectures and for giving me a graduation opportunity under his professional supervision.

- ir. R. Ramponi (my first daily supervisor) for her guidance, valuable knowledge and experience in every stage of this research. The many scientific discussions and constructive comments greatly improved this research. Also I would like to thank her for her continued support, patience and enthusiasm during my research.

- ir. W.D. Janssen for her guidance, valuable advice and comments during project meetings including her clear vision on the research which was very helpful.

Finally, I would like to thank my family, friends and boyfriend for all their invaluable support, interest and encouragement.

Eindhoven, November 2013

Laura de Coo
Outdoor ventilation is important for the removal of pollutants and heat in the street canyons. In combination with the growth in the urban population, outdoor air quality is a matter of concern for a healthy and comfortable outdoor living space. The outdoor ventilation is strongly influenced by the wind speed and direction and by the urban density, determined by the geometry and size of the streets and buildings.

In this research, the effect of a central main street on the outdoor ventilation efficiency in the surrounding area is studied on simplified urban configurations with equal and unequal street widths.

Numerical simulations are performed with 3D steady Reynolds-Averaged Navier Stokes (RANS) equations in combination with the Standard k-ε turbulence model on two types of building configurations. First, validation cases with a simplified uniform distribution are simulated for a wide range of plan and frontal area densities. The results are compared to the wind tunnel measurements provided by the Tokyo Polytechnic University for validation. Overall, the simulations show a fairly accurate agreement with the measurements with a slight deviation for the plan area density of 0.6.

Next, main street cases with equal and unequal street widths are studied for different wind directions, plan and frontal area densities and the influence of a main street on the outdoor ventilation efficiency is evaluated.

The results of the main street cases show that the presence of a main street improves the ventilation efficiency in the downstream area for oblique wind directions (22.5°, 45° and 67.5°). This is due to the fact that the flow of the main street acts as a source of fresh air. For the wind direction parallel (0°) and perpendicular (90°) to the main street, the effect of the main street on the ventilation efficiency is less beneficial in the downstream area. This is due to the channeling effect which occurs when the wind flows in the direction of the street canyons. Furthermore an increase in frontal area density due to higher building heights, results in a reduction of the ventilation efficiency, because less interaction between the ambient and canyon flow is obtained for a higher frontal area density.
# Table of contents

Acknowledgements  
**Summary**  

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1</td>
<td>Background</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Research question</td>
<td>2</td>
</tr>
<tr>
<td>1.3</td>
<td>Research methodology</td>
<td>2</td>
</tr>
<tr>
<td>1.4</td>
<td>Outline thesis</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Literature study</td>
<td>5</td>
</tr>
<tr>
<td>2.1</td>
<td>General wind flow pattern</td>
<td>5</td>
</tr>
<tr>
<td>2.2</td>
<td>Outdoor ventilation efficiency</td>
<td>8</td>
</tr>
<tr>
<td>2.3</td>
<td>Research methods for assessment of the urban air quality</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>Building configurations</td>
<td>11</td>
</tr>
<tr>
<td>3.1</td>
<td>Validation cases</td>
<td>11</td>
</tr>
<tr>
<td>3.2</td>
<td>Main street cases</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>Experimental data</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>Numerical model</td>
<td>19</td>
</tr>
<tr>
<td>5.1</td>
<td>Computational domain</td>
<td>19</td>
</tr>
<tr>
<td>5.2</td>
<td>Grid generation</td>
<td>20</td>
</tr>
<tr>
<td>5.3</td>
<td>Boundary conditions</td>
<td>25</td>
</tr>
<tr>
<td>5.4</td>
<td>Solver settings</td>
<td>27</td>
</tr>
<tr>
<td>5.5</td>
<td>Scale effects</td>
<td>28</td>
</tr>
<tr>
<td>5.6</td>
<td>Local mean age of air</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>Results</td>
<td>33</td>
</tr>
<tr>
<td>6.1</td>
<td>Results validation cases</td>
<td>33</td>
</tr>
<tr>
<td>6.1.1</td>
<td>Wind pressure coefficients on the windward façade</td>
<td>33</td>
</tr>
<tr>
<td>6.1.2</td>
<td>Configuration A</td>
<td>34</td>
</tr>
<tr>
<td>6.1.3</td>
<td>Configuration B</td>
<td>34</td>
</tr>
<tr>
<td>6.1.4</td>
<td>Configuration C</td>
<td>35</td>
</tr>
<tr>
<td>6.1.5</td>
<td>Summary of validation cases</td>
<td>36</td>
</tr>
<tr>
<td>6.2</td>
<td>Results main street cases</td>
<td>36</td>
</tr>
<tr>
<td>6.2.1</td>
<td>Flow pattern</td>
<td>37</td>
</tr>
<tr>
<td>6.2.2</td>
<td>Distributions graphs of normalized local mean age of air</td>
<td>39</td>
</tr>
<tr>
<td>6.2.3</td>
<td>Contour plots of normalized local mean age of air</td>
<td>40</td>
</tr>
<tr>
<td>Chapter</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>7</td>
<td>Discussion</td>
<td>43</td>
</tr>
<tr>
<td>8</td>
<td>Conclusions</td>
<td>45</td>
</tr>
<tr>
<td>9</td>
<td>Recommendations for further research</td>
<td>47</td>
</tr>
<tr>
<td>10</td>
<td>References</td>
<td>49</td>
</tr>
</tbody>
</table>
1 Introduction

1.1 Background

A trend of ongoing urbanization is expected worldwide (United Nations, 2010) resulting in a growing amount of built-up areas. In these built-up areas, an increasing amount of pollutants and heat occurs due to urban pollutants and urban heat island effect. Urban pollutants are generated by various reasons such as the increasing use of vehicles and industrial activities. The pollutants and heat are associated with health (Brunekreef and Holgate, 2002) and thermal comfort problems (Moonen et al., 2012). In combination with the growing population in urban environments, urban air quality is a matter of concern to maintain a healthy and comfortable outdoor living space. In order to remove the pollutants and heat, outdoor ventilation is an important aspect in urban environments. Problems are particularly relevant at pedestrian level, which is the outdoor living space in cities and therefore an important area of interest.

The air transport through street canyons is overall important for the outdoor air quality in urban environments. The urban wind flow is strongly influenced by the urban density which is determined by the geometry and size of the streets and buildings. The urban density can be described by various parameters, such as the plan area density and frontal area density, which are the ratio between the building plan and frontal areas and the lot area. The flow pattern through the street canyon varies for different urban densities from isolated roughness flow for configurations with a low density to wake interference flow and skimming flow for configurations with a higher density (Oke, 1988) (see figure 1.1).

Past research on urban wind flow represented the urban environment in three different ways: two-dimensional street canyons (Oke, 1988; Baik and Kim, 1999; Li et al., 2005; Salizzoni et al., 2009), three-dimensional simplified urban configurations of regular arrays of buildings (Macdonald et al., 2002; Yoshiie et al., 2007; Bady et al., 2011; Buccolieri et al., 2010; Princevaci et al., 2010; Hang et al., 2011; Hu and Yoshiie, 2013) and real case studies (Stathopoulos and Baskaran, 1996; Van Hooff and Blocken, 2010; Panagiotoulou et al., 2013). When dealing with outdoor ventilation in street canyons, three-dimensional simplified urban configurations of regular arrays of buildings are studied instead of two-dimensional canyons due to the fact that canyon flows are intrinsically three-dimensional phenomena. On the contrary, real case studies such as models of real cities are computationally demanding, very complex and case dependent.

Research on simplified urban configurations have mainly focused on uniform distribution of buildings, therefore this research studies configurations with equal and unequal street widths by creating a central main street which is a common street type in Europe. This distribution allows generating a model which is a step towards a more realistic model while it is still a...
generic study. This study contains configurations with various plan and frontal area densities obtained by varying the width of the central main street and the building height.

1.2 Research question

The central research question of this study is:

What is the effect of a central main street on the outdoor ventilation efficiency of simplified urban configurations with equal and unequal street widths?

In order to answer the central research question, the research is divided in two different cases. First, a validation study is performed to test the accuracy of 3D steady RANS models to predict the urban wind flow. Then a case study of urban configurations with equal and unequal street widths is simulated to test the effect of the urban densities on the outdoor ventilation efficiency.

The urban configurations consist of low-rise buildings and the distribution varies from uniform to equally spaced building blocks in the x-direction and non-uniform distribution in the y-direction. The urban density varies by increasing the width of the main street (plan area density) and varying the building heights of the model (frontal area density). This study is limited to pedestrian level which is the outdoor living space of inhabitants and therefore a critical area.

1.3 Research methodology

The methodology shown in figure 1.2 has been applied. The research starts with a literature review which contains theory about the wind flow around buildings, a definition of the urban density and description of a suitable indicator to assess the ventilation efficiency in urban environment and the relevance of using Computation Fluid Dynamics for predicting the urban air quality. Next, the validation study (case 1: validation cases) is performed where simplified uniformly distributed cases are analyzed in terms of parametric studies to the geometrical conditions and the solution verification. The cases are compared to experimental data to test the accuracy of 3D steady RANS models to predict the urban wind flow. With the settings of the validation study, the numerical simulations for the urban configurations with equal and unequal street widths (case 2: main street cases) are performed where first the model geometry of the urban configurations is defined within the range of the plan and frontal area density of the validation cases. The results of the main street are analyzed and provide an answer to the central research question to test the effect of the urban densities on the outdoor ventilation efficiency. At last, the research findings are described in this report.

Figure 1.2 – Methodology of the research in a schematic overview.
1.4 Outline thesis

The thesis is structured as follows; in section 2, a literature review is given. In section 3, the model geometry of the various cases is described. In section 4, the experimental data which are used for validating the numerical model are outlined and in section 5 the settings of the numerical simulations for both cases are given. Section 6 contains the results; the validation cases (numerical model) are compared to the experimental data and the results of the main street cases are shown. In section 7, the discussion is provided and in section 8; the conclusion is given where the central research question is answered. Finally, recommendations for future research are suggested in section 9.
2 Literature study

The first section contains theory about wind flow around isolated and non-isolated buildings, the influencing parameters of plan and frontal area density are explained, the flow regimes are given and the influencing parameters in previous research are shown. Further on in section 2.2, indicators of the outdoor ventilation efficiency are given and the local mean age of air is explained. Last, the relevance of using CFD for predicting the urban air quality and the corresponding equations are shown in section 2.3.

2.1 General wind flow pattern

The prediction of wind flow around a building is very complex. Wind speed, turbulence intensity and pressure are depending on each other. The wind flow distribution around an isolated building is shown in figure 2.1 where the approaching flow is perpendicular to the windward façade. Near the windward façade, a high pressure zone occurs which result in an approaching flow which will partly flow over and around the building (1). The pressure on the windward façade reaches a maximum at approximately 60 - 70% of the building height depending on the geometry of the building. At this point a stagnation point (2) is created from where the air flows to lower pressure zones in the upwards (3), sidewards (4) and downwards (5) direction of the point. The upwards and sidwards flows are separated from the façade at the top and edges of the building. Under pressure zones are created on the top and edges which will develop a recirculation zone (6) with low wind speeds and high turbulence intensity. The size of the recirculation zone depends on the building shape and wind profile. The downwards flow from stagnation point to the ground level creates a standing vortex (7) in front of the building where the main direction of the flow is the opposite direction to the approaching flow. Another stagnation point occurs at the point where the approaching flow meets the standing vortex. This creates low wind speeds in front of the building at ground level. From the standing vortex, the wind will flow around the building resulting in corner streams (8) due to the separation flow at the edges. The corner streams have high wind speeds. At the leeward side of the building, a recirculation zone (9) occurs due to under pressure. In this zone, the wind speed is low and air flows in opposite direction and results in slowly rotating vortices (10) near the building surface. After the recirculation zone, the air flows in normal direction.

Figure 2.1 – Wind flow around isolated rectangular building with perpendicular flow to the windward façade (adapted from Hosker, 1981).
In figure 2.2, the wind pressures on the façades of an isolated building are shown. The pressure increases with the height of the building. Only at the top and edges, the pressure is lower due to the separation flow at the edges. The stagnation point (point 2 in figure 2.1) is shown at approximately 60 – 70% of the building height.

![Figure 2.2 – Wind pressures on the façades of an isolated building (modified from (HK Green Building Technology Net, n.d.)).](image)

For non-isolated building configurations, the flow pattern is depending on various parameters such as the density of configuration, arrangement and wind direction. In figure 2.3, a schematic overview of non-isolated flow pattern is shown. The approaching flow will flow over, around and through the street canyons. At the leeward side of each building, a recirculation zone (1) is created due to the low pressure and the direction of the main flow changes. Lateral channeling of the flow (2) is shown where the flow will leave the canyon. The flow around the building will be separated from the surface at the edge of the windward façade (3) which will lead to low pressure regions (4) at both sides of the canyon. The low pressure zones enhance the flow in the direction out of the canyon. The re-attachment flow (5) occurs in the canyons further downstream where the flow direction is towards the canyon center. By this change of direction of the main flow outside, an inwards flow in the canyon is developed. At the leeward side of the group of buildings, a recirculation zone (6) occurs due to low pressure. In this zone, the wind speed is low and air flows in opposite direction close to the ground. After the recirculation zone, the air flows in normal direction.

![Figure 2.3 – Schematic flow around non-isolated buildings (adapted from (Princevac et al., 2010)).](image)
The generic flow pattern around non-isolated building blocks shown in figure 2.3 is slightly different from the isolated building due to the many obstacles which are influencing the wind flow. The urban air flow in non-isolated configurations is influenced by a large amount of parameters. The urban density has a strong impact on the urban air flow. The urban density includes the shape and dimensions of the streets and buildings and can be described by various parameters. In this research, the plan area density and frontal area density (Oke, 1988) will be applied. The concept of the plan and frontal area density are shown in figure 2.4 where the plan area density \((\lambda_p)\) is the building plan area \(A_p\) divided by the lot area \(A_{lot}\) and the frontal area density \((\lambda_f)\) is the building frontal area \(A_f\) divided by the lot area \(A_{lot}\). The lot area is defined as the building plan plus twice the center of the street width as shown in figure 2.4.

\[
\lambda_p = \frac{A_p}{A_{lot}} \quad \lambda_f = \frac{A_f}{A_{lot}}
\]

*Figure 2.4 – Plan area density \((\lambda_p)\) and frontal area density \((\lambda_f)\) and the definition of the lot area of a building.*

When the urban density varies, different flow regimes can be observed in street canyons. Figure 2.5 shows the three flow regimes described by Oke (1988). For configurations where buildings are far apart from each other, isolated flow occurs where the flow fields do not affect each other. When the density increases, wake interference flow occurs where the density is close enough that the wakes are disturbed by with each other. For a configuration with an even higher density, skimming flow occurs where the main flow flows over the canyon instead of in the canyon. Instead of two-dimensional models, (Grimmond and Oke, 1999) analyzed roughness parameters in various three-dimensional urban areas to analyze the urban density characteristics of city models for different flow regimes where the isolated roughness flow has a \(\lambda_p\) of 0.05 – 0.40, the wake interference flow of 0.30 – 0.50 and the skimming flow of 0.50 – 0.80. Note that there is an overlap in plan area densities due to the fact that flow regime is not only depending on this parameter.

*Figure 2.5 – Flow regimes in urban street canyons which are associated with different building-height-to-street-width ratios (Oke, 1988).*

Various factors are influencing the flow regimes such as the geometry of the streets and buildings. Many studies have been performed on urban wind flow on three-dimensional simplified urban configurations of regular arrays of buildings with varying influencing factors.

Bady et al. (2011) performed wind tunnel experiments to investigate the influence of various wind directions and arrangements of simplified buildings on the wind flow characteristics and air quality in a dense urban area. The research states that building configurations and wind directions are very important factors for the ventilation within urban environments.
Kim and Baik (2004) investigated the effects of ambient wind direction on flow and dispersion around simplified buildings by numerical simulations and identified three flow patterns for wind angles in a range of 0° to 45°. The air quality in canyons reduces when the wind angle increases except for the perpendicular wind direction of 90°.

Princevac et al. (2010) carried out water channel experiments to examine the arrangement sizes of buildings and the frontal area densities when the central building is doubled in height. Princevac found that for 3x3 uniform building blocks more rural air is attracted in the canyon if the central building is doubled in height. This is the effect of the lateral spreading of the downdraft near the ground as result of the high central building. For 5x5 uniform building blocks, the downdraft of the high central building is strong enough to block the inflow near the ground and reverses the flow direction of canyon inflow.

Hanna et al. (2002) performed numerical simulations to analyze various plan area densities and building arrangements on wind flow characteristics in urban-type areas. The results show a significant decrease of mean wind speeds in the canyons for higher plan area density and an increase of wind speeds in the canyons for square building arrangements compared to staggered buildings due to the channeling effect between buildings.

Hu and Yoshie (2013) conducted a numerical study on effects of building arrangements, plan and frontal area densities on the ventilation efficiency. Configurations with low plan area density and high frontal area density have higher ventilation efficiency. Staggered buildings arrangements have increased ventilation efficiency when comparing to square arrangement for 0 and 45° and reduced ventilation efficiency compared to the square arrangement for 90° due to the blockage of the air paths by the staggered arrangements.

These studies show that parameters such as the arrangement of buildings, size of configurations, plan and frontal area density and wind direction influence the urban wind flow.

### 2.2 Outdoor ventilation efficiency

The air quality in urban environments is a matter of concern. To maintain a good air quality, ventilation is important to limit health and comfort problems. The ventilation efficiency is mainly assessed in indoor environments by indicators such as the air change rate, wind velocity ratio, spatially-average normalized concentration, purging flow rate, residence time, visitation frequency (Kato et al., 2003), age theory (Sandberg, 1983) and the six indices SVE1-6 (Kato and Murakami, 1992). (Huang et al., 2006) proved that some of the indoor ventilation efficiency indicators can also be applied in urban enclosed environments.

The ventilation efficiency in this research is assessed by the local mean age of air which is described by (Etheridge and Sandberg, 1996) and indicates the air quality in a room by calculating the time that a particle takes to be removed. A room is filled by a tracer gas till a homogeneous situation is obtained. Then the decay of this tracer gas is measured and defines the air quality of a room.

The local mean age of air has been applied in the field of urban environment by Hang et al. (2009) and Buccolieri et al. (2010). By transferring the concept of the local mean age of air from indoor to outdoor environment, there are some difficulties which are explained in detail in section 5.6. For measuring the local mean age of air in the urban environment, the homogeneous emission method is used where a uniform pollutant with the same material properties as the air is released in the entire domain. This is the worst case scenario due to the fact that the pollutant is everywhere. The local mean age of air is applied to assess the outdoor air quality because it is suitable to evaluate and map the distribution of the ventilation efficiency.
2.3 Research methods for assessment of the urban air quality

Wind flow problems can be solved by various research methods. The mathematical models are derived from the basic equations of fluid dynamics and heat transfer. In-situ measurements are performed on a site or certain location in full scale. Laboratory measurements include wind tunnel or water channel experimenting, often in reduced scale. Numerical simulations are performed in a computational domain which is not affected by scaling issues.

In this research, numerical modeling with computational fluid dynamics (CFD) is used due to fact that it is less time-consuming and less expensive for the cases in this study with many variants of urban configurations. Another advantage is that whole-flow field data are obtained in every point of the domain. On the other hand, the accuracy and reliability of modeling with CFD is a concern. The choice of parameters has a major impact on the results. Parametric studies to the geometrical conditions and the solution verification should be performed on the numerical model and the results should always be validated by comparing the results of the numerical model to experimental measurements. This study consists only of CFD simulations and verification and validation are performed on the numerical model.

Wind flow around a building is solved by the Reynolds-Averaged Navier Stokes equations which are defined in equation 2.1 and 2.2.

\[
\frac{\partial}{\partial x_i} (\rho \overline{u}_i) = 0 \quad (2.1)
\]

\[
\frac{\partial}{\partial x_j} (\rho \overline{u}_i \overline{u}_j) = -\frac{\partial \rho}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \mu \left( \frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial \overline{u}_k}{\partial x_k} \right) + \frac{\partial}{\partial x_j} (-\rho \overline{u}_i \overline{u}_j) \right) \quad (2.2)
\]

Where:
- \( x_i \) = Cartesian coordinate [m]
- \( \rho \) = Density [kg/m\(^3\)] (constant = 1.225)
- \( \overline{u}_i \) = mean velocity [m/s]
- \( \rho \overline{u}_i \overline{u}_j \) = mean pressure [kg/ms\(^2\)]
- \( \mu \) = dynamic viscosity [kg/ms]
- \( \delta_{ij} \) = Kronecker delta [-]
- \( -\rho \overline{u}_i \overline{u}_j \) = Reynolds stress [kg/ms\(^2\)]

The Reynolds-Averaged Navier Stokes equations solve only the mean flow. To close the equations, a turbulence model is used to approximate the Reynolds stresses. In this research, the k-\( \epsilon \) model is applied (see section 5.1). The k and \( \epsilon \) are defined by equation 2.3 and 2.4. The Standard k-\( \epsilon \) model is most widely used in practice. It should be noted that this model has deficiencies. An overestimation of k around the frontal and sideways corners and an underestimation at the recirculation zone might occur. This might result in a less accurate prediction of the separation and reverse flow at the building roof (Tominaga et al., 2008).

\[
k = \frac{1}{2} \overline{u}_i' \overline{u}_i' \quad [m^2/s^2] \quad (2.3)
\]

\[
\epsilon = \nu \frac{\partial \overline{u}_i' \overline{u}_j'}{\partial x_j \partial x_j} \quad [m^2/s^3] \quad (2.4)
\]

Where:
- \( u_i' \) = fluctuating velocity component [m/s]
- \( \nu \) = kinematic viscosity [kg/ms]
The pollutant is treated as a passive scalar. The scalar is solved by the steady-state scalar transport equation (equation 2.6 and 2.7) where the source term is equal to the convection term minus the diffusion term.

\[
\frac{\partial}{\partial x_i} \left( \rho u_i \phi - I \frac{\partial \phi}{\partial x_i} \right) = S_\phi
\]  

(2.6)

\[
J = - \left( \rho D + \frac{\mu_t}{S_{C,t}} \right) \nabla Y
\]  

(2.7)

Where:

- \( \phi \) = concentration of scalar [-]
- \( I \) = mass diffusivity coefficient [m\(^2\)/s]
- \( S_\phi \) = Source term of scalar / emission rate of scalar [kg/m\(^3\)/s]
- \( D \) = Molecular diffusion coefficient [m\(^2\)/s] (set in Fluent as 2.88e-05)
- \( \mu_t \) = Turbulent viscosity [kg/ms] (constant = 1.7894e-05)
- \( S_{C,t} \) = Schmidt number [-] (default value of 0.7)
- \( Y \) = Mass fraction of species

The turbulent Schmidt number (Sc\(_t\)) is defined as the ratio of turbulent viscosity to turbulent mass diffusivity. There is no universal value for the Sc\(_t\) (Tominaga and Stathopoulos, 2007) due to the fact that Sc\(_t\) is case-dependent (Rossi and Iaccarino, 2009). For that reason, the Sc\(_t\) set at 0.7 which is the default setting and often used in research.
3 Building configurations

Two types of building configurations are analyzed in this research: the validation cases and the main street cases. In section 3.1, the model geometry of the validation cases is described and in section 3.2, the model geometry of the main street cases with equal and unequal street widths is given.

3.1 Validation cases

In order to test the accuracy of 3D steady Reynolds-Averaged Navier Stokes (RANS) to predict the urban wind flow, the numerical model should be validated by comparison with experimental data. An extensive database of experimental pressure coefficient measurements in the wind tunnel was obtained by (Quan et al., 2007a, 2007b). The purpose of the research was to quantify the effect of various factors on the wind pressures of the central building. The influence of arrangement of surrounding buildings, type of roofs, plan area density, height of buildings and wind direction were tested in the wind tunnel on reduced-scale models.

The influence of the urban density will be studied in this research by changing both the street width (plan area density) and the building height (frontal area density). For the validation, configurations with different plan area densities of 0.1, 0.3 and 0.6 and various building heights of 0.06, 0.12 and 0.18m in reduced-scale (resulting in frontal area densities ranging from 0.03 till 0.45) are simulated for the wind directions of 0 and 45° and compared to the experimental data. All models consist of a regular distribution of uniform buildings with flat roofs and a fixed building ground plan of 0.24 x 0.16 m² (L x W, reduced-scale). The accuracy of 3D steady RANS models is tested on the cases and will result in validated numerical models with a wide range of plan and frontal area densities.

At first, a detailed analysis is performed for the case with plan area density of 0.3 and building height of 0.18 m (in reduced scale). To assess the influence of computational parameters, an analysis is performed for the grid and turbulence models. Then the case is simulated in full scale and compared to the reduced-scale result. With the settings of the validated case, the other cases are simulated in full scale and compared to the experimental data. In table 3.1, the cases with different plan and frontal area densities are shown.
Table 3.1 – The validation cases with various plan area densities and building heights. Every case is simulated for 0° and 45°.

<table>
<thead>
<tr>
<th>Plan area density (λₚ)</th>
<th>Building height [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (λₚ = 0.1)</td>
<td>H₁ = 6 m</td>
</tr>
<tr>
<td>B (λₚ = 0.3)</td>
<td>H₂ = 12 m</td>
</tr>
<tr>
<td>C (λₚ = 0.6)</td>
<td>H₃ = 18 m</td>
</tr>
</tbody>
</table>

3.2 Main street cases

Simplified uniformly distributed cases with plan area densities ranging from 0.1 to 0.6 and frontal area densities ranging from 0.03 to 0.45 were used for validation. The results of the validation cases show a good agreement with experimental measurements (section 6.1). Only for plan area density of 0.6, a slight deviation occurs. For the main street cases, the plan and frontal area density are taken within the ranges of the validation cases. It should be noted that the values are taken below the plan area density of 0.6.

The main street cases consist of urban configurations with equal and unequal street widths where nine cases are defined. The roof type and building plan are similar to the validation study. The building heights are varying from 6, 12 to 18 m (in full scale) which is common in European urban areas. The distribution and plan area density varies from completely uniform to equally spaced building blocks in the x-direction and non-uniform distribution in the y-direction due to the main street which will be implemented. The wind direction is changing in steps of 22.5°. Due to the symmetrical geometry, only five wind directions (0, 22.5, 45, 67.5 and 90°) are simulated.

For a realistic distribution of streets, three types of common Dutch streets are identified. The streets are indicated by searching in the digital basic maps of Eindhoven for the most common street types. In figure 3.1, the three streets are presented. The street elements of the three streets are summarized in table 3.2 with the corresponding element dimensions which are defined according to the guidelines of the Stichting Centrum voor Regelgeving en Onderzoek in de Grond-, Water- en Wegenbouw en de Verkeerstechniek (CROW, 2004). In these guidelines, the minimum dimensions of street elements are described. Also the resulting street width for the three streets is given in table 3.2.
Figure 3.1 – Photos of three streets in Eindhoven, the Netherlands (a) Heilige Geeststraat, (b) Grote Berg and (c) Edenstraat (source: Google street view).

Table 3.2 – Dimensions of the street elements [m] and the total street width of the three streets.

<table>
<thead>
<tr>
<th>Street elements with corresponding dimensions [m]</th>
<th>Street 1</th>
<th>Street 2</th>
<th>Street 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garden</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Sidewalk</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Parking lot</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Cycling path</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Road</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Garden</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Parking lot</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Sidewalk</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Garden</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td><strong>Total street width [m]</strong></td>
<td><strong>8.5</strong></td>
<td><strong>16.0</strong></td>
<td><strong>24.0</strong></td>
</tr>
</tbody>
</table>

For the first urban model geometry, a uniform configuration is obtained with street widths of 8.5 m for all the streets. Due to the uniform case, the name MS-0 (main street 0) will be used to indicate this street. In the next cases (MS-1 and MS-2), the width of the main street is increased from 8.5 to 16 and 24 m. Figure 3.2 shows the geometry of the three configurations where the central building is surrounded by 2 rows of buildings as suggested by Yoshie et al. (2007) in order to have a representable environment around central building by the surrounding buildings. The red dotted line presents the lot area of the central building and the corresponding plan area densities are given in figure 3.2.

Figure 3.2 – Plan view of three main street cases with the corresponding street widths and plan area densities for the central building.

In table 3.3, the main street cases with various plan area densities and building heights are shown. Note that the plan and frontal area densities are in between the ranges of the validation cases. Every case is simulated for 5 wind directions (0, 22.5, 45, 67.5 and 90°).
Table 3.3 – Main street cases with various plan area densities and building heights are shown. Every case is simulated for 5 wind directions.

<table>
<thead>
<tr>
<th>Plan area density (λ_p)</th>
<th>Building height [m]</th>
<th>0°, 22.5, 45, 67.5 and 90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS-0 (λ_p = 0.48)</td>
<td>MS-0(H_1)</td>
<td>H_1 = 6 m</td>
</tr>
<tr>
<td></td>
<td>MS-0(H_2)</td>
<td>H_2 = 12 m</td>
</tr>
<tr>
<td></td>
<td>MS-0(H_3)</td>
<td>H_3 = 18 m</td>
</tr>
<tr>
<td>MS-1 (λ_p = 0.42)</td>
<td>MS-1(H_1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MS-1(H_2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MS-1(H_3)</td>
<td></td>
</tr>
<tr>
<td>MS-2 (λ_p = 0.37)</td>
<td>MS-2(H_1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MS-2(H_2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MS-2(H_3)</td>
<td></td>
</tr>
</tbody>
</table>
4 Experimental data

The measurements used for validation were performed by Quan et al. (2007a, 2007b) in the atmospheric boundary layer wind tunnel of Tokyo Polytechnic University in Japan. The cross-section of the wind tunnel is 2.2 x 1.8 m$^2$ (W x H). For the measurements, the buildings were placed on a turntable with a diameter of 2 m (see figure 4.1). The experiments were in reduced scale; 1:100 for geometry and 1:3 for velocity. The influence of various plan area densities, arrangement of surrounding buildings, type of roofs, height of buildings and wind directions was tested for the wind pressures of the central building.

The cases with plan area density of 0.1, 0.3, and 0.6 are used for validation. Figure 4.1 illustrates the plan area density of 0.3 in detail. The configurations are composed by a uniform distribution of buildings. The buildings have a flat roof and a fixed ground plan of 0.24 x 0.16 m$^2$ (L x W, reduced-scale) and heights varying between 0.06, 0.12 and 0.18 m. In figure 4.2, the dimensions of the buildings are shown.

In order to avoid the influence of the wind tunnel walls on the results, a maximum blockage ratio of the wind tunnel section is recommended to be below 3%. The blockage ratio is the frontal area of the buildings divided by the cross-section of the wind tunnel. For plan area density of 0.3, the maximum blockage ratio is 5.4% (see figure 4.1). Also for the plan area densities of 0.1 and 0.6 the maximum blockage ratio is higher than the recommended 3%, respectively 3.8 and 7.0%.

![Figure 4.1](image1) The buildings on the turntable in the wind tunnel section are shown. The dark grey building is the center building and the dashed line around the center building is the lot area. On the right, the blockage ratio of the section is shown.

![Figure 4.2](image2) Building dimensions are 0.24 x 0.16 m$^2$ (L x W) with height of 0.18, 0.12 and 0.06 m (in reduced-scale).
The mean velocity and turbulence intensity profiles were measured in the empty wind tunnel at the middle of the turntable (figure 4.3). At a reference height of 0.10 m (in reduced scale), the mean streamwise wind speed is 7.8 m/s and the turbulence intensity is 25%.

![Figure 4.3 – Measured inlet profiles of the mean wind speed (U) and turbulence intensity (TI) by Quan et al. (2007a, 2007b) in the empty wind tunnel (scale 1:100) at the center of the turntable where H = 0.5 m in reduced scale and H_b shows the building height of 0.18 m in reduced scale.](image)

In the experiments, an aerodynamic roughness length of 0.002 m in reduced scale (0.2 m full scale) is applied to simulate a suburban area. This roughness corresponds to the terrain category III of Architectural Institute of Japan (2004). According to Choi (2009), this roughness is similar to closely placed low-rise obstructions with 3 - 5 m space in between. Spires, roughness blocks and carpet are applied to represent the roughness length. The roughness elements are placed in the wind tunnel to generate the proper wind profile (figure 4.4).

![Figure 4.4 – Photos of the experimental setup in the wind tunnel of the Tokyo Polytechnic University (Source: website of Tokyo Polytechnic University: http://www.wind.arch.t-kougei.ac.jp).](image)

The wind pressure on the central building is measured by pressure taps connected to a scanivalve pressure measurement system through synthetic resin tubes. The taps are uniformly placed over the surfaces and roof of the building with 0.02 m (in reduced scale) space in between. The measurements are repeated 10 times and the average wind pressure is used for calculating the wind pressure coefficient ($C_p$) (see equation 4.1).

\[
C_p = \frac{p}{0.5 \rho U_h^2} \quad [-] \quad (4.1)
\]
Where:

\[ p = \text{measured wind pressure (Pa)} \]
\[ \rho = \text{density of air (kg/m}^3\text{)} \]
\[ U_H = \text{mean wind speed at reference height of 10 m (7.8 m/s)} \]
5 Numerical model

The settings of the numerical models of the validation and main street cases are described in this chapter. The first section defines the computational domain. In the next section, the computational grid is explained. Section 5.3 contains the boundary conditions where the wind profile and horizontal homogeneity are shown. Further on in section 5.4, the solver settings are given. And at last in section 5.5 the local mean age of air is explained.

5.1 Computational domain

The dimensions of the computational domain are defined with respect to the existing guidelines by Franke et al. (2007) and Tominaga et al. (2008) and the wind tunnel measurement setup (Quan et al., 2007a, 2007b). According to the guidelines, the distance from the inlet to the area of interest is advised to be 5 times the maximum height of the building (H). However, to limit the development of unintended streamwise gradients the upstream length can be reduced up to 3H (Blocken et al., 2007a, 2007b). The minimum distances from the area of interest to the lateral sides and top of the domain is 5H and to the outlet at least 15H according to the guidelines.

The dimensions of the computational domain are defined with respect to guidelines. However, for validation purposes the dimensions of the cross-section of the computational domain will remain the same as the wind tunnel geometry. The cross-section of the wind tunnel is 2.2 x 1.8 m² (W x H in reduced-scale) and it should be noted that this section results in high values of the blockage ratio (section 4). The resulting dimensions of the computational domain in reduced-scale are L x W x H = 5.19 x 2.2 x 1.8 m³ (519 x 220 x 180 m³ in full scale), as shown in figure 5.1. The maximum blockage ratio is determined for two cross-sections: one over the length of the domain (section over L₀) and one over the width of the domain (section over W₀). In the computational domain, the maximum blockage ratios are 2.4% (section over L₀) 5.4% (section over W₀).

For the simulations with wind direction of 45°, the sides of the computational domain are too close to the area of interest with only two cells between the last building and the wall. In order to avoid deviations in the results by the limited cells, the width of the computational domain in this case was extended of 0.1 m at each side of the domain, with a resulting total width of 2.4 m.

For the main street cases, the dimensions of the computational domain are defined with respect to the existing guidelines (Franke et al., 2007; Tominaga et al., 2008) and the upstream length as proposed by (Blocken et al., 2007a, 2007b). Applying these dimensions, the maximum blockage ratio exceeds the recommended 3% (Franke et al., 2007). By varying the height of the domain from 6H to 10H (same height as the domain of the validation case) the blockage ratios are 2.3% (section over L₀) and 2.1% (section over W₀). The resulting dimensions of the computational domain are L x W x H =536 x 392 x 180 m³ (in full scale) (figure 5.2). Note that the dimensions for the upstream, downstream and the lateral sides are measured when the buildings are rotated in the worst case scenario which is 45°.
5.2 Grid generation

The computational grid is generated according to the guidelines by Franke et al. (2007) and Tominaga et al. (2008). The buildings and streets have at least 10 cells in the length and width of the surface. For the widths of two adjacent cells, the stretching ratios are less than 1.3 and the pedestrian height (1.75 m in full scale) is in the third cell from the ground. Furthermore, the surface-grid extrusion technique by van Hooff and Blocken (2010) is used for generating the grid to ensure more control over the cell shapes and sizes. The grids consist of hexahedral cells.

In order to reduce the influence of the grid resolution on the results, a grid sensitivity analysis is performed for the validation case. Three structured grids are generated by refining and coarsening the basic grid by a factor $\sqrt{2}$ in the three directions. The cell distribution on the building is of $18 \times 12 \times 14$ cells ($L \times W \times H$) for the basic grid resulting in a total number of $1,596,048$ cells (figure 5.3 and 5.4). The fine grid has $22 \times 16 \times 18$ cells on the buildings and a total of $3,290,148$ cells; the coarse grid has $14 \times 8 \times 12$ cells on the building and $846,544$ cells in total. Figure 5.5 shows the three grids for the grid sensitivity analysis.
Figure 5.3 – Top view of basic grid (1,596,048 cells) for Case B(H3).

Figure 5.4 – Perspective view of basic grid for Case B(H3).

Figure 5.5 – A zoom of the top view of the (from left to right) fine, basic and coarse grids are shown.

Figure 5.6 shows the streamwise wind speed along a vertical line upstream the central building. The line is placed in the middle of the street canyon with 0.10 m (10 m in full scale) upstream the central building. Figure 5.7 and 5.8 show the wind pressure coefficients along a horizontal and vertical line around the central building. The analysis shows that the grid resolution does not influence the results. Although the use of the coarse grid would save some computing power, the basic grid is chosen for further analyses because it is in accordance with the guidelines (Franke et al., 2007; Tominaga et al., 2008).
Figure 5.6 – The velocities in the middle of the street (point A) are shown for the three grids. The gray block on the side of the graph represents the building height.

Figure 5.7 – The wind pressure coefficients of the different grids are shown along a horizontal line around the central building.
Figure 5.8 – The wind pressure coefficients of the different grids are shown along a vertical line around the central building.

For the validation cases with different plan area densities and heights, the total cell number is given in table 5.1. The cell number on the buildings is constant for the length and width. For the different building heights, the cells vary from 12 cells for $H_2$ and 10 cells for $H_1$.

Table 5.1 – Total number of cells for the validation cases.

<table>
<thead>
<tr>
<th>Plan area density ($\lambda_p$)</th>
<th>Building height [m]</th>
<th>$H_1 = 6$ m</th>
<th>$H_2 = 12$ m</th>
<th>$H_3 = 18$ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>A ($\lambda_p = 0.1$)</td>
<td></td>
<td>682,128</td>
<td>677,376</td>
<td>797,008</td>
</tr>
<tr>
<td>B ($\lambda_p = 0.3$)</td>
<td></td>
<td>1,514,520</td>
<td>1,555,284</td>
<td>1,596,048</td>
</tr>
<tr>
<td>C ($\lambda_p = 0.6$)</td>
<td></td>
<td>1,360,332</td>
<td>1,340,810</td>
<td>1,320,506</td>
</tr>
</tbody>
</table>

For the main street cases, the cell number on the buildings is equal to the validation case of 18 x 12 cells (L x W) and 10 cells for $H_1$, 12 cells for $H_2$ and 14 cells for $H_3$. The total numbers of cells for the different configurations are given in table 5.2. Figure 5.9 and 5.10 shows the top view of the grid and a zoom view for the MS-0($H_3$) case.
### Table 5.2 – Total number of cells for the MS-configurations.

<table>
<thead>
<tr>
<th>Plan area density ($\lambda_p$)</th>
<th>Building height [m]</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H₁ = 6 m</td>
<td>H₂ = 12 m</td>
<td>H₃ = 18 m</td>
<td></td>
</tr>
<tr>
<td>MS-0 ($\lambda_p = 0.48$)</td>
<td>1,459,236</td>
<td>1,488,298</td>
<td>1,517,360</td>
<td></td>
</tr>
<tr>
<td>MS-1 ($\lambda_p = 0.42$)</td>
<td>1,459,236</td>
<td>1,488,298</td>
<td>1,517,360</td>
<td></td>
</tr>
<tr>
<td>MS-2 ($\lambda_p = 0.37$)</td>
<td>1,496,110</td>
<td>1,496,110</td>
<td>1,525,424</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5.9** – Top view of MS-0(H₃) case with a total grid containing 1,517,360 cells.

**Figure 5.10** – Perspective view of MS-0(H₃) with a grid distribution on the building of 18 x 12 x 14 cells (L x W x H).
5.3 Boundary conditions

The same boundary conditions are applied for the validation cases as for the main street cases. The inlet profile imposed at the inlet of the computational domain was generated from the wind tunnel measurements. A logarithmic mean wind speed profile (see equation 5.1) and the upstream roughness were calibrated to fit the experiments. The profile of the turbulent kinetic energy is derived by equation 5.3. The parameter ‘a’ is a constant value equal to 0.5, 1, or 1.5 (Ramponi and Blocken, 2012). As recommended by Tominaga et al. (2008) this parameter is taken as 1. The turbulence dissipation rate is given by equation 5.4 and in equation 5.5, the specific dissipation rate is shown. The inlet profile for the numerical simulations in terms of the mean wind speed, turbulent kinetic energy and turbulence dissipation rate are shown in figure 5.11.

\[
\begin{align*}
  u(z) &= \frac{U_{ABL}^*}{\kappa} \ln \left( \frac{z + z_0}{z_0} \right) \quad \text{[m/s]} \\
  U_{ABL}^* &= \frac{\kappa \times U_{ref}}{\ln \left( \frac{z_{ref} + z_0}{z_0} \right)} \quad \text{[m/s]} \\
  k(z) &= a \times \left( I_u(z) \times U(z) \right)^2 \quad \text{[m}^2\text{s}^{-2}] \\
  \varepsilon(z) &= \frac{U_{ABL}^*^3}{k(z) \times (z + z_0)} \quad \text{[m}^2\text{s}^{-3}] \\
  \omega(z) &= \frac{\varepsilon(z)}{C_{\mu} \times k(z)} \quad \text{[1/s]}
\end{align*}
\]

**Where:**
- \(u(z)\) = mean wind speed at height \(z\) [m/s]
- \(U_{ABL}^*\) = friction velocity [m/s] (see equation 3.2)
- \(\kappa\) = von Karman constant (= 0.42) [-]
- \(z\) = vertical coordinate [m]
- \(z_0\) = aerodynamic roughness length [m]
- \(U_{ref}\) = velocity at reference height \(z_{ref}\) [m/s]
- \(z_{ref}\) = reference height [m]
- \(k(z)\) = turbulent kinetic energy at height \(z\) [m\(^2\)/s\(^2\)]
- \(a\) = constant value equal to 0.5, 1, or 1.5 [-]
- \(I_u(z)\) = streamwise turbulence intensity at height \(z\) [-]
- \(\varepsilon(z)\) = turbulence dissipation rate at height \(z\) [m\(^2\)/s\(^3\)]
- \(\omega(z)\) = specific dissipation rate at height \(z\) [1/s]
- \(C_{\mu}\) = parameter in k-\(\varepsilon\) turbulence model (= 0.09) [-]
A horizontal homogeneity analysis is performed studying the development of the approaching flow along the computational domain. When there are no unintended streamwise gradients in the vertical profiles of mean flow and turbulence, horizontal homogeneity is obtained (Blocken et al., 2007a, 2007b). To assess the horizontal homogeneity, a 3D steady RANS simulation with Standard k-ε model is performed in an empty computational domain with the same settings as the validation cases (section 5.4). The mean velocity, turbulent kinetic energy and turbulence dissipation rate near the inlet are compared to the results at the position where the first buildings would be present (see figure 5.12). The results show minor streamwise gradients for the velocity and the turbulence dissipation rate. For the turbulent kinetic energy, the streamwise gradients have a larger difference from the ground plane to the top of the building. Note that figure 5.12 shows only the profiles up to 3 times the building height of 0.18m in reduced-scale.

Figure 5.11 – The inlet profile of the mean wind speed (U), turbulent kinetic energy (k) and turbulence dissipation rate (ε) is given where H is the domain height of 1.8 m (in reduced scale and 180 m in full scale).
On the ground, an aerodynamic roughness length ($z_0$) of 0 m is applied to approach the wind tunnel conditions in the immediate surroundings of the turn table. This assumption agrees with the validation study by Kim et al. (2012) which performed a comparable study to the effect of the wind pressures on non-isolated low-rise buildings with various area densities. To define the roughness of the ground, the standard wall functions by Launder and Spalding (1974) are applied. Also for the building surfaces, the standard wall functions are applied where the surfaces are assumed to be smooth. At the lateral sides and top of the domain, symmetry boundary conditions are set with zero normal velocity and zero normal gradients of all variables. And at the outlet of the domain, zero static pressure is imposed with the same turbulent kinetic energy and turbulence dissipation rate profiles as in the inlet boundary conditions.

### 5.4 Solver settings

The simulations of the validation cases and main street cases are performed using ANSYS Fluent 12.1.4 (ANSYS, Inc., 2009). The 3D steady Reynolds-Averaged Navier Stokes equations (RANS) are solved in combination with a turbulence model to close the equations. In the next paragraph, an analysis of the influence of different turbulence models is described. The SIMPLE algorithm is used for pressure-velocity coupling. For pressure interpolation, second order is used and also for the convection terms and the viscous terms of the governing equations the second-order discretization schemes are used. The numerical simulations are assumed to be converged when the residuals have leveled off and have reached a minimum of $10^{-4}$ for continuity, $10^{-5}$ for $\varepsilon$, $10^{-6}$ for $k$ and $x$ velocity and $10^{-7}$ for $y$ and $z$ velocity.

To find the most suitable turbulence model, the following models are tested: the Standard $k$-$\varepsilon$ model (Jones and Launder, 1972), Renormalization Group $k$-$\varepsilon$ model (Yakhot et al., 1992; Choudhury, 1993), Realizable $k$-$\varepsilon$ model (Shih et al., 1995), Standard $k$-$\omega$ model (Wilcox, 1998), Shear stress transport $k$-$\omega$ model (Menter, 1994) and Reynolds stress model (Laurens et al., 1975). The wind pressure coefficients obtained with various turbulence models are compared to the experimental data (Quan et al., 2007a, 2007b) along a horizontal and a vertical line on the surfaces of the central building (figure 5.13 and 5.14). The lines correspond to the measurement points of the experimental data.

The results show that all the turbulence models have a quite good agreement in comparison to the experimental data with only minor differences. The Standard $k$-$\omega$ model, SST $k$-$\omega$ model and the RNG model have the largest deviations of average wind pressure coefficients on a vertical line on the windward façade of respectively 20.7%, 17.6% and 16.2%. The Standard $k$-$\varepsilon$ model has the best performance in predicting wind pressure coefficients with a deviation of 9.7%. Therefore, this model is chosen as turbulence model in this research. It should be noted that that Standard $k$-$\varepsilon$ model has some deficiencies which might affect the predicting of the separation and reverse flow at the building roof (Tominaga et al., 2008).

The results of the turbulence model RSM are not reported due to the fact that the RSM shows a non-symmetrical flow, while the geometry is symmetrical. Oscillations occur when applying RSM and second order schemes in symmetric domains. By running the RSM simulation with first order discretization schemes and higher numerical diffusion, the oscillations disappeared.

---

*Figure 5.12 – The profiles of velocity ($U$), turbulent kinetic energy ($k$) and turbulence dissipation rate ($\varepsilon$) at the inlet (continuous lines) ($x = 0.1$ m) and at the building position (dashed lines) ($x = 0.54$ m) in the empty domain. The dotted line represents the building height of 0.18 m in reduced scale.*
However, first order schemes are less accurate than second order schemes and not preferable. Therefore the RSM is not taken into account in this analysis of turbulence models.

Figure 5.13 – The wind pressure coefficients of turbulence models are shown along a horizontal line around the central building.

Figure 5.14 – The wind pressure coefficients of turbulence models are shown along a vertical line around the central building.

5.5 Scale effects

The measurements were obtained in the wind tunnel at the reduced scale (1:100). For validation purposes, the validated numerical model of case B(H3) was also performed at reduced scale. The main street cases will be in full scale. In order to transform from reduced to full scale, a Reynolds numbers independent flow should be obtained which occurs when the Reynolds numbers exceeds the value of 11,000 (Snyder, 1972). The reference mean wind
speed at 10 m is 8.79 m/s and for characteristic length, the building height of 0.18 m (in reduced scale and 18 m in full scale) is taken. This results in a Reynolds number for case B(H₃) at reduced-scale of 108,340 and at full scale of 10,833,958. Furthermore, the case in reduced- and full scale is analyzed by the wind pressure coefficients on the building surface along a horizontal (figure 5.15) and a vertical (figure 5.16) line and the pressure coefficients on the front façades (figure 5.17). The results show no significant difference between the reduced-scale and full scale. Therefore, full scale models are used for further analysis based on the reduced-scale validation study.

**Figure 5.15** – The wind pressure coefficients of the model in reduced and full scale in a horizontal line around the central building are given.

**Figure 5.16** – The wind pressure coefficients of the model in reduced and full scale are shown along a line vertical around the central building.
Figure 5.17 – The wind pressure coefficients on windward façade of the central building are shown in reduced-scale (left) and full scale (right).

5.6 Local mean age of air

In order to assess the outdoor air quality, the concept of local mean age of air is applied. To simulate the local mean age of air, a passive scalar is used as tracer gas with the same material properties as the air. A homogeneous emission rate of the scalar is set at $10^{-6}$ kg/m$^3$s in the total computational domain. The local mean age of air is given in equation 5.6 where the scalar is divided by the emission rate. A high value of the local mean age of air implies a poorly ventilated region where the time a particle takes to be removed is large.

$$\bar{t}_p = \frac{c_p}{Q_U} \ [s] \tag{5.6}$$

Where:
- $c_p = \text{concentration at point } p \ [\text{kg}]$
- $Q_U = \text{uniformly distributed emission rate } \ [\text{kg/s}]$

When the local mean age of air is applied to the urban environment, some aspects need to be considered. At first, the boundaries; the indoor environment has closed boundaries such as walls, floor and ceiling with only two interruptions of the wall for the inlet and outlet flow. Due to the closed boundaries, the contaminated air particles never return. The urban environment has open boundaries where the particles might return. In this research, the boundaries of the urban domain will be defined as the total computational domain. Although the geometry of the cases varies, the results in terms of local mean age of air at pedestrian level are comparable for different building heights due to the homogeneous situation that is created. On the other hand, a homogeneous situation is a worst case scenario due to the fact that the contaminated air particles will be present everywhere.

Secondly when the entire domain is filled by a tracer gas, the local mean age of air depends strongly on the distance from the inlet of the domain to the buildings of interest. Figure 5.18 gives the local mean age of air in a plan at pedestrian level for the empty domain and for the MS-0(H3) case with wind direction of 0 and 45° and shows the time in seconds that a particle takes to be removed. When the wind direction varies, the distance from the inlet to the area of interest (indicated by the red dashed line) is also different. To be able to compare these cases, the upstream distance should be removed. By subtracting the minimum local mean age of air at the inlet canyon openings of the buildings from the local mean age of air the upstream effects are ruled out and the local mean age of air will start at 0 seconds from the openings.
Figure 5.18 – The development of the local mean age of air through the empty domain, MS(H3) case for 0 and 45°.

The normalization of the local mean age of air is performed according to equation 5.7. In the following paragraphs, the minimum local mean age of air and flow rate through opening areas far upstream are defined.

\[
\tau_p^* = \left( \tau_p - \tau_0 \right) \frac{Q_{ref}}{V} \quad \text{[\text{\text{\text{-}}}]}
\]  

(5.7)

Where:
- \( \tau_p \) = local mean age of air at point p [s]
- \( \tau_0 \) = minimum local mean age of air at openings of \( \tau_{01} \) and \( \tau_{02} \) [s]
- \( Q_{ref} \) = flow rate through opening area far upstream [m²/s]
- \( V \) = street volume up to pedestrian level (=13923 m³ for MS-0; 15944 m³ for MS-1; 18100 m³ for MS-2)

The minimum local mean age of air is defined by the lowest value of the mean local mean age of air of the inlet of street openings. Due to the different wind directions, varying from 0 to 90°, two openings are selected to calculate the minimum local mean age of air. In figure 5.19, these openings are indicated by \( \tau_{01} \) and \( \tau_{02} \) where the mean local mean age of air of the openings is calculated on a horizontal line at pedestrian level (1.75 m). The lowest value of the two openings is taken as the minimum local mean age of air.

The flow rate through an opening area far upstream is calculated by the average velocity far upstream [m/s] multiplied by the area openings [m²]. The average velocity far upstream is 4.0 m/s which is obtained by averaging the velocity in a plane near the inlet (at 15 m in the x-direction in full scale) up to pedestrian height. The area openings are defined by the openings where the flow enters the streets (blue lines in figure 5.19). Due to the changing wind direction, the openings at two sides of the buildings are taken into account and the area of the openings is computed by the surface of the opening when it is perpendicular to the inlet as shown in figure 5.19. The flow rates (\( Q_{nol} \)) per case are given in table 5.3.
Figure 5.19 – The positions of τ₀₁ and τ₀₂ are given and all the area openings of streets till pedestrian level (1.75 m) are shown for the wind direction of 0 and 45°.

Table 5.3 – The flow rates (Q<sub>ref</sub>) [m<sup>3</sup>/s] of the main street cases.

<table>
<thead>
<tr>
<th></th>
<th>MS-0</th>
<th>MS-1</th>
<th>MS-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>238.00</td>
<td>290.50</td>
<td>346.50</td>
</tr>
<tr>
<td>22.5°</td>
<td>310.96</td>
<td>359.47</td>
<td>411.20</td>
</tr>
<tr>
<td>45°</td>
<td>336.58</td>
<td>373.71</td>
<td>413.30</td>
</tr>
<tr>
<td>67.5°</td>
<td>310.96</td>
<td>331.05</td>
<td>352.48</td>
</tr>
<tr>
<td>90°</td>
<td>238.00</td>
<td>238.00</td>
<td>238.00</td>
</tr>
</tbody>
</table>
6 Results

In this research, two types of building configurations are analyzed: the validation cases and the main street cases. The results of these cases are described in this chapter. Section 6.1 shows the results of the validation study which consist of cases with various plan and frontal area densities. Section 6.2 contains the results of the main street cases where equal and unequal street widths are studied.

6.1 Results validation cases

The validation cases consist of full scale simulations varying in plan area density (0.1, 0.3 and 0.6, further on mentioned as configuration A, B and C respectively), buildings height ($H_1 = 6$ m, $H_2 = 12$ m and $H_3 = 18$ m) and wind direction (0° and 45°). The numerical results are compared to the experimental data in terms of (i) wind pressure coefficients along a vertical line on the windward façade of the central building (section 6.1.1) and (ii) contour plots of wind pressure coefficients on the windward façade of the central building (section 6.1.2 – 6.1.4). The wind pressure coefficient ($C_p$) is calculated using equation 4.1 in which the measured wind speed of the numerical model is 8.79 m/s at a reference height of 10 m.

6.1.1 Wind pressure coefficients on the windward façade

The wind pressure coefficients along a vertical line on the central building are shown in figure 6.1 for different plan area densities and building heights for a wind direction of 0°.

![Figure 6.1 – Wind pressure coefficients along a vertical line on the windward façade of the central building for 0° are shown for the three building heights $H_1$, $H_2$ and $H_3$.](image)

For the configurations with building height $H_1$ (6 m), the results of the numerical simulations of configurations A, B and C have a good agreement with the experimental data. The simulations of building height $H_2$ (12 m) give an overestimation of $C_p$ at the bottom and middle part of the building of 0.13 for configuration A, 0.60 for configuration B and 0.23 for configuration C.
configuration C. At the top of the windward surface, there is a good agreement for configurations B and C. For configuration A, an underestimation of 0.13 ($C_p$) occurs at the top of the front façade.

For the $H_3$ (18 m) configurations, configuration A agrees with the experimental data with only a small deviation of the pressure coefficient at the top of the building surface of 0.22 ($C_p$). Furthermore, an overestimation occurs for configuration B with a deviation of maximal 0.10 and 0.20 for configuration C.

### 6.1.2 Configuration A

Configuration A consists of configurations with a plan area density of 0.1 and different building heights: $H_1 = 6$ m, $H_2 = 12$ m and $H_3 = 18$ m. The results show the wind pressure coefficients on the windward façade for the cases of 0° and 45° and a comparison to the experimental data (figure 6.2).

![Configuration A](image)

Figure 6.2 – Wind pressure coefficients on the windward façade for plan area density of 0.1 with 0° and 45°.

For the results of 0°, an overestimation occurs at the top of the building surface and a decrease in pressure occurs on bottom of the front façade. For the results of 45°, a slight overestimation at the top right of the building surface occurs while an underestimation is shown at the bottom right of the building surface. An increase of wind pressure coefficients at the top of the front façade occurs for the numerical model. This might be due to the usage of the k-ε turbulence model where the turbulent kinetic energy is over predicted at the front and sideway corners.

### 6.1.3 Configuration B

Configuration B are the cases with a plan area density of 0.3 where the building height varies from $H_1 = 6$ m, $H_2 = 12$ m to $H_3 = 18$ m. The results of the wind pressure coefficients on the windward façade for 0° and on the same façade for 45° are shown and compared to the experimental data (figure 6.3).
The pressure on the windward façade of the numerical models shows a good agreement with the experimental data. For the results of 0°, an overall underestimation of 0.10 (C_p) occurs on the front façade. Configuration B(H_2) with 0° shows an asymmetrical geometry which might be the result of the use of RANS (Prevezer and Holding, 2002). A decrease in the simulated wind pressure coefficients for the wind direction of 45° is located at the lower part of the façade.

6.1.4 Configuration C

The results of configuration C with a plan area density of 0.6 and building heights varying from \( H_1 = 6 \text{ m} \), \( H_2 = 12 \text{ m} \) to \( H_3 = 18 \text{ m} \) are shown in figure 6.4. The wind pressure coefficients on the windward façade for 0° and 45° are shown and compared to the experimental data.
The numerical results do not have a really good agreement with the experimental data. The prediction of the numerical results is less accurate compared to the lower plan area densities of configurations A and B. For the results of the wind direction of 0°, an overall underestimation of 0.10 – 0.20 ($C_p$) occurs for $H_2$ and $H_3$. Configuration C($H_1$) for 0° shows an asymmetrical geometry which might be due to the use of RANS (Prevezer and Holding, 2002). Also the results of the configuration for 45° show an underestimation of 0.20 for $H_3$ and 0.1 for $H_2$.

6.1.5 Summary of validation cases

For the validation cases with equal street widths, the results of the simulations with various plan and frontal area densities are compared to the experimental data obtained by Quan et al. (2007a, 2007b). The results of the validation cases are expressed in wind pressure coefficients on the building façade and are in good agreement with the experimental data for configurations A and B. For configuration C, a slight deviation occurs and there is a deviation due to the use of RANS as shown in the results of B($H_2$) and C($H_1$) (Prevezer and Holding, 2002). Overall, 3D steady RANS is fairly accurate to predict the urban wind flow in a wide range of plan and frontal area densities. It should be noted that the wind pressure coefficients on building surfaces are less accurate to predict using the RANS equations compared to wind speeds in canyons (Stathopoulos and Baskaran, 1996; Nore et al., 2010). Given this knowledge and the results of the validation cases, the prediction of results of the main street cases which are expressed in wind speeds through canyons at pedestrian level are expected to be accurate enough with steady RANS (Blocken et al., 2007a).

6.2 Results main street cases

The main streets cases consist of full scale simulations varying in plan area density by increasing a main street from 8.5 m (MS-0) to 16 m (MS-1) and 24 m (MS-2). Simulations are performed with building heights $H_1 = 6$ m, $H_2 = 12$ m and $H_3 = 18$ m and wind directions 0°, 22.5°, 45°, 67.5° and 90°. The results of the main street cases are given in this section. First the flow pattern is described by velocity vectors (section 6.2.1). Then, the local mean age of air is calculated and the results of the frequency of the local mean age for the various cases are shown in distribution graphs (section 6.2.2). To clarify these distributions graphs, contour plots of the local mean age of air are shown in section 6.2.3.

The area of interest is defined in figure 6.5 by a red dashed line. The two surrounding building rows upstream of the area of interest are not taken into account as suggested by Yoshi et al. (2007). The last building row downstream of the area on interest is also not taken into account due to the reattachment flow and the influence on the local mean age of air of this re-entering flow. For the results which are expressed in normalized local mean age of air ($\tau_{p}$), the $\tau_{p}$ is calculated for 120 sampling points in the area of interest. The positions of the sampling points are given in figure 6.5. The frequency of the local mean age of air is categorized in intervals and shown in a graph where the distribution of the spatial frequency is shown in percentages. The $\tau_{p}$ is mapped also in contour plots in a plan at pedestrian level (1.75 m).
6.2.1 Flow pattern

The flow pattern is described by velocity vectors which are shown in a plan at pedestrian level (1.75 m) and in a cross-section through the central building. First, the velocity vectors are given for the wind direction of 45° and 90° for the uniformly distributed case MS-0(H₃) (figure 6.6). Then the velocity vectors of MS-0(H₃) are compared to MS-2(H₃) for wind directions 45° (figure 6.7) and 90° (figure 6.8).

In figure 6.6, the normalized velocity vectors are shown for the uniform configurations MS-0(H₃) with wind directions 45° and 90°. In the plan for the uniform cases, various flow characteristics are clearly shown. These flow characteristics are: the corner streams with higher wind speed (1), higher wind speed between buildings (2), re-attachment flow where the wind along the building group flows in the canyon (3), standing vortices at the leeward side of the building group with slowly rotation velocity streams (4), recirculation flow where the wind speed decrease and the flow directions are opposite to the normal direction (5). After the recirculation zone, the wind speed increases and the wind flows in the normal direction of the wind flow. The flow characteristics show similarity to the flow characteristics described by Princevac et al. (2010) (section 2.1).

Figure 6.6 – The plan at pedestrian level (1.75 m) of the normalized velocity vectors for case MS-0(H₃) with wind direction 45° and 90° are shown where U_ref is 8.79 m/s.

In figure 6.7, the normalized velocity of cases MS-0(H₃) and MS-2(H₃) are compared for the wind direction of 45°. Before entering the main street, the flow pattern of both cases is approximately the same. The corner streams at the sides of the building group and the increase of velocity between buildings is clearly shown for both cases. When the width of the main street increases, a recirculation zone is developed in the main street for case MS-2.
where slowly rotating vortices occur with low wind speeds. After the vortices, the wind speed increases and the wind direction changes into the direction of the width of the main street.

For the cases with 45°, increasing the main street has no major impact on the wind speed in the area of interest. However, the flow paths are changing when increasing the width of the main street. The flow of case MS-0 travels through the building rows with an oblique wind direction of 45° (from the left to the upper right building). The flow in case MS-2 travels through the building rows similar to case MS-0 until it enters the main street where the flow follows the direction of the street which is the path of least resistance. The flow of the main street acts as a source of fresh air.

![Figure 6.7](image)

*Figure 6.7 – The normalized velocity vectors of the cases MS-0 and MS-2 are shown for 45° where “CB” represents the central building.*

In figure 6.8, the flow pattern of configuration MS-0 is compared to configuration MS-2 for 90°. The flow patterns are similar until the flow enters the main street for both configurations. The corner streams at the sides of the buildings and the increase of velocity between buildings is clearly shown for both cases. When the flow enters the main street, a recirculation zone is increased for MS-2 to a size where slowly rotation vortices with low wind speed occur.

The MS-0 case has a channeling effect due to the fact that the wind flow and street canyons are in the same direction. When increasing width of the main street increases, the wind flow is interrupted in the main street and the wind speed is not strongly affected in the area of interest.
6.2.2 Distributions graphs of normalized local mean age of air

The results of the normalized local mean age of air ($\overline{\tau_p}$) are described in spatial-frequency distributions graphs. The spatial-frequency distribution of $\overline{\tau_p}$ for different wind directions is shown in figure 6.9 for each case. The $\overline{\tau_p}$ is calculated for 120 sampling points in the area of interest and arranged in distribution intervals of 0.2 with the total range of 0 – 2.2 []. The $\overline{\tau_p}$ starts from 0 at the area opening with the minimum $\overline{\tau_p}$ (indicated by a blue color) and reaches a maximum value of 2.2 in the canyons (indicated by a red color). High values of $\overline{\tau_p}$ indicate poorly ventilated regions where the ventilation efficiency is low.

Figure 6.9 shows an increase in $\overline{\tau_p}$ when the frontal area density is higher due to higher building heights. For the uniform cases of the three building heights, the skimming flow regime (Oke, 1988) occurs. Most of the ambient air flows over the building and has minor interaction with the flow in the canyon. The canyon flow has more interaction for the cases with $H_1$ compared to the cases of $H_2$ and to the cases of $H_3$ due to the low frontal area density which leads to lower $\overline{\tau_p}$ values in the canyon (see figure 6.11).

For the uniform cases, lower $\overline{\tau_p}$ occurs in the area downstream for the wind directions parallel ($0^\circ$) and perpendicular ($90^\circ$) to the main street compared to the oblique wind direction ($22.5^\circ$, $45^\circ$ and $67.5^\circ$). This is due to the channeling effect which occurs when the wind flows in the direction of the street canyons.

A higher $\overline{\tau_p}$ is expected for the perpendicular wind direction compared to the parallel wind direction due to the higher frontal area density. However, a higher $\overline{\tau_p}$ occurs for the parallel...
wind direction. This is probably due to larger the area of interest influenced by channeling effects.

Overall when increasing the width of the main street (implies lower plan area densities in these cases), lower values of $\tau_p$ occur. For the wind directions parallel and perpendicular to the main street, the $\tau_p$ is not strongly affected when increasing the main street. For the oblique wind directions of 22.5°, 45° and 67.5°, increasing the width of the main street results in a lower $\tau_p$ due to the sink effect where the flow in the main street acts as a source of fresh air.

Figure 6.9 – Spatial-frequency distribution graphs of normalized local mean age of air ($\tau_p$) in percentage for the main street cases with various plan area densities, building heights and wind directions are shown.

6.2.3 Contour plots of normalized local mean age of air

The normalized velocity vectors and contour plots of the normalized local mean age of air ($\tau_p$) are given in figure 6.10 for the cases MS-0 and MS-2 with building height $H_0$ and wind directions of 0°, 45° and 90°. The plots show the area of interest at pedestrian level to clarify some aspects noticed in the spatial-frequency distribution graphs.
Figure 6.10 – The normalized velocity vector and the contour plots of the distribution of $\overline{\tau_p}$ are shown in a plan at pedestrian level (1.75 m) for MS-0 and MS-2 with 0°, 45° and 90° for $H_3$.

For the uniformly distributed cases with a wind direction parallel (0°) or perpendicular (90°) to the main street, channeling effect occurs. This effect is clearly shown in figure 6.10 by the normalized velocity vectors and contour plots of $\overline{\tau_p}$.

Also the larger area of interest where channeling effects occur is shown for the parallel wind direction compared to the perpendicular wind direction. This larger area by channeling effects is probably the result of a higher $\overline{\tau_p}$ for the parallel wind direction while the frontal area density is lower than at the perpendicular wind direction.
For the wind directions parallel and perpendicular to the main street, the values of the $\overline{a}$ are not strongly affected when increasing the width of the main street. For the parallel flow, the channeling effect still occurs. For the perpendicular flow, the flow is interrupted by the main street and this disturbs the channeling effect. Although the $\overline{a}$ is not strongly affected, the distribution in the area of interest shifts from downstream of the central building to the surrounding area.

When increasing the width of the main street for the oblique wind directions of 22.5°, 45° and 67.5°, lower $\overline{a}$ occurs. The wind speed in the main street increases and the wind flow changes direction and flows out of the main street as shown in figure 6.10. The flow in the main street acts as a source of fresh air which will lead to a lower $\overline{a}$ in the region downstream of the main street.

Figure 6.10 shows that the flow at the right side of the plot of MS-0 and MS-2 for 90° will re-enter the canyon and interacts with the canyon flow as a results of the low pressure zone behind the building (reattachment flow).

A noticeable aspect is that the $\overline{a}$ is not symmetrically distributed in the main street for case MS-2 with 90°. Due to the symmetrical geometry and the upstream wind direction perpendicular to the buildings, the concentration would expect to be symmetrical. Also the normalized velocity vectors in figure 6.10 do not show a symmetrical distribution in the main street. This is probably the result of small oscillations in residuals of the simulation or the use of RANS (Prevezer and Holding, 2002).

When the frontal area density increases due to higher building heights, an increase in $\overline{a}$ occurs (see figure 6.9). For the uniform cases of the three building heights, the skimming flow regime (Oke, 1988) occurs. Most of the ambient air flows over the building and has minor interaction with the flow in the canyon. In figure 6.11, the normalized velocity vectors for MS-0 of 90° are compared for the building heights of H₁ (6 m) and H₃ (18 m). Figure 6.11 shows that the ambient flow mostly flows over the buildings and has minor interaction with the flow in the canyon. For lower building heights (lower frontal area densities), the ambient flow has more interaction with the canyon flow which results in higher ventilation efficiency in the canyon for the cases with H₁ compared to H₃.

Figure 6.11 – The normalized velocity vectors of MS-0 for 90° are shown for H₁ (6 m and H₃ (18 m).
7 Discussion

Numerical simulations of two types of urban configurations are performed in this research. First, a validation study is performed for simplified uniformly distributed urban configurations with various plan and frontal area densities and the results are compared to the experimental data obtained by Quan et al. (2007a, 2007b). Then main street cases are simulated for simplified building blocks with equal street widths in the x-direction and unequal street widths in the y-direction. A detailed analysis of a wide range of plan and frontal area densities and wind directions is performed for the main street cases and the influence on the outdoor ventilation efficiency is studied. The local mean age of air is used to assess the outdoor ventilation efficiency in the urban environment and to map the distribution of the ventilation efficiency.

Despite the limitations of RANS in predicting the wind pressure coefficients on the building surfaces (Stathopoulos and Baskaran, 1996; Nore et al., 2010), the results of the validation cases are in good agreement with the experimental data (section 6.1) with only a slight deviation when the plan area density increases to 0.6.

The results of the main street cases show that the highest ventilation efficiency occurs for the wind flow parallel (0°) and perpendicular (90°) to the main street compared to the oblique wind directions due to the channeling effect for each building height and street configuration. The channeling effect occurs when the wind flows in the direction of the street canyons. When increasing the width of the main street, the ventilation efficiency is not strongly affected for the parallel and perpendicular wind directions. However for cases with an oblique wind flow (22.5°, 45° and 67.5°), the ventilation efficiency is higher in the downstream area. This is due to the fact that the flow of the main street increases in wind speed and changes direction and flows out of the canyon. The flow of the main street acts as a source of fresh air which has higher ventilation efficiency the area downstream. Furthermore an increase in frontal area density due to higher building heights, results in a reduction of the ventilation efficiency. Although skimming flow (Oke, 1988) occurs for all three building heights, less interaction between the ambient and canyon flow is obtained for a high frontal area density.

Some limitations of the study are summarized below:
- Wind flow in canyons is caused by wind and buoyancy effects due to local density differences. In this study, the air is assumed to have a constant density and temperature and buoyancy effects are not taken into account.
- Simulations using the steady Reynolds-Averaged Navier Stokes (RANS) equations are performed. The RANS equations are averaged in time and will lead to a steady solution. The turbulence is simulated by using the Standard κ-ε turbulence model. To have more accurate results, unsteady simulations with Large Eddy simulations (LES) should be considered (Tominaga and Stathopoulos, 2011). It should be noted that LES are more computationally demanding than RANS.
- The aerodynamic roughness length ($z_0$) of the street canyon is considered to be 0 m for validation purposes. In reality, streets are occupied by obstacles such as trees, cars and street poles where the wind flow is interrupted on a very local basis.
- There are minor deviations in the symmetry of some results due to oscillations in the residuals even though the simulations are converged. Another deviation is the asymmetry of flow in some cases due to the use of RANS to predict the wind speed (Prevezer and Holding, 2002).
A relatively small area of building blocks is modeled with two building rows upstream of the area of interest (Yoshie et al., 2007) and one building row downstream. The wind flow behind the building group re-enters the canyon and interacts with the canyon flow as a result of the low pressure zone behind the building (reattachment flow). In future research, adding more building blocks should be considered.

This study reports some insights on air transport through urban areas with various plan and frontal area densities and wind direction. It should be noted that even though the geometry is very general, the results of this research combined with previous and future studies might support the development of guidelines for urban planners.
8 Conclusions

The central research question of this research is:

What is the effect of a central main street on the outdoor ventilation efficiency of simplified urban configurations with equal and unequal street widths?

To answer the central research question, two types of urban building configurations were analyzed. First, the validation cases with a simplified uniform distribution and different plan and frontal area densities are simulated to test the accuracy of the 3D steady RANS model for urban analysis. The results of the validation cases are in good agreement with the experimental data obtained by Quan et al. (2007a, 2007b) with only a slight deviation when the plan area density increases to 0.6. Overall, the 3D steady RANS is fairly accurate to predict the urban wind flow in a wide range of plan and frontal area densities.

Next, the main street cases with simplified urban configurations with equal and unequal street widths are simulated to test the effect of the main street on the outdoor ventilation efficiency.

The results of the main street cases show that the main street increases the ventilation efficiency in the downstream area for oblique wind directions (22.5°, 45° and 67.5°). This is due to the fact that the flow of the main street acts as a source of fresh air which has higher ventilation efficiency. For the wind direction parallel (0°) and perpendicular (90°) to the main street, the effect of the main street on the ventilation efficiency is less beneficial in the downstream area. This is due to the channeling effect which occurs when the wind flows in the direction of the street canyons. Furthermore an increase in frontal area density due to higher building heights, results in a reduction of the ventilation efficiency. This is due to less interaction between the ambient and canyon flow for a higher frontal area density.

Overall, the following aspects are analyzed in this research. A wide range of cases with various plan and frontal area densities and different wind directions are obtained to study the effect of a central main street on the ventilation efficiency. The local mean age of air is used as an indicator to evaluate the outdoor air quality and to map the distribution of the ventilation efficiency. In order to give a visual representation of the obtained results, the local mean age of air is presented in spatial-frequency distribution graphs.
9 Recommendations for further research

Based on the limitations of the research, some recommendations for further research can be made and are summarized as follows:

- Perform the simulations with Large Eddy Simulation (LES) instead of the $\kappa$-$\epsilon$ model and compare the accuracy of the results.

- Compute an unsteady thermodynamic simulation where the buoyancy effect is taken into account and the thermal effects on the flow dispersion are considered.

- Model a configuration with an extensive representation of a common neighborhood in Europe and compare the results to this generic study.

- Simulate different building shapes or arrangements (intersections) and assess the outdoor air quality of various geometries.

- Investigate the influence of the outdoor air quality on the indoor air quality by natural ventilation.
10 References

HK Green Building Technology Net, n.d.


Quan, Y., Tamura, Y., Matsui, M., Cao, S., Yoshida, A., Xu, S., 2007a. Interference effect of a surrounding building group on wind loads on flat roof of low-rise