Natural Ventilation of Buildings through Light Shafts. Design-Based Solution Proposals

Miguel Ángel Padilla-Marcos¹, Alberto Meiss¹, Jesús Feijó-Muñoz¹

¹ Av. Salamanca, 18. Universidad de Valladolid. 14014 Valladolid. Spain
miguelangel.padilla@uva.es

Abstract. This work analyses how the built environment affects the quality of the air to be introduced into buildings from light shafts. Several factors such as urban environment and building design intervene in the ability of the light shaft to produce its air change process. Urban areas continuously pollute the air in cities which affects the human health and the environment sustainability. Poor air quality outside buildings supposes a big energy waste to promote an acceptable air quality inside buildings. That requires a large flow rate to maintain the indoor air quality which is translated to an energy efficiency term.

The main objective focuses on the impact of standardized architecture design in the quality of the indoor air dependent on the air change in the light shaft. The air change capacity of the outdoor space is numbered analysed using the concept of air change efficiency (ACE). ACE is determined by the built environment, the wind conditions and the design of the building containing light shafts. This concept is comparatively evaluated inside a control domain virtually defined to obtain the mean age of the air for a known air volume.

The longer the light shaft in the wind direction is, the better the ACE is compared with other options. Light shafts up to 12 metres high are the most suitable in order to obtain acceptable efficiency results. Other studied cases verify that assumption.

Different simplified tools for the technicians to evaluate the design of buildings containing light shafts are proposed. Some strategies of architectural design of buildings with light shafts to be used for ventilation are presented.

1. Introduction
Population growth led to the uncontrolled urban development of cities in the 20th century. Peripheral expansion and urban centres have been constructed using architectural models that often do not improve the quality of life of their users. These shortcomings extent to various fields of architecture and are usually solved by the use of technologies that imply a high economic and energy expenditure (active measures).

However, solutions related to architectural design (passive measures) can help to improve living conditions without requiring other resources. Thus, the criteria for the efficient design of buildings and their relationship with the environment can improve the behaviour of the outside air. Such improvements imply a greater airflow in outdoor spaces, which directly affects the safety, healthiness, comfort and energy consumption characteristics of indoor spaces with air conditioning.

The urban configuration of buildings, empty spaces, courtyards and urban corridors [1,2] causes a moving air to become obstructed in the lower layers of the atmosphere and determines the airflow patterns in those areas [3–6], hindering the process of air exchange, particularly in confined outdoor...
spaces between built volumes [2,3,7–9]. Accordingly, geometry has an influence on the quality of the air volume that constitutes the exterior space of buildings [3,10].

By analysing the behaviour of airflow patterns, one can relate the shape, orientation and composition of ideal building groups with their impact on air quality in confined outdoor spaces. The efficiency of these architectural designs can be numerically quantified by studying the process of change in air quality as a result of displacement.

The shape of a building, volume of air, and wind exposure are fundamental factors that determine air patterns in exterior spaces [11,12]. The influence of the architectural form on the air exchange efficiency was already shown [13]. However, the impact of wind at different velocities on interior air circulation has not been analysed yet.

Wind constitutes the primary aerodynamic phenomenon in urban areas [14,15], and buildings can alter its trajectory [4]. Air intake in outdoor spaces of buildings depends on their wind exposure, wind velocity [6], and the shape of the building. The building geometry affects air drag and displacement in such spaces [10].

In principle, outdoor air is considered to be of better quality than the air within buildings. This quality depends on multiple conditions [14,16], such as wind velocity and its predominant direction, presence of vegetable mass [17,18], and pollution due to factories or high traffic vehicular roadways [3,19,20].

In many cases, streets, urban corridors, and green spaces allow for a good exchange with atmospheric air (Figure 1), which facilitates obtaining interior air of acceptable quality [12]. However, confined spaces, such as light shafts, reduce access to the air for outdoor ventilation because there are less surfaces in contact with the atmospheric air [2,10]. Hence, it is necessary to guarantee a progressive, continual [21,22] exchange of air volume to obtain an acceptable quality that will be used in buildings’ indoor ventilation [3,11,12].

The objective of the present study is to analyse the air behaviour in different building dimensions containing confined spaces such as light shafts when the wind velocity is variable. The purpose is to create guidelines that define the relationship between wind velocity and exterior ventilation efficiency and quality in different urban architectural models [23,24]. The selected architectural forms match the types present in contemporary cities and whose designs are part of the architectural tradition of recent centuries [19,25].

The present study is also narrowly related with energy factors due to the increased repercussions of airflow exchange on electricity consumption in buildings [3,10,26–28]. It is advisable to obtain an optimal air quality in confined spaces that provide air for interior ventilation. This would allow for a reduction in airflow required to dilute interior contaminants, which would lower the energy impact involved in the air exchange process [11,23,29]. Energy term is not treated in this work.

2. Fundamentals: outdoors air change efficiency
Boundary conditions allow linking the physical properties of the model with air parameters (internal friction, height of boundary layer, etc.) [30–32]. These parameters affect its movement in the free state and therefore, within the confined volume being studied [4], which allow, to a greater or lesser degree, for moving air to adhere, detach, or flow at higher or lower velocities along the surfaces that enclose the spaces [6,33–35].

Continuous variation of wind direction and velocity in short time periods makes it essentially impossible to exactly predict its behaviour [36,37]. Any study of outdoor air requires the assumption of several premises that significantly reduce the complexity of the physical model [5,38,39]. The simplification consists of reducing the random temporal variables to one variable dependent on the height over the earth’s surface, which is constant in time. In this way, the physical definition of the contour conditions of the fluid is modelled through vertical profiles of wind speed, intensity, and turbulence dissipation [16,24,40–44] (Equations 1-5),
\[ U = \frac{U^*}{k} \cdot \ln \left( \frac{z-d}{z_0} \right) \]  
\[ k_{nw} = \frac{0.045 \cdot U_m (\alpha+1)^2 \cdot \rho}{z \left( \frac{U_m h_t (\alpha+1)}{\mu} \right)^{0.25}} \]  
\[ k_e = k_{nw} + \frac{z}{h_t} \left( 0.002 \cdot (U_m (\alpha + 1))^2 - k_{nw} \right) \]  
\[ \varepsilon = \frac{C_p \cdot 0.75 \cdot k_e^{1.5}}{k \cdot z} \quad \text{if} \quad z \leq 0.085 \cdot h_t \]  
\[ \varepsilon = \frac{C_p \cdot 0.75 \cdot k_e^{1.5}}{0.085 \cdot h_t} \quad \text{if} \quad z > 0.085 \cdot h_t \]

where \( U \) is the velocity (m/s) at height \( z \) (m); \( U^* \) is the friction velocity (m/s); \( k \) is the von Karman dimensionless constant \((k \approx 0.41)\); \( d \) is the displacement height (m); \( z_0 \) is the roughness height of the physical medium (m); \( k_{nw} \) is the near-wall turbulence \((m^2/s^2)\); \( U_m \) is the mean velocity profile (m/s); \( \alpha \) is the power profile equivalent index; \( \rho \) is the air density \((1.204 \text{ kg/m}^3 \text{ to } 293.15 \text{ K})\); \( h_t \) is the total height of the simulated model (m); \( \mu \) is the dynamic viscosity of air \((1.825 \cdot 10^{-5} \text{ N} \cdot \text{s} / \text{m}^2 \text{ to } 293.15 \text{ K})\); \( k_e \) is the turbulent energy \((m^2/s^2)\); \( \varepsilon \) is the turbulence dissipation \((m^2/s^2)\); and \( C_\mu \) is the dimensionless empirical constant \((\text{determined by Launder and Spalding (1974)} \quad [44] \text{ with an approximate value of } 0.09)\).

The wind profile defines the vertical distribution of speed and turbulence \([6,31,41,45,46]\). These profiles provide dynamic and kinetic energy for the distribution of non-uniform pressure over the constructed surfaces \([5,16]\). Turbulent phenomena produce chaotic air displacement, which facilitates vortex formation and air stagnation in the areas protected from the direct wind \([1,10]\).

Airflow behaviour close to and in each space constitutes the efficiency pattern study. Ideal ventilation efficiency \([47]\) is obtained from the minimum required atmospheric (clean) airflow to maintain optimal comfort and hygiene conditions in the space. The relationship between outdoor exchange efficiency and the design of outdoor spaces can be expressed by the geometric efficiency \([2,10,35,48]\).

The age of the air concept is used to assess the average time that an air particle takes to travel from one point to another in a model. Each particle’s trajectory originates in a succession of vector changes and different external parameters that intervene in the behavioural pattern \([44]\).

A ventilation efficiency value for the volume is obtained from the residence time ratio (Equations 6 and 7). This ratio analyses the mean age of the air contained in a volume and the minimum exchange time obtained in the model’s outflow (Equations 8) \([47]\),

\[ \tau_e = \frac{V}{Q} \]  
\[ \tau_t = 2 \cdot \langle \bar{t} \rangle \]  
\[ \varepsilon_a = \frac{\tau_e}{\tau_t} \leq 1 \]

, where \( \tau_e \) is the minimum exchange time; \( V \) is the volume of the analysed air; \( Q \) is the control volume balanced airflow; \( \tau_t \) is the mean age of outflow air (residence time of air in the control volume); \( \langle \bar{t} \rangle \) is the mean age of the air volume; and \( \varepsilon_a \) is the outdoor air exchange efficiency.
The boundary of the model to be considered is based on previous studies and on the air volumes that warrant analysis [49]. The study of ventilation efficiencies in exterior spaces requires the definition of a simplified model of a turbulence simulation [50]. In this way, we can determine the averaged integration of the variables based on contour conditions [40–42], ignoring extreme values that could result from the chaotic, natural effect of the wind [22,50,51]. In this study, the RANS model (Reynolds-averaged Navier-Stokes) is selected to obtain mean velocity values, turbulence coefficients, and age of the air parcels [52–55] as opposed to instantaneously calculating variables (for example, through the LES model – large eddy simulation) [56,57].

3. Methodology

Previous research has validated the outdoor air change efficiency concept inside light shafts [35]. It is crucial to determine the field of action, choosing a specific domain, named “control domain” (CD). CD delimits the outdoor space at various levels of observation [43] into a bigger computational domain (CPD) that represents the experimental wind tunnel section. CPD covers a huge part of the urban environment around the building to be analysed. Dimensions of the CPD covers more than 5·H times around in the horizontal plane and up to 15·H times downstream from the centre of the light shaft. In the vertical dimension, CPD reaches up to 6·H as was already said by authors such as Sharples and Bensalem (2001) [58] and Li and Ward (2007) [36].

A proper choice for the CD, inside the CPD, ensures the correct representation of the air flow in the immediate vicinity of the building and its influence on the air distribution in the light shaft. The choice of an ideal CD based on proportions relative to a reference dimension of the building was investigated for the air change efficiency application [43]. For buildings with a light shaft, the building width (c_r) was chosen as the reference dimension (Figure 1). This choice allows the air change efficiency of the air volume contained in the light shaft to be evaluated, delimiting the surfaces through which the air enters and exits the domain. This CD reduces computational costs from the whole CPD and keeps the evaluation reliable. It was assumed that the flow equilibrium condition was satisfied (Figure 2).

Figure 1. Dimensions of the control domain (CD) based on the light shaft geometry
To evaluate the adequacy of a light shaft design in regard to air change, the flow field at the top of the light shaft must be determined [45,46]. This distribution provides information on the behaviour of the air at the top of the light shaft and the motion that will be generated in the space by means of the vertical flow. The vertical flow field at the top of the light shaft was obtained from the signs of the velocities, which are generated by the aerodynamics of the building when exposed to wind.

The 175 evaluated cases assumed that the building centreline width (c_r) was 10 m. The horizontal dimensions L and W were varied between 2 m and 6 m, and the height H was varied between 6 m and 42 m (1 < H/L < 21). The used boundary conditions are included in Table 1.

| Table 1: Boundary conditions for the analysis | boundary conditions of the inlet |
|---------------------------------------------|----------------------------------|
| air characteristics (fluid)                | reference velocity               |
| model height (H)                           | reference height                 |
| air density                                | turbulence energy                |
| temperature                                | turbulence dissipation           |
| Reynolds number                            | equations 4 and 5                |
| kinetic viscosity                          | turbulence height                |
| dynamic viscosity                          | 64.000 m                        |
| wall conditions                            | isothermal boundary conditions   |
| roughness height                           | exponential law                  |
| displacement height                        | friction velocity                |
| temperature                                | roughness height                 |
| upper and lateral walls defined            | displacement height              |

From the efficiency values obtained, it was determined that the greatest changes in efficiency were achieved by means of varying the longitudinal dimension. The complexity of the analysis makes it difficult to be represented with mathematical functions. The obtained results confirmed the effect of the
building and light shaft dimensions on the air quality distribution. However, the effects of parameters such as the wind velocity and the building width, which affect the tendency of the flow over the roof to follow the roof line, were not analysed.

4. Results and discussions

The results indicate that the light shaft transverse dimension (W) has a negligible effect on the process efficiency ($\varepsilon$). The height (H) and the light shaft longitudinal dimension (L) significantly affect the air exchange, defining the H/L ratio, where the efficiency increases as the length increases and as the height decreases. Efficiency values between 1.06\% and 42.62\% were obtained; these were the extreme cases.

The wind blowing over the top of the light shaft affects the movement of air and pollutants in the light shaft, affecting the air change process [2]. The wind velocity and the forces and viscous stresses facilitate the entrainment of air that has changed direction after colliding with an obstruction and allow the flow direction to return to the wind direction.

When air in motion encounters a building, the flow is deflected. The change in the direction of the velocity vector of the air near the cornice line of the building is promoted by a predominantly ascending vertical component. The effect of the wind on the confined volume of air depends on the change in the flow over the building cornice. When the velocity of the air that interacts with the air in the light shaft changes, the flow field in the plane at the top of the light shaft is altered (Figure 3). This interaction entails a change in the distribution of the mass transfer that depends on the wind velocity [8]. The distance between the cornice and the opening of the light shaft affects the air change process. The light shaft axial length (L) regarding the region where the flow attachment occurs depends on the relationship between velocity and width. A vortex forms at the top of the light shaft that facilitates the change of the air volume dependant on the H/L ratio. The effects of the building shape, its location and the wind velocity on this vortex were investigated (Figure 3).

![Figure 3. Analysis of the air flow in the light shaft](image)
The domain defined by the light shaft dimensions was evaluated as if it were an indoor space isolated from the ambient air. The influence of the air flow at the top of the light shaft affects the displacement of the air within the light shaft.

4.1. Effect of wind velocity

Table 2 shows the air change efficiency for 9 light shaft sizes with 5 wind velocities that were analysed with the validated CFD models. The reference value was the air change efficiency for perfect mixing at 50 %.

| light shaft dimensions | wind velocity |
|------------------------|--------------|
|                        | 0.75 m/s | 1.50 m/s | 3.00 m/s | 6.00 m/s | 9.00 m/s |
| 2x 3y                  | 9.0      | 10.78%   | 5.09%    | 3.69%    | 3.34%    | 2.77%    |
| 3x 3y                  | 6.0      | 9.89%    | 5.13%    | 3.32%    | 3.27%    | 2.98%    |
| 4x 3y                  | 4.5      | 10.87%   | 6.08%    | 3.70%    | 3.75%    | 3.73%    |
| 5x 3y                  | 3.6      | 12.75%   | 8.13%    | 4.87%    | 4.48%    | 4.41%    |
| 6x 3y                  | 3.0      | 15.16%   | 11.62%   | 6.81%    | 6.15%    | 5.99%    |
| mean efficiency        | 11.89%   | 7.21%    | 4.48%    | 4.20%    | 3.98%    |
| mixing model efficiency|          |          |          |          | 50.00%   |

The air change efficiency decreased as the wind velocity increased. Furthermore, the air change efficiency increased as the longitudinal dimension \( L \) increased. However, when the light shaft length was fixed and the width \( W \) was varied (Table 3), the variation in the efficiency was sufficiently small that mean values could be calculated.

Table 3: Air change efficiency for \( L = 3 \) m

| light shaft dimensions | wind velocity |
|------------------------|--------------|
|                        | 0.75 m/s | 1.50 m/s | 3.00 m/s | 6.00 m/s | 9.00 m/s |
| 3x 2y                  | 10.52%   | 5.14%    | 2.91%    | 2.76%    | 2.45%    |
| 3x 3y                  | 9.89%    | 5.13%    | 3.32%    | 3.27%    | 2.98%    |
| 3x 4y                  | 6.0      | 9.63%    | 4.81%    | 3.54%    | 3.63%    | 3.40%    |
| 3x 5y                  | 9.50%    | 5.36%    | 3.76%    | 3.94%    | 3.72%    |
| 3x 6y                  | 9.39%    | 5.46%    | 4.13%    | 4.32%    | 4.06%    |
| mean efficiency        | 9.79%    | 5.18%    | 3.53%    | 3.58%    | 3.32%    |
| mixing model efficiency|          |          |          |          | 50.00%   |

As the wind velocity increases, the drag force from the deflection of the air next to the cornice increases, generating a curvilinear trajectory. The extent of this deflection and the effect that it has on the mixing of the air in the light shaft depends on the wind velocity, as shown in Figure 4. Turbulence and drag cause a partial return flow of the air that has already been mixed. The efficiency increased in those cases in which the formation of a vortex at the opening of the light shaft caused the air to flow toward the region that did not affect the quality of the light shaft air.

The results indicate that the effect of the vortex decreases at higher wind velocities, reducing the renewal of air in the light shaft. The vertical flow at the cornice increases with the wind velocity so that the vector component remains proportional, resulting in a similar attachment in all cases. However, the resulting intensity depends on the wind velocity; i.e., the greater the horizontal component of wind velocity, the greater the airflow across the opening.
The air change increases as the wind velocity increases. However, the diffusion of the clean air is reduced because of its trajectory, reducing the ratio between the ideal and actual renewal times, thereby affecting the efficiency. Therefore, the mean age of the air in the light shaft decreases as the wind velocity increases and is independent of the calculated minimum air residence time.

As expected, it can be observed from the age of the air distribution that there is a descending vertical gradient, with the maximum age of the air at the bottom of the light shaft and the minimum value at the top, verifying that the value decreases as the velocity increases.

The trajectories followed by the stream lines in the interior of the light shaft reflect the air change caused by the dynamic influence of the wind. At higher velocities, the air change affects the age, but the mixing of “young” incoming fresh air from the flow into the city is hindered by the deflection effect.

The results show the insignificant influence of the light shaft transverse dimension (W). Maximum errors of ± 0.34% were obtained in the analysis of the effect of velocity for a fixed length. The error for the various wind velocities was ± 5.69%, which implies a relative variation of ± 47.86% with respect to the maximum of the resulting mean efficiencies. Thus, it can be concluded that the mean efficiency approximately corresponds to the efficiency of a 3 m × 3 m light shaft. In addition, since the light shaft has a square shape (1:1 ratio), the movement of air in the space can be evaluated regardless of the orientation of the wind what directly affects the design of the building.

4.2. Discussion of results and architectonic application
The ratio between the height of the light shaft and the length in the wind direction (H/L) corresponds to the number of vortices which are generated inside. This non-dimensional parameter defined the ability of the air to penetrate from the top into the light shaft which is used to determine some design strategies. The rates selected for this study demonstrate that the larger this ratio is, the more difficult it is for the air to penetrate. These rates eventually affected the efficiency index.

In general, large centreline widths joined to light shafts with small proportional ratios should be selected. Moreover, results also show the relationship between geometry and wind velocity, which would allow designers to compare some different hypothetical cases in several climate conditions. The
results classified by the evaluated parameter, which entailed the proposal for comparative building design strategies, can be summarized depending on its impact.

It was shown that the efficiency varies inversely proportional with the wind velocity \((U_{\text{ref}})\) and directly proportional with the centreline building width \((c_r)\) and the light shaft dimension parallel to the wind direction \((L)\).

5. Conclusions
The efficiency results prove numerically that the light shafts are generally heavily deficient in their air ventilation. The analysis of the residential light shaft cases in Spain, of sizes up to 6 m long, 6 m wide, and 42 meters high, values a bracket of efficiencies dependent on its dimensions. The analysis of design impact on the air renovation quality, along with the methodology and hypotheses applied make it possible to verify that its mean efficiency improves as the dimension on the wind’s direction gets bigger and the height gets smaller.

Independently of the mean efficiency in the whole light shaft, it is stated that air masses at its higher portion present a greater capacity of renovation. The mean efficiency in the lower third of the light shaft encompasses approximately half of the mean efficiency of the light shaft, which impacts negatively on the contained air quality.

It can be graphically observed that the efficiency pattern on the horizontal planes at the light shafts keeps a regular tendency in approximately lineal strata. The efficiency varies co-directionally to the wind. Therefore, the efficiency analysis simplification of a vertical plane that encompasses the longitudinal computational domain is justified, which leads to the bi-dimensional simulation proposal.

Although the obtained results of initial analysis suggest that the wind velocity has a negligible effect on the mixing process with outdoors incoming air, it has been verified that it has an impact on air renovation quality. It varies irregularly, enabling the definition of influence patterns as the efficiency gradient tends to stabilize at greater speeds. For a series of light shafts 3 meters wide and 18 meters high, a 11.89% mean efficiency is obtained, for a speed of 0.75 m/s and a 3.98% mean efficiency for a speed of 9 m/s.

Acknowledgment(s)
This study has been developed with the technical support of the national research project —The outdoor space of the DB HS3 "indoor air quality": development of alternative solutions (reference: VIVIENDA-26562)—funded by the Ministry of Housing, whose endowment enabled the CFD simulations. This study represented part of the methodology developed by the Spanish national research project — Energy impact of airtightness level in residential buildings in Spain: analysis and characterization of the air leakage. INFILES (reference: BIA2015-64321-R 2016-2018)—funded by the Spanish Ministry of Economy and Competitiveness, which is use to evaluate the impact of the outdoor air quality in the building airtightness. We are particularly grateful for the data and series of experimental results contributed by the Meteorological Institute of Universität Hamburg via the CEDVAL project for validation of the study.

References
[1] Salizzoni P, Soulhac L, Mejean P. Street canyon ventilation and atmospheric turbulence. Atmos Environ. 2009;43(32):5056–67.
[2] Hall DJ, Walker S, Spanton AM. Dispersion from courtyards and other enclosed spaces. Atmos Environ. 1999;33(8):1187–203.
[3] Ahmad Zaki S, Hagishima A, Tanimoto J. Experimental study of wind-induced ventilation in urban building of cube arrays with various layouts. J Wind Eng Ind Aerodyn. 2012;103:31–40.
[4] Salizzoni P, Van Liefferinge R, Soulhac L, Mejean P, Perkins RJ. Influence of wall roughness on the dispersion of a passive scalar in a turbulent boundary layer. Atmos Environ. 2009;43(3):734–48.
Theurer W, Baehlin W, Plate EJ. Model Study of the Development of Boundary Layers Above Urban Areas. 1992;44:41–4.

Ahmad K, Khare M, Chaudhry KK. Wind tunnel simulation studies on dispersion at urban street canyons and intersections - A review. J Wind Eng Ind Aerodyn. 2005;93(9):697–717.

Blocken B, Carmeliet J, Stathopoulos T. CFD evaluation of wind speed conditions in passages between parallel buildings-effect of wall-function roughness modifications for the atmospheric boundary layer flow. J Wind Eng Ind Aerodyn. 2007;95(9–11):941–62.

Kubota T, Miura M, Tominaga Y, Mochida A. Wind tunnel tests on the relationship between building density and pedestrian-level wind velocity: Development of guidelines for realizing acceptable wind environment in residential neighborhoods. Build Environ. 2008;43(10):1699–708.

Kastner-Klein P, Berkowicz R, Britter R. The influence of street architecture on flow and dispersion in street canyons. Meteorol Atmos Phys. 2004;87(1–3):121–31.

Vardoulakis S, Fisher BEA, Pericleous K, Gonzalez-Flesca N. Modelling air quality in street canyons: A review. Atmos Environ. 2003;37(2):155–82.

Yassin MF. Impact of height and shape of building roof on air quality in urban street canyons. Atmos Environ. 2011;45(29):5220–9.

Padilla-Marcos MA, Feijó-Muñoz J, Meiss A. Confined-air quality based on the geometric efficiency of urban outdoor spaces. Cases study. Int J Vent. 2016;15(1):15–30.

Skote M, Sandberg M, Westerberg U, Claesson L, Johansson A V. Numerical and experimental studies of wind environment in an urban morphology. Atmos Environ. 2005;39(33):6147–58.

Hang J, Sandberg M, Li Y. Effect of urban morphology on wind condition in idealized city models. Atmos Environ. 2009;43(4):869–78.

Eliasson I, Offerle B, Grimmond CSB, Lindqvist S. Wind fields and turbulence statistics in an urban street canyon. Atmos Environ. 2006;40(1):1–16.

Amorim JH, Rodrigues V, Tavares R, Valente J, Borrego C. CFD modelling of the aerodynamic effect of trees on urban air pollution dispersion. Sci Total Environ. 2013;461–462:541–51.

Endalew AM, Hertog M, Delele MA, Baetens K, Persoons T, Baelmans M, et al. CFD modelling and wind tunnel validation of airflow through plant canopies using 3D canopy architecture. Int J Heat Fluid Flow. 2009;30(2):356–68.

Xiaomin X, Zhen H, Jiasong W. The impact of urban street layout on local atmospheric environment. Build Environ. 2006;41(10):1352–63.

Leitl B, Meroney R. Car exhaust dispersion in a street canyon. Numerical critique of a wind tunnel experiment. J Wind Eng Ind Aerodyn. 1997;67–68:293–304.

Leitl BM, Kastner-Klein P, Rau M, Meroney RN. Concentration and flow distributions in the vicinity of U-shaped buildings: Wind-tunnel and computational data. J Wind Eng Ind Aerodyn. 1997;67–68:745–55.

Kim JJ, Baik JJ. A numerical study of the effects of ambient wind direction on flow and dispersion in urban street canyons using the RNG k-ε turbulence model. Atmos Environ. 2004;38(19):3039–48.

Hang J, Sandberg M, Li Y. Age of air and air exchange efficiency in idealized city models. Build Environ. 2009;44(8):1714–23.

DePaul FT, Sheih CM. Measurements of wind velocities in a street canyon. Atmos Environ. 1986;20(3):455–9.

Oke TR. Street design and urban canopy layer climate. Energy Build. 1988;11(1–3):103–13.

Memon RA, Leung DYC. On the heating environment in street canyon. Environ Fluid Mech. 2011;11(5):465–80.

Muhaisen AS. Shading simulation of the courtyard form in different climatic regions. Build Environ. 2006;41(12):1731–41.

Yang X, Li Y, Yang L. Predicting and understanding temporal 3D exterior surface temperature distribution in an ideal courtyard. Build Environ. 2012;57:38–48.
[28] Firlag S, Murray S. Impacts of airflows, internal heat and moisture gains on accuracy of modeling energy consumption and indoor parameters in passive building. Energy Build. 2013;64:372–83.
[29] Corke TC, Nagib HM. Flow near a building model in a family of surface layers. 1979;5:139–58.
[30] Counihan J. Adiabatic atmospheric boundary layers: A review and analysis of data from the period 1880-1972. Atmos Environ. 1975;9(10):871–905.
[31] Paterson D a., Apelt CJ. Simulation of wind flow around three-dimensional buildings. Build Environ. 1989;24(1):39–50.
[32] Montazeri H, Blocken B. CFD simulation of wind-induced pressure coefficients on buildings with and without balconies: Validation and sensitivity analysis. Build Environ. 2013;60:137–49.
[33] Stathopoulos T, Baskaran A. Boundary treatment for the computation of three-dimensional wind flow conditions around a building. J Wind Eng Ind Aerodyn. 1990;35(1):177–200.
[34] Byrne CEI, Holdo AE. Effects of increased geometric complexity on the comparison between computational and experimental simulations. J Wind Eng Ind Aerodyn. 1998;73:159–79.
[35] Li J, Ward IC. Developing computational fluid dynamics conditions for urban natural ventilation study. School of Architecture, the University of Sheffield. 2007;1090–6.
[36] Baik J-J, Kim J-J, Fernando HJS. A CFD Model for Simulating Urban Flow and Dispersion. J Appl Meteorol. 2003;42(11):1636–48.
[37] van Hooff T, Blocken B. Coupled urban wind flow and indoor natural ventilation modelling on a high-resolution grid: A case study for the Amsterdam ArenA stadium. Environ Model Softw. 2010;25(1):51–65.
[38] Castro IP, Apsley DD. Flow and dispersion over topography: A comparison between numerical and laboratory data for two-dimensional flows. Atmos Environ. 1997;31(6):839–50.
[39] Hargreaves DM, Wright NG. On the use of the k-ε model in commercial CFD software to model the neutral atmospheric boundary layer. J Wind Eng Ind Aerodyn. 2007;95(5):355–69.
[40] Richards PJ, Hoxey RP. Appropriate boundary conditions for computational wind engineering models using the k-ε turbulence model. J Wind Eng Ind Aerodyn. 1993;46–47(0):145–53.
[41] Lien FS, Yee E, Cheng Y. Simulation of mean flow and turbulence over a 2D building array using high-resolution CFD and a distributed drag force approach. J Wind Eng Ind Aerodyn. 2004;92(2):117–58.
[42] Yang Y, Gu M, Chen S, Jin X. New inflow boundary conditions for modelling the neutral equilibrium atmospheric boundary layer in computational wind engineering. J Wind Eng Ind Aerodyn. 2009;97(2):88–95.
[43] Launder BE, Spalding DB. The numerical computation of turbulent flows. 1974;3:269–89.
[44] Paterson DA, Apelt CJ. Computation of wind flows over three-dimensional buildings. J Wind Eng Ind Aerodyn. 1986;24(3):193–213.
[45] Counihan J. Wind tunnel determination of the roughness length as a function of the fetch and the roughness density of three-dimensional roughness elements. Atmos Environ. 1971;5(8):637–42.
flow. Int J Heat Fluid Flow. 2003;24(2):147–56.

[52] Jeong SJ, Andrews MJ. Application of the k-ε turbulence model to the high Reynolds number skimming flow field of an urban street canyon. Atmos Environ. 2002;36(7):1137–45.

[53] Moonen P, Dorer V, Carmeliet J. Evaluation of the ventilation potential of courtyards and urban street canyons using RANS and LES. J Wind Eng Ind Aerodyn. 2011;99(4):414–23.

[54] Hertwig D, Efthimiou GC, Bartzis JG, Leitl B. CFD-RANS model validation of turbulent flow in a semi-idealized urban canopy. J Wind Eng Ind Aerodyn. 2012;111:61–72.

[55] Murakami S, Mochida A, Hayashi Y. Examining the k-ε model by means of a wind tunnel test and large-eddy simulation of the turbulence structure around a cube. J Wind Eng Ind Aerodyn. 1990;35:87–100.

[56] Hertwig D, Leitl B, Schatzmann M. Organized turbulent structures-Link between experimental data and LES. J Wind Eng Ind Aerodyn. 2011;99(4):296–307.

[57] Sharples S, Bensalem R. Airflow in courtyard and atrium buildings in the urban environment: A wind tunnel study. Sol Energy. 2001;70(3):237–44.