

Editorial

# Recent Advances in Urban Ventilation Assessment and Flow Modelling

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## 1. Introduction

The *Atmosphere* Special Issue “Recent Advances in Urban Ventilation Assessment and Flow Modelling” collects twenty-one original papers and one review paper published in 2017, 2018 and 2019 dealing with several aspects of ventilation in urban areas ([https://www.mdpi.com/journal/atmosphere/special\\_issues/urban\\_ventilation](https://www.mdpi.com/journal/atmosphere/special_issues/urban_ventilation)).

The ventilation of cities is fundamental to the removal of heat and airborne pollutants. An increasing number of people are exposed to high temperatures and air pollution levels due to the ongoing intense urbanization. The study of ventilation becomes of critical importance as it addresses the capacity with which a built urban structure is capable of replacing the polluted air with ambient fresh air. Here, ventilation is recognized as a transport process that improves local microclimate and air quality and closely relates to the term “breathability” [1,2]. The efficiency at which street canyon ventilation occurs depends on the complex interaction between the atmospheric boundary layer flow and the local urban morphology [3].

This Special Issue includes contributions on recent experimental and modelling works, techniques and developments mainly tailored to the assessment of urban ventilation on flow and pollutant dispersion in cities. In the next section, the individual contributions to this issue are summarized and categorized into four broad topics: (1) outdoor ventilation efficiency and application/development of ventilation indices, (2) relationship between indoor and outdoor ventilation, (3) effects of urban morphology and obstacles to ventilation and (4) ventilation modelling in realistic urban districts. Please note that most of the papers cover more than one topic, but for simplicity each paper has been categorized in one of the above topics.

## 2. Summary of This Special Issue

### 2.1. Outdoor Ventilation Efficiency and Application/Development of Ventilation Indices

Ho et al. [4] employed reduced-scale physical models and wind tunnel experiments to study the dynamics over hypothetical areas (surface mounted ribs in crossflows) to enrich the understanding of the street-level ventilation mechanism. They found that the drag coefficient  $C_d$  is able to characterize the transport processes such that the street-level turbulent component of the air change rate ( $ACH$ ) is proportional to the square root of the drag coefficient. This parameterization was then extended to formulate a new indicator, the vertical fluctuating velocity scale in the roughness sublayer (RSL) for breathability assessment in urban areas.

Wang et al. [5] found that the temporal decay profile of tracer gas concentration in urban canopy layer (UCL) models accords with the exponential decay law, and it is effective to introduce the

concentration decay method into computational fluid dynamics (CFD) simulations to predict the net air change rate per hour (*ACH*) flushing UCL space and never returning. Street-scale, medium-dense (frontal area index  $\lambda_f =$  planar area index  $\lambda_p = 0.25$ ), urban-like geometries were studied under neutral atmospheric conditions. They found that larger urban size attains smaller *ACH*. For square overall urban form, parallel wind attains greater *ACH* than non-parallel wind, but it experiences smaller *ACH* than the rectangular urban form under most wind directions. Open space increases *ACH* more effectively under oblique wind compared to parallel wind. *ACH* calculated by the concentration decay approach has been proven effective to evaluate the effects of urban morphologies on the overall UCL ventilation capacity induced by mean flows and turbulent diffusion, which seems to be a better ventilation index than *ACH* calculated by the volumetric flow rates integrating the normal mean velocity or fluctuation velocity across UCL boundaries.

The paper by You et al. [6] assessed regional spatial ventilation performance for optimizing residential building arrangements. The ventilation index net escape velocity (*NEV*) was employed to quantify the influence of design variation on ventilation efficiency within four typical spaces, which refer to space form, size and position changing. Spatial mean velocity magnitude (*VM*) and visitation frequency (*VF*) were also employed. Using CFD simulations, several multi-residential building arrangements, referring to building length, lateral spacing and layout variations, were investigated under the effect of surrounding buildings. Results show that *NEV* is useful to comprehensively reflect the pollutant removal ability of wind velocity and flow recirculation in different regional spaces. *VM* and *VF* are also useful indices that can reflect the air flow rates and recirculation phenomena of the calculated domains, respectively. Some design strategies are also provided.

Nguyen Van and De Troyer [7] have elaborated, via a computationally intensive analysis, a surrogate model to calculate wind pressure coefficient (*C<sub>p</sub>*) values of several urban patterns. This multiple linear regression model, with different functions for different orientations, is based on other surrogate models developed based on field measurements, wind tunnel measurements and CFD simulations. The developed meta-model of *C<sub>p</sub>* allows for the inclusion of the effect of the schematic urban environment. The regression functions of this meta-model show a high correlation with the values of the existing surrogate model. This meta-model is able to predict the *C<sub>p</sub>* values on different surfaces very quickly and is thus very significant when a huge number of simulations is required. The developed surrogate model is fast, and can easily be integrated in a dynamic energy simulation tool like EnergyPlus for optimization of natural ventilation in urban areas.

Peng et al. [8] investigated a quantitative correlation between urban-like geometries of different building site coverage (*BSC*) and six ventilation indices. The floor area ratio (*FAR*) was kept constant at 5.0, while *BSC* gradually increased from 11% to 77% (building heights *H* decreased from 135 m to 21 m, respectively), resulting in a total of 101 asymmetrical idealized configurations. Results show that, among the indices investigated, the purging flow rate (*PFR*), the residence time (*TP*), and the mean age of air ( $\tau_p$ ) better correlate with urban morphological parameters. Further, when *FAR* is intermediate, *BSCs* (and building heights) may experience airflow channels by controlling the layout, which is an effective way to increase the overall ventilation and thus the ability of pollutant dispersion. These results show that by using *BSC* and *FAR* as morphological parameters, the ventilation performance of void spaces can be effectively improved in high-density cities by reducing the average height of buildings and designing the architectural layout appropriately in urban design.

## 2.2. Relationship between Indoor and Outdoor Ventilation

The review by Bo et al. [9] focuses on the studies dealing with the assessment of indoor–outdoor particulate matter air pollution. The aim was to review recent developments in site-specific approaches to evaluate emissions, concentrations and exchange parameters of ambient and non-ambient pollutants in indoor and outdoor contexts. A variety of research developed both in work and life environments and for engineering and epidemiological purposes were considered. From the different adopted methodological approaches and technologies, concentration indicators and ventilation exchange

factors were analysed. Data and plots reassume the most common points between the different approaches and the strength or weakness of the researcher's choices. Thus, this review represents a step towards a comprehensive understanding of indoor and outdoor exposures and may stimulate the development of innovative tools for further epidemiological and multidisciplinary research.

Hong et al. [10] present results obtained from CFD simulations to determine the effects of four typical building-tree grouping patterns on the outdoor wind environment and the indoor/outdoor relationships for PM<sub>2.5</sub> as a result of partly wind-induced natural ventilation in Beijing; the relationship between the resulting wind pressure differences and indoor PM<sub>2.5</sub> concentrations; and which building-tree grouping pattern could provide the best ventilation potential or provide the lowest indoor PM<sub>2.5</sub> concentrations. Results clearly indicate that airflow and indoor/outdoor PM<sub>2.5</sub> dispersion strongly depend on the relationships of building layouts, tree arrangements, and orientation towards the prevailing wind.

Suszanowicz [11] presents the results of research on heat loss from various types of residential buildings through ventilation systems. A model of heat loss from the discharge of exhaust air outside through air ducts has since been developed. Experiments were conducted on three experimental systems of building ventilation: gravitational, mechanical, and supply-exhaust ventilation systems with heat recovery. Results show that mechanical intake-exhaust ventilation systems with heat recovery should be used in residential buildings or in communal residential buildings because they may meet the requirements of the air quality in residential spaces and at the same time minimize the loss of heat from the ventilated rooms, making it possible to reduce the heat demand for heating buildings by 9–12%.

### *2.3. Effects of Urban Morphology and Obstacles to Ventilation*

Chew et al. [12] studied pedestrian-level wind enhancement in urban street canyons with wind catchers. Water channel experiments with idealized models of street canyons revealed that a wind catcher could enhance pedestrian-level wind speed by up to 2.5 times in two-dimensional canyons. CFD simulations are performed to extend the study to three-dimensional canyons and show that a wind catcher with closed sidewalls enhances pedestrian-level wind speed by up to 4 times. The findings encourage better designs of wind catchers, which have applications such as heat and pollutant dispersion in street canyons.

Dong et al. [13] analyzed the impact of seasonal changes, including solar radiation and anthropogenic heating effects, on an idealized urban canyon ventilation, as well as pollutant dispersion characteristics by CFD simulations. Results show a more evenly distributed surface temperature with relatively weak diurnal fluctuation in winter. The summer afternoon case shows a multi-vortex flow structure due to strong buoyance disturbance generated by heated adjacent building walls, with low near-ground velocity and poor pollutant removal performance. The proposed research method offers an effective solution for urban ventilation and wind path designs.

Kellnerová et al. [14] present an advanced statistical technique for qualitative and quantitative validation of large eddy simulations (LES) of turbulent flow within and above a two-dimensional street canyon. Time-resolved data from three-dimensional (3D) LES were compared with those obtained from time-resolved 2D particle image velocimetry (PIV) measurements. The standard validation approach based solely on time-mean statistics was extended by a novel approach based on analyses of the intermittent flow dynamics. While the standard Hit rate validation metric indicates not so good agreement between compared mean values of both the stream-wise and vertical velocity within the canyon canopy, the Fourier, quadrant and proper orthogonal decomposition (POD) analyses demonstrate very good LES prediction of highly energetic and dominant transient features in the flow. These findings indicate that although the mean values predicted by the LES do not meet the criteria of all the standard validation metrics, the dominant coherent structures are simulated well.

Kristóf and Papp [15], by assuming an analogy between heat and mass transport processes, utilized a graphics processing unit based software to model urban dispersion. The software allows for

the modification of the geometry as well as the visualization of the transient flow and concentration fields during the simulation. By placing passive turbulence generators near the inlet, a numerical wind tunnel was created, capable of producing the characteristic velocity and turbulence intensity profiles of the urban boundary layer. The model results show a satisfactory agreement with wind tunnel experiments examining a single street canyon. The effect of low boundary walls placed in the middle of the road and adjacent to the walkways, as well as the impact made by the roof slope angle, were also investigated. The approach can be used in the early phase of urban design, by screening the concepts to be tested with high accuracy models.

The impacts of wind catchers were also investigated by Liu et al. [16] in short road tunnels. CFD simulations were performed for thirty-five cases with long and short wind catchers. The intake fraction (*IF*) was applied to assess the in-tunnel ventilation conditions and pollutant exposure. Results show that long-catcher designs experience poor ventilation due to extremely strong velocity reduction effects in the upstream region and large recirculation zones behind the catcher entrance. A downstream vortex could be found in short-catcher cases to help transport the pollutant from one pedestrian side to the other and from lower to upper levels. Consequently, pollutants accumulate at the left-top (or right-top) of the tunnel. Among all cases, the closer wind catchers were positioned at the tunnel entrance, so they can provide better ventilation for the inner-tunnel environment. Design of double short-catchers in parallel arrangement is thus recommended for providing natural ventilation in short road tunnels, with the smallest *IF* being only 61% of the base case.

#### 2.4. Ventilation Modelling in Realistic Urban Districts

Gronemeier et al. [17] investigated the ventilation of Kowloon, Hong Kong, under unstable conditions by means of large eddy simulations (LES). The purpose was to show the differences in city ventilation occurring between a neutral and an unstable atmospheric stratification under weak-wind conditions. The often-used definition of velocity ratio was changed to better compare ventilation under different stratification. By using their LES model PALM, it was shown that the ventilation is altered significantly by different stratification. A correlation between the plan-area index and the ventilation, also found by other studies, was confirmed for the neutral case as well as the unstable case. However, in the unstable case, the correlation is larger. In weak-wind unstable conditions, the plan-area index has a high impact on the ventilation. In contrast to other studies, no correlation is found between ventilation and average building height. This might be due to the idealized cases which are often used in other studies. It is finally suggested that in air ventilation assessments not only neutral but also unstable atmospheric conditions should be investigated to allow city planners to better react to poor-ventilated areas within a city.

Liu et al. [18] performed a CFD study to explore the ventilation effectiveness on the microclimate and pollutant removal in the urban street canyon based on the rebuilt Southern New Town region in Nanjing, China, under parallel and perpendicular wind directions. A novel pressure coefficient was defined. Results reveal that there is little comfort difference under two ventilation patterns in the street canyon. Air stagnation occurs easily in dense building clusters, especially under the perpendicular wind. In addition, large pressure coefficients ( $C_p > 1$ ) appear at the windward region, contributing to promising ventilation. The investigation of the air age shows that young air is distributed where the corresponding ventilation is favourable and the wind speed is large. Results can be useful in further city renovation for the street canyon construction and municipal planning.

Santiago et al. [19] investigated the role of trees on NO<sub>x</sub> pollutant dispersion in a real neighborhood in Pamplona (Spain). Aerodynamic and deposition effects were jointly studied by means of CFD modelling. Scenarios changing the tree-foliage and introducing new vegetation in a tree-free street with traffic are simulated. Results suggest the predominance of aerodynamic effects, which induce an increase of concentration, versus deposition. The distribution of pollutant is modified by the inclusion of new trees not only in that street but also in nearby locations. Therefore, the use of trees in streets with traffic cannot be considered as a general air pollution mitigation strategy. Some

general recommendations can be provided but the suitable location of trees should be analyzed for each particular case.

Tan and Deng [20] investigated the natural ventilation potential of residential buildings based on a typical single-story house in the three most populous climate zones in Australia using the simulation software TRNSYS (Transient System Simulation Tool). Simulations were performed for all seasons in three representative cities, i.e., Darwin (hot humid summer and warm winter zone), Sydney (mild temperate zone) and Melbourne (cool temperate zone). Results reveal that natural ventilation potential is related to the local climate. The greatest natural ventilation potential is observed in Darwin, while the least natural ventilation potential is found in the Melbourne case. Moreover, summer and transition seasons (spring and autumn) are found to be the optimal periods to sustain indoor thermal comfort by utilising natural ventilation in Sydney and Melbourne. By contrast, natural ventilation is found throughout the whole year in Darwin. In addition, indoor thermal comfort can be maintained only by utilising natural ventilation for all cases during the whole year, except for the non-natural ventilation periods in summer in Darwin and winter in Melbourne. These findings could improve the understanding of natural ventilation potential in different climates, and are beneficial for the climate-conscious design of residential buildings in Australia.

Yuan et al. [21] employed the building energy optimization software BEopt to evaluate the influence of the inter-building effect (IBE) with a highly-reflective (HR) building envelope on building energy use in different scenarios. Results indicate that the building with surrounding buildings is more effective than that without surrounding buildings in terms of reducing annualized energy use, annualized utility bills and annualized energy related costs for five representative cities of Japan. Specifically, it is necessary to consider the influence of IBE, including mutual shading and mutual reflection within a network of buildings, when evaluating the energy consumption of buildings. In addition, the IBE with HR building envelope can better contribute to annualized energy savings and annualized utility bill savings.

Kurppa et al. [22] examined the impact of orientation and shape of perimeter blocks on the dispersion and ventilation of traffic-related emissions in a planned city boulevard. High-resolution simulations were conducted using the LES model PALM together with a Lagrangian particle model over a highly detailed representation of an 8 km<sup>2</sup> urban domain including street trees and forested areas. To include the role of meteorology, two contrasting inflow conditions with neutral and stable atmospheric stratification and different wind directions were applied. Pollutant ventilation is shown to improve and mean concentration at pedestrian level to decrease up to 9% by introducing variability in building height and limiting the length of street canyons along the boulevard with high traffic rates. However, the impact of smaller scale variability in building shape was shown to be negligible. This is the first high-resolution, neighbourhood-scale LES study applying sophisticated measures to provide realistic estimations for the removal of non-reactive gaseous air pollutants from the pedestrian level. The results are directly applicable by local urban planners but support urban planning in other cities as well.

Kwak et al. [23] investigated spatial and temporal variations of air pollutant concentrations in a street canyon in a central business district of Seoul, Republic of Korea, on multiple days based on complementary approaches using a mobile laboratory and a CFD model. In the emission and dispersion processes of on-road air pollutants, the high emitting vehicles (HEV) portion and the street-canyon ventilation are the determining factors of spatial and temporal variations in their on-road concentrations. Among the seven traffic compositions, RV/SUV appears to be the most responsible for poor air quality in the street canyon. Air quality at a signalized intersection is aggravated by up to 25% over that between signalized intersections due to the emission increase that is partially compensated by efficient lateral ventilation. Consequently, controlling the number of HEVs and the in-canyon ventilation near signalized intersections can effectively manage on-road air quality in street canyons.

Ming et al. [24] investigated flow and pollutant dispersion in a 3D geometrical model based on a street canyon section with a typical traffic tidal phenomenon in the 2nd Ring Road of Wuhan, China.

The number and driving speeds of vehicles on the road during different periods of one day were measured; then, the emission rate of pollutants in two parallel roads was calculated with the CFD simulation method. Simulation results indicate that in the 3D asymmetrical shallow street canyon, when pollution sources in the street are non-uniformly distributed and the wind flow is perpendicular to the street axis, a stronger source intensity near the leeward side than near the windward side will cause expansion of the pollution space even though the total source intensity remains equal. However, with increasing wind speeds and when the wind direction is not perpendicular to the street, the concentration of pollutants in the whole street shows a decreasing trend, i.e., the effect of the non-uniform distribution of the pollution source on pollutant dispersion characteristics is weakened. Additionally, the source intensity significantly impacts the level of pollutant concentration in the street canyon. With decreasing source intensity, the level of pollutant concentration at pedestrian breathing level decreased proportionally, suggesting that for the control of urban street vehicle pollution, a reduction of pollution source intensity is the most direct and effective way.

Nguyen et al. [25] present the results of a source apportionment module implemented in the SIRANE urban air-quality model tested on a real case study (the urban agglomeration of Lyon, France, for the year 2008) focusing on the NO<sub>2</sub> emissions and concentrations. This module uses the tagged species approach and includes two methods, named SA-NO and SA-NO<sub>x</sub>, in order to evaluate the sources' contributions to the NO<sub>2</sub> concentrations in air. Results of a data assimilation method (SALS), which uses the source apportionment estimates to improve the accuracy of the SIRANE model results, are also presented. Results of the source apportionment with the SA-NO and SA-NO<sub>x</sub> models are similar. Both models show that traffic is the main cause of NO<sub>2</sub> air pollution in the studied area. Results of the SALS data assimilation method highlight its ability in improving the predictions of an urban atmospheric model. Results suggest the usefulness of the source apportionment method for the assessment of emission reduction strategies at an urban scale.

### 3. Conclusions

This Special Issue assembles twenty-two contributions discussing a wide range of aspects on the ventilation of urban areas by international experts. Results and approaches presented and proposed will be of great interest to experimentalists and modelers and may constitute the starting point for the improvement of numerical simulations of flow and pollutant dispersion in the urban environment, for the development of simulation tools and the implementation of mitigation strategies. In this regard, we hope that the research presented here will stimulate new ideas and indicate future research directions.

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