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Analysis of the urban non-uniformities influence on pollutant dispersion patterns emitting from roof-based sources using a tuned RANS closure

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SUMMARY:
We use Computational Fluid Dynamics (CFD) to study how urban layouts affect the air quality within the built environment, employing 40 generic variations of morphological parameters, including planar density, building dispositions, height variation (vertical heterogeneity), and array orientation. A "pollutant" is modelled as a passive scalar emitted from a roof-based source, and a Reynolds-Averaged Navier-Stokes (RANS) method is used to model the governing conservation equations. In our work, the standard $k-\varepsilon$ closure has been tuned for atmospheric dispersion flows in compact urban settings. With this, we achieve improved prediction of experimental validation cases when compared to the standard model (up by 8% for the concentration and 56% for the turbulence fields). To assess the impact of each arrangement on urban ventilation and pollutant dispersion, three indicators of normalized concentration (C^*), velocity ratio (V^*), and retention time (τ) are considered as dependent variables, while the selected urban indices are taken as independent variables. The findings of this parametric investigation can contribute to urban planning practices by deepening our knowledge of this subject and quantifying the impacts of simulated urban forms on pollutant diffusion.

Keywords: atmospheric boundary layer, morphological indices, pollutant dispersion

1. INTRODUCTION

The urban demographic surge in the past centuries has led to the continual variation of building configurations, which generally promotes more compact arrangements (Yang et al., 2022). Given the profound effects of urban structures and layouts on flow diffusion, if these changes are not carefully planned, they may result in poor air quality, by degrading urban ventilation. In this regard, developing a series of parametric studies to assess pollutant dispersion patterns within generic forms of building arrangements could greatly benefit urban planners. Several studies investigated how urban morphology impacts dispersion and flow in idealized and regular settings, yielding valuable and fundamental results (Li et al., 2021). However, actual urban layouts are often completely heterogeneous, resulting in distinct effects on the flow field. Some studies have been conducted in recent years to investigate the atmospheric airflow characteristics within irregular building arrays (Juan et al., 2021), with very few devoted to the pollutant transport phenomenon.

Jiang et al. (2021) investigated the dependency of urban air quality on morphological indices at the mesoscale. Two realistic neighborhoods with different geometric characteristics were modeled, and correlations between the pollutant concentrations and morphological parameters were derived and used to suggest case-specific recommendations for improving air quality. In another attempt, da Silva et al. (2022) studied the combined impacts of three block classifications and three geometry indices on the dilution of traffic-originated pollutants. Due to the limited number of cases, comprehensive conclusions such as formulating guidelines could not be offered, and the authors proposed some general suggestions. Far-field dispersion of a radioactive pollutant emitting from a ground-based source located far upstream of a vertically heterogeneous array was studied by Huang et al. (2022). The authors attempted to quantify the relationship of ventilation indicators with building height variations. This parametric study provides beneficial guidelines to promote city breathability at pedestrian heights; however, its application is somewhat limited as many other influencing factors are omitted for simplification, including planar density and source location.

To complement the recent urban planning trends, our parametric study has been designed to quantitatively investigate the impacts of typical urban non-uniformity on urban ventilation. The synergistic effects of building dispositions, height variation, planar density, and array orientation on near-field pollutant transport from rooftop sources has been systematically studied. Given the interest in mean quantities, a Reynolds-Averaged Navier-Stokes (RANS) method coupled with the standard $k-\varepsilon$ model is adopted in this work. Due to the established shortcomings of this method, we have made efforts to optimize closure coefficients to improve the validation of the chosen model in the context of urban flow within compact settings.

2. METHODOLOGY

We have numerically modeled the atmospheric dispersion of a passive and inert gas from a roof-based source with coupled RANS and Eulerian transport equations. The standard $k-\varepsilon$ closure is fine-tuned using a stochastic optimization method for dispersion flow in generic compact urban settings. We used a dispersion dataset of a full-scale experiment within a generic urban form to comprehensively assess the validity of the modeling settings. The statistical analysis for the concentration field was done on defined validation metrics of geometric bias (MG, quantifying the systematic error), geometric variance (VG, quantifying random error), and the fraction of predictions within a factor of 2 of the measurements (FAC2). For the predicted flow and turbulence fields, FAC2 was replaced with a more strict measure, commonly referred to as hit-rate (HR).

Following the implementation of the proposed modeling framework, a series of systematic studies were executed to contribute to the geometry standardization of urban pollutant dispersion modeling. Considering roof-based sources made it possible to identify the influence of urban morphology on the gas dispersion above the urban canopy and near the potential locations for fresh intakes. Most of the available studies mainly focus on the pollutant dispersion around the buildings and within street canyons by assuming ground-based source locations (e.g., traffic-originated air pollution). To achieve the objectives of this research, an idealized array of 7 by 7 cubical blocks was formed to define case studies with planar and vertical heterogeneity (Fig. 1).

Taking the reference dimension of $W = 10$m, three levels of block disposition are defined with $S = 0.5W, 0.75W, W$. Four different planar densities are also selected in the horizontally heterogeneous cases with $L = 0.5W, W, 1.5W, 2W$. To investigate the effects of vertical heterogeneity, six height

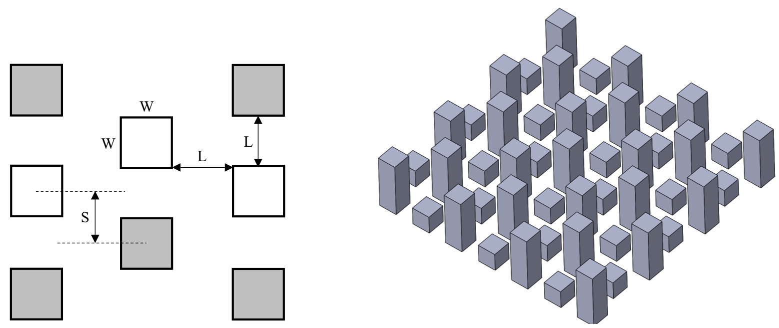

Figure 1. Partial planar schematic of the proposed irregular array (left), an example of the geometries (right).

variation scenarios inspired by the typical building layouts are defined in a regularly arranged array ($S = 0$). In Scenarios 1 and 2, shaded blocks are $2W$ and $3W$ tall, respectively, while the plain ones are $1W$ tall (Fig. 1, right). For Scenario 3, taller blocks are located at the center of the array, while a reverse arrangement is considered for Scenario 4. Blocks gradually become taller from the windward side in Scenario 5, and reverse configuration is defined in Scenario 6. The parametric studies are further extended to two extreme cases with both planar and vertical non-uniformity to reinforce and evaluate the conclusions and findings. Two inflow wind directions perpendicular and oblique to the Cartesian faces of the obstacle block layout are also considered for the defined cases.

3. RESULTS

A thorough analysis of results produced during the validation and optimization process suggests that a closure model with coefficients of $C_\mu = 0.147$, $C_\varepsilon = 1.344$, $C_{\varepsilon 2} = 1.693$, $\sigma_\varepsilon = 1.196$, and $\sigma_k = 0.927$ leads to predictions that agree best with observations. Table 1 shows that FAC2 for concentrations (among 74 sampling points) and HR for turbulence kinetic energy (among 9 sampling points) are up by 8% and 56%, respectively, while both models produce similar velocity fields.

Table 1. Performance evaluation of the standard (original) and modified (optimized) $k-\varepsilon$. Validation metrics have ideal values of 1.00.

Closure coefficients	Velocity			TKE			Concentration		
	MG	VG	HR	MG	VG	HR	MG	VG	FAC2
Original	0.84	1.07	0.67	0.82	1.06	0.44	0.98	1.82	0.72
Optimized	0.86	1.06	0.67	0.92	1.01	1.00	1.05	1.63	0.80

All 40 cases with heterogeneous building layouts are simulated using the proposed modeling framework for urban dispersion studies. Three different urban ventilation indicators have been calculated and analyzed to evaluate how the urban layouts disperse scalar pollutant. For each array arrangement, velocity ratio (V^*) quantifies the wind availability at the height of interest for urban ventilation (this is where fresh intake sits on most buildings), normalized concentration (C^*) measures the level of dilution of pollutants, and retention time (τ) evaluates the permeability of the geometry and pollutant removal rate in the selected regions. Fig. 2 depicts C^* and V^* distributions for two example cases with different planar densities and similar scales of disposition. The clear distinction between the resulting dispersion and wind flow patterns indicates a relationship between urban air quality and morphological indices, advocating the value of this parametric investigation.

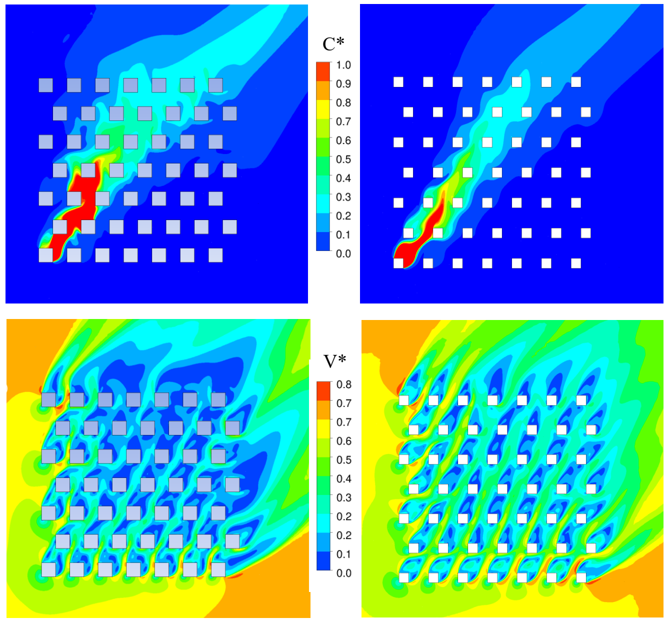

Figure 2. Normalized concentration (C^*) and velocity (V^*) for “regular” (left) and “loosely packed” (right) arrays.

4. CONCLUSION

We have demonstrated the insight which can be obtained using CFD to model dispersion in generic heterogeneous building layouts using a recalibrated turbulence closure model (8% and 56% higher accuracy compared to the original model for concentration and turbulence fields, respectively). Future work will aim to improve the current understanding of the dispersion pattern of pollutant streams emitting from roof-based sources in the presence of urban non-uniformity. This enables us to propose specific and comprehensive strategies for mitigating pollutant concentration levels in compact urban settings. From here we can identify the highly contaminated zones to be avoided when situating fresh air intakes, or even propose generic regressions (formulated guidelines) for estimating the ventilation indicators based on the urban morphological characteristics.

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