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Numerical analysis of the urban ventilation performance of different morphologies in a compact urban area

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SUMMARY:
Air pollution and heat stress are two significant issues increasingly jeopardizing livability, resilience, and sustainability in urban areas. Existing cities often appear insufficiently prepared to face these phenomena, which are particularly concerning in areas characterized by high urbanization and that experience an increase in air temperature and frequency of heat waves (like Europe and, specifically, the Mediterranean area). The detrimental effects of air pollution and heat stress can be partly mitigated by enhancing urban ventilation performance. Urban ventilation is closely related to urban morphology. Hence, adequately planning the renovation of existing urban areas may contribute to an enhancement of urban ventilation. The present study aims to analyze the ventilation performance and assess the effectiveness in this regard of several urban morphologies characterized by different building typologies of an actual urban area in Rome, Italy. 3D steady-state Reynolds-averaged Navier-Stokes (RANS) simulations have been performed, and several indices have been used for the investigation. Results show a high dependency of urban ventilation on wind directions and highlight morphologies that enhance urban ventilation. To the best of the authors' knowledge, a similar study has not been done before and provides new data towards climate-oriented planning of existing urban areas renovation.

Keywords: urban ventilation, urban morphology, computational fluid dynamics

1. INTRODUCTION

Air pollution and heat stress are two significant issues increasingly jeopardizing livability, resilience, and sustainability in urban areas. The prolonged exposure to air pollution and heat stress is responsible for augmented morbidity and mortality and increased building energy demand for air cooling and cleaning (EEA, 2020). These phenomena are particularly concerning in areas characterized by high urbanization and industrialization that experience an increase in air temperature and frequency of heat waves, like Europe and, specifically, the Mediterranean area.

Existing cities often appear insufficiently prepared to face the abovementioned phenomena. They need, therefore, to be regenerated by implementing resilience and sustainability to improve human health and well-being. The detrimental effects of air pollution and heat stress can be partly mitigated by enhancing urban ventilation performance. Urban ventilation represents the capacity of urban areas to dilute pollutants and heat from their tissues by introducing fresh air into the urban canyons. This capacity is closely related to the three-dimensional structure of urban areas and depends on both the characteristics of single buildings and their mutual arrangements, i.e., urban morphology. Hence, adequately planning the renovation of existing urban areas may contribute to an enhancement of urban ventilation, improving citizens' health and well-being.

In this regard, it is essential to investigate urban ventilation in real urban areas by analyzing the relationship between actual urban morphologies and urban ventilation performance. In the past, a few attempts have been made to relate urban morphology and urban ventilation using actual urban areas, e.g., Tsichritzis and Nikolopoulou (2019). Nevertheless, to the best of the authors' knowledge, a detailed investigation of the urban ventilation performance by assessing the effectiveness of real compact morphologies has not yet been performed. Hence, the present study aims to analyze the ventilation performance of several urban morphologies characterized by different building typologies of an actual urban area in Rome, Italy. The performance has been evaluated by conducting 3D steady-state Reynolds-averaged Navier-Stokes (RANS) simulations and employing three indices, i.e., the spatially averaged mean wind velocity ratio of the entire area (mWVR), the local age of air (τ_{loc}), and spatially averaged mean wind velocity ratio of specific morphologies (γ_{case}).

2. CASE STUDY

The actual urban area selected for conducting the study is the Tuscolano-Don Bosco district in Rome, Italy. The district can be considered representative of a compact city in the Mediterranean area for its morphological characteristics and is located in the South-East area of Rome (41°51'25.1" N 12°33'43.5" E). Overall, the district presents an orthogonal structure following the orientation of its longitudinal axis, i.e., via Tuscolana, that is tilted at approximately 40° from the West-East axis. This axis divides the district into two areas characterized by different morphological features. Higher buildings, larger public spaces, and urban canyons with long and continuous building facades characterize the North area. The prevailing building typologies in this area are the court and the multi-story slab typologies. The South area is conversely characterized by lower buildings, urban canyons with fragmented fronts, and more open morphologies determined by the following building typologies: multi-story slabs, pavilion-tower, and pavilion-palazzina. Figure 1a shows the building height map of the case study. The dark red long-dashed polygon identifies the area of interest (AoI), i.e., the area surrounded by at least one block for each wind direction considered. To investigate the urban ventilation performance of real compact morphologies, 14 subareas (cases) labeled from A to N have been selected within the AoI. For the sake of brevity, detailed information about the morphological characteristics of the AoI and the fourteen cases will be provided in the full paper.

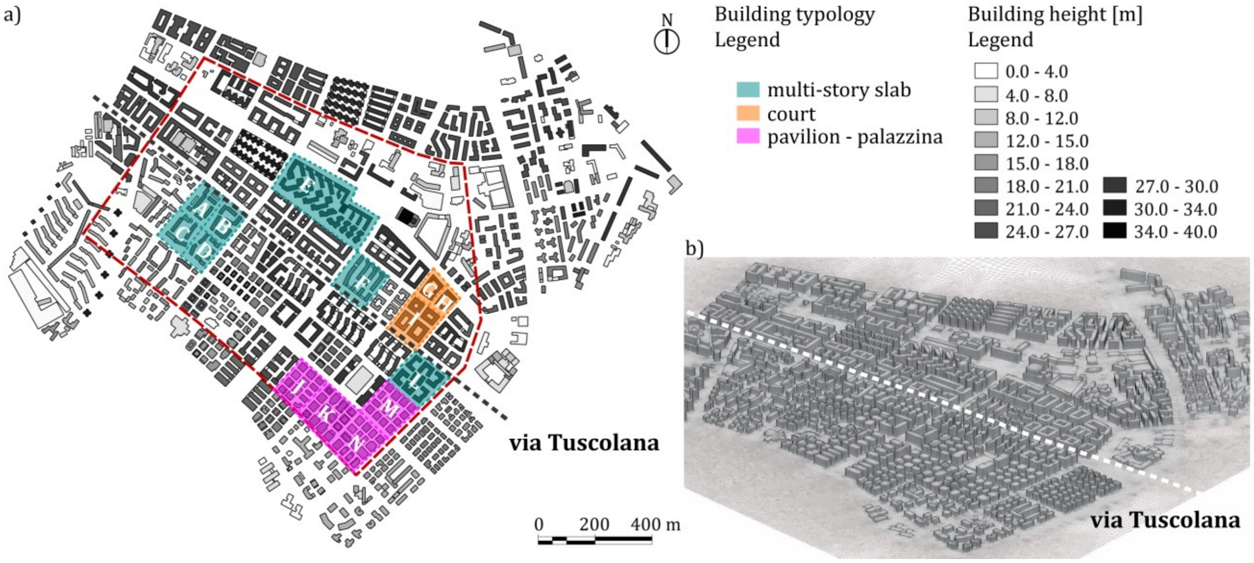

Figure 1. Building height map highlighting the area of interest and the selected morphologies (a). Perspective view of perspective view of the computational grid (b).

3. CFD SIMULATIONS

In line with the scope of the study, the selected urban area has been modeled as realistic as possible (Fig. 1b). The computational domain and grid have been built in accordance with the best practice guidelines, e.g., (Franke et al., 2007). Hence, the height of the domain is equal to 240 m, and the dimensions on the horizontal plane are 5000 m × 5000 m to allow the full development of the wake region irrespective of the wind direction. The computational grid has been generated using the surface-grid extrusion technique presented by van Hooff & Blocken (2010) and consists of about 86 million hexahedral cells. The simulations have been performed for 12 wind directions imposing a wind speed of 3 m/s at 10 m height at the inlet and using for the inflow profiles the equations provided by Richards & Hoxey (1993). The 3D steady RANS equations have been solved with the realizable k-ε model (Shih et al., 1995). Finally, the homogeneous emission method has been employed to calculate the age of air (Hang et al., 2009). A validation study has been performed by applying the "sub-configuration validation procedure" (Oberkampf et al., 2004; Franke et al., 2007). Hence, the wind tunnel data provided by Soulhac et al. (2009) have been used. It has been concluded that validation study has been satisfactorily conducted since values well above 0.5 as prescribed by Schatzmann et al. (2010) have been obtained for the employed validation metrics. Detailed information about the validation study and the computational settings has been published in a previous paper (Palusci et al., 2022).

4. RESULTS

The results are presented in terms of mWVR and $\tau_{loc\text{-}AoI}$ for the AoI and in terms of γ_{case}, and $\tau_{loc\text{-}case}$ for the 14 cases. mWVR is the ratio between the spatially averaged mean velocity and the velocity magnitude imposed at the same level at the inlet plane for each wind direction. Hence, mWVR represents the mean velocity reduction at the pedestrian level due to the presence of the urban area. τ_{loc} is the difference between the spatially averaged age of air computed for each wind direction and the minimum value found in the area under investigation. γ_{case} is the ratio between the spatially averaged mean velocity calculated for each case averaged over the twelve wind directions and the same quantity calculated for the AoI. It has been decided to use this index because it is considered adequate to represent the effectiveness of specific morphologies to enhance urban ventilation. In this way, $\gamma_{case} > 1$entails that the reduction in the mean wind velocity due to the specific case is less than that due to the entire AoI. Hence, the morphology representative of the case may be used to improve urban ventilation. On the other hand, $\gamma_{case} < 1$ entails worsening the urban ventilation performance. All the above-mentioned indices have been calculated at the pedestrian level. Regarding mWVR, the lowest and highest values are 0.40 ($\alpha = 210°$) and 0.77 ($\alpha = 0°$ and 270°), respectively, and the average over the twelve directions is 0.63. The range is large and demonstrates a high dependency on the wind direction. This dependency is due to long canyons, continuous or discontinuous, and their orientation compared to the wind direction. Regarding $\tau_{loc-AoI}$, it ranges from 297 s for $\alpha = 330°$ to 392 s for $\alpha = 210°$, confirming that the latter corresponds to the weakest wind conditions. Figure 2 shows the bar charts of γ_{case} and $\tau_{loc-case}$. Regarding γ_{case}, cases C, G, H, and L show a clear enhancement of urban ventilation. Finally, case E presents the highest value of $\tau_{loc-case}$. The full paper will provide detailed results and discussion, including the analysis of other indices, for both the AoI and fourteen cases.

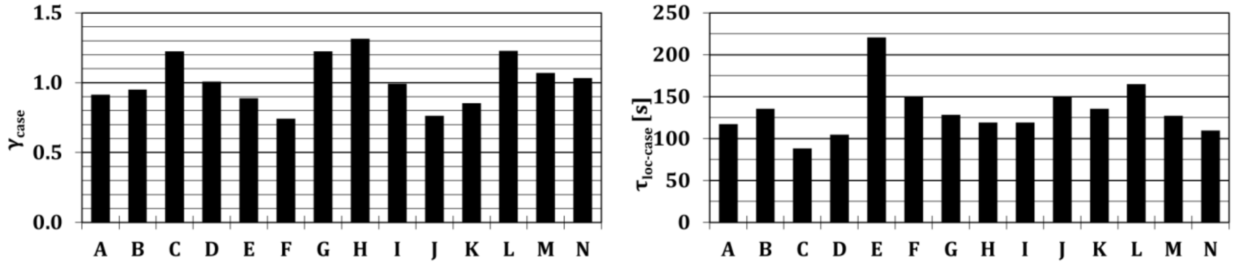

Figure 2. Bar charts of γ_{case} and $\tau_{loc-case}$.

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