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NUMERICAL AND PHYSICAL MODELLING TO ASSESS PEDESTRIAN WIND COMFORT: THE CASE STUDY OF AN OPEN SPACE AUDITORIUM IN PORTUGAL

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Abstract: Pedestrian wind comfort levels are an important requirement for comfort and safety in urban areas. José Afonso Auditorium, an open space owned by the municipality of Setúbal, in Portugal, is often exposed to strong wind conditions due to its location and configuration. In this work, the wind patterns were assessed for the auditorium area, through a set of experiments for the reference scenario using a wind tunnel, together with a set of numerical simulations using the CFD model VADIS. Furthermore, a series of mitigation measures initially proposed by the municipality, including 4 front panels, 4 back panels and a set of new trees, were tested to assess their effectiveness in mitigating the wind discomfort in the area.
Both the wind tunnel experiments and the CFD simulations were carried out for an inflow wind blowing from north-northwest and south, with an initial speed of 2, 4 and 6 $m.s^{-1}$, identified as prevailing meteorological conditions of the neighborhood. The CFD results indicate an effective attenuation of the wind speed within the Auditorium up to 80% induced by the mitigation measures. The velocity ratio reduction varies from 60% to 80% in the audience area for an inflow wind from south. The wind tunnel results also point out an overall attenuation of the wind speed promoted by the mitigation measures, with reductions up to 71% in case of the north-northwest direction and up to 80% in case of south direction.
The CFD and the wind tunnel data are in good agreement. The NMSE denotes a better correlation between the measurements and the simulations for an inflow wind blowing from north-northwest, with values varying from 0.15 to 0.18 for the reference scenario and from 0.09 to 0.18 for the mitigation scenario. In case of a wind blowing from south, the NMSE ranges from 0.20 to 0.24 in the reference and from 0.25 to 0.35 in the mitigation scenarios.
The pedestrian wind comfort assessment confirms the citizens' perception of wind discomfort. The overall results support the implementation of the mitigation measures to improve the pedestrian wind comfort levels within the area.

Key words: *urban microclimate, pedestrian-level wind comfort, CFD modelling, wind tunnel measurements, José Afonso Auditorium.*

INTRODUCTION

Urban areas are frequently affected by extreme weather events, heat island phenomena, air quality degradation, etc. The complexity of the built environment plays an essential role on local meteorology, atmospheric emissions and pollutants dispersion. A better understanding of this microclimate requires accurate measurements, physical (e.g. wind tunnel) and numerical modelling of the turbulent exchanges within the atmospheric boundary layer. Computational Fluid Dynamics (CFD) models are a powerful tool to assess urban microclimate. These computational tools have been widely used to assess urban microclimate, in particular the urban heat island, air ventilation and atmospheric pollutants dispersion within the urban surface layer. In addition, several CFD simulations, as well as wind tunnel experiments, have been conducted to assess pedestrian wind conditions for urban areas (Blocken *et al.*, 2012 and Weerasuriya *et al.*, 2018).

In Portugal, several urban areas are often exposed to strong wind conditions, mainly the coastal areas bounded by the Atlantic Ocean. However, there are no national law or official recommendations for urban authorities requiring pedestrian wind comfort studies before grant permits for new buildings. Therefore, the location and configuration of new buildings in these areas should be planned to ensure pedestrian comfort. In Setúbal municipality, José Afonso Auditorium is often exposed to strong wind conditions due to its location and configuration. After several citizens' complains, the municipality, together with stakeholders, has decided to perform a wind comfort assessment over the area to understand the problem and to assess the effectiveness of some mitigation measures, in order to guarantee comfort and safety criteria.

METHODOLOGY

The city of Setúbal is located in the Southern part of Portugal, within the Lisbon Metropolitan Area. The José Afonso auditorium is an open space and was built-up using an arch structure in a portico shape. This building is suited for festivals and other animation activities, held mostly during the summer months.

A micro-meteorological study has been performed using data from the meteorological tower of Setúbal, located nearby the auditorium. The meteorological data analysis was performed considering a 5 years' time series from 2011 until 2016. The measured data at the reference height of 10 m indicate the wind blowing predominantly from 4th quadrant, in particular, from north-northwest (34%). The wind blowing from north-northwest and south directions, as well as the wind speeds of 2, 4 and 6 m.s^{-1} were selected as typical conditions. These typical conditions were used at the inlet of the domain in the CFD simulations and the wind tunnel experiments, applying the logarithmic profile.

Mitigation measures

The mitigation measures were designed according to the intervention proposal presented by the municipality of Setúbal. The proposed scheme consists of the implementation of four panels upstream, and another four panels downstream the portico. The dimensions of the panels vary according to their position: the panel located upstream the portico has a maximum height of 12 m, while the downstream panels height varies from 3 up to 9 m. In addition, the proposal includes the implementation of 25 trees upstream the auditorium and 16 trees in the roundabout of Luísa Todi Avenue (Figure 1b)).

a) b)

Figure 1. a) Study area with the location of the wind tunnel measurement points. b) 2D view of the computational domain for the CFD simulations with the indication of the reference and mitigation scenario.

CFD model

VADIS is the CFD model applied to the José Afonso auditorium neighbourhood to assess local scale turbulent flow dynamics. FLOW is the Eulerian module of VADIS able to simulate the turbulent flow dynamics under stationary conditions within the atmospheric boundary layer. This module numerically solves the Navier-Stokes equations by means of finite differences (SIMPLE solver), over a Cartesian tri-dimensional grid, for the wind velocity components, the turbulent viscosity, pressure and the turbulent kinetic energy, applying Reynolds averages (the so-called Reynolds-Averaged Navier Stokes approach - RANS). FLOW applies a first-order k-ε closure scheme, adding two additional equations, to compute the turbulent kinetic energy and dissipation rate (Borrego *et al.*, 2003, Amorim *et al.*, 2013).

The numerical simulations were performed for a computational domain with vertical and horizontal extensions of $5H_{max}$, while the downwind extension was set equal to $15H_{max}$, where H_{max} indicates the height of the tallest building. The simulations were performed for a domain of 2400 m x 800 m x 270 m, centred in the auditorium, with a grid resolution of 3 m x 3 m x 3 m. Figure 1b) presents the baseline computational domain, including the buildings (30) and trees (155) location, corresponding to the current morphological data of the study area. The implementation of the mitigation scenario, involved some modifications of the computational domain, although the dimensions were kept the same, as well as the grid resolution. These modifications resulted in an overall increase of obstacles, up to 47 and up to 168 trees.

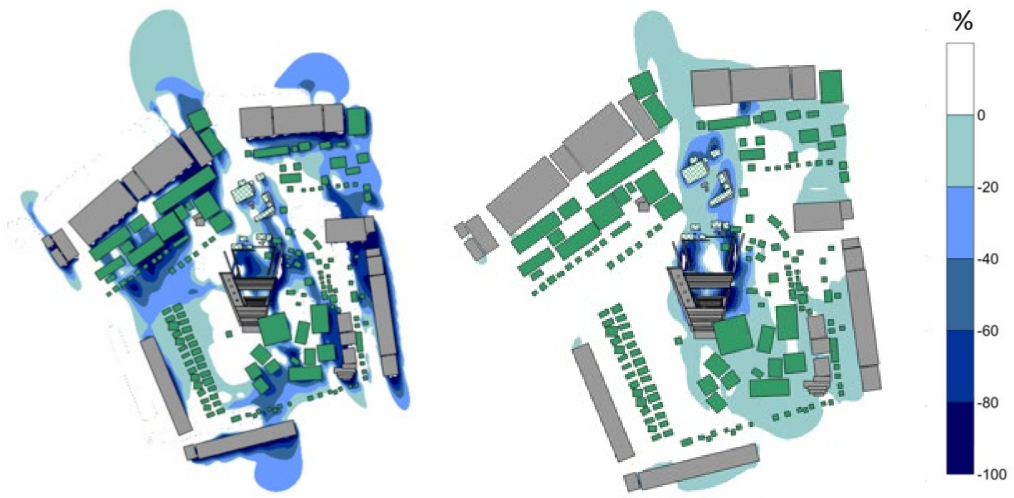
Wind tunnel set-up

To evaluate the flow around the auditorium, a set of physical simulations were performed using the wind tunnel facilities of the University of Aveiro. The wind tunnel is an open-circuit suction-type with a test section of 6.5 m x 1.5 m x 1.0 m, where the atmospheric boundary layer is simulated using a specific setup of turbulence generators and floor roughness elements upstream the test section.

The flow analysis in the surroundings of the auditorium was carried out through wind speed measurements using the hot wire anemometry technique. Figure 1a) highlights the location of measurement points (1-11) within the study area. Measurements were taken for both current and mitigation scenarios at different heights, up to a maximum height of 38.5 m, in real scale. A 1:130 scaled interchangeable model was built, covering a full-scale horizontal extension of approximately 195 m.

CFD RESULTS DISCUSSION

The wind fields simulated for the reference scenario point out a channelling effect of the turbulent flow, with an increase of the wind speed, in front of the auditorium, due to its configuration. The highest wind speeds are simulated in the audience area of the auditorium. The maximum wind speed registered within the auditorium is equal to 13 $m.s^{-1}$, for both wind directions.



a) b)

Figure 2. Horizontal iso-contour plots at 1.5 m high, for an inflow wind speed of 6 $m.s^{-1}$. Differences between the mitigation and the reference scenarios for a wind blowing from a) north-northwest and b) south.

Effectiveness of the mitigation scenario

CFD results show a general reduction of the wind speed within the auditorium with the application of the mitigation measures. The results also denote an attenuation in the formation of recirculation near the wall, upstream the auditorium, at the East entrance, with an effective reduction of the wind speed in this area. Figure 2 points out a reduction of the wind speed within the José Afonso auditorium, varying between 20% and 80%, i.e. 4 and 6 m.s^{-1}, for a wind blowing from NNW. In particular, in the audience area, the wind speed reduces between 20% and 40%. For an inflow wind blowing from south (Figure 2b)) the effectiveness of the mitigation measures can vary between 20% and 80% across the auditorium. At the audience area, the reduction is more significant, with reductions between 60% and 80%. However, it is noteworthy that less than 20% of reduction have been achieved at the South entrance.

WIND TUNNEL RESULTS DISCUSSION

The hot-wire anemometry was used to quantify the wind speed in several points of the study area, for the reference and the mitigation scenarios. The velocity ratio was calculated from the hot-wire measurements and the initial wind speed at the inlet of the wind tunnel. Figure 3 shows the velocity ratio calculated for an inflow wind blowing from north-northwest (Figure 3a)) and from south (Figure 3b)).

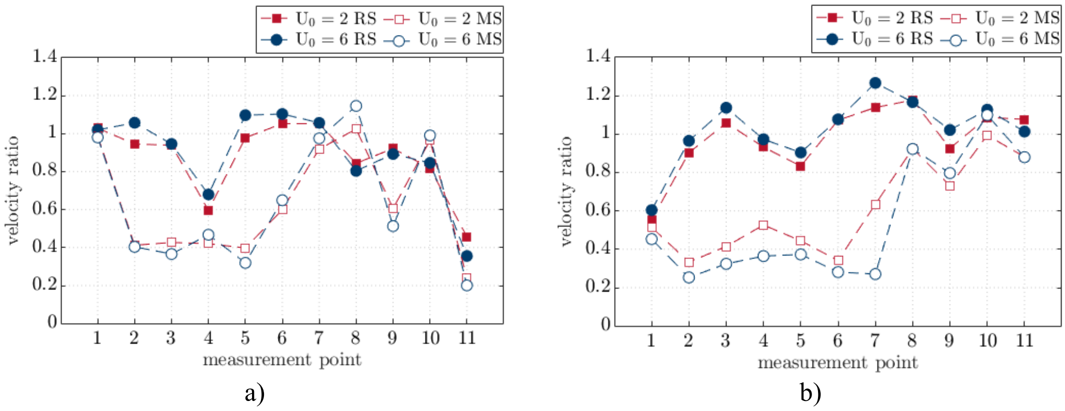


Figure 3. Velocity ratios calculated from the measurements at 1.5 m high, at the different measurement points, for the reference and the mitigation scenarios, for an inflow wind blowing a) from north-northwest and b) from south.

The overall results point out the strong impact of the mitigation measures for both directions. A reduction of wind speed is observed with the implementation of the mitigation measures in all the measurement points ranging from 4% up to 60% (inflow wind speed of 2 m.s^{-1}) and 71% (inflow wind speed of 6 m.s^{-1}). The minimum reduction of wind speed is registered at point 1 located at the inlet of the domain. The maximum wind speed is recorded at point 5, for both cases, due to its location immediately after the front panels. Within the auditorium, point 6 records a high reduction of wind speed, while point 7 only records a slight reduction. These results indicate that the flow is channelled through the west side of the portico. South from the portico, the measurements denote a slight decrease of wind speed (points 8 to 11). Therefore, back panels may have less impact on the attenuation of wind speed, for a wind blowing from north-northwest.

Figure 3b) shows the wind speed measurements for an inflow wind blowing from south. An overall reduction of wind speed is again recorded with the implementation of the mitigation measures in all the measurement points. The attenuation of wind speed ranges from 7% up to 70%, in case of an inflow wind speed of 2 m.s^{-1}, and from 13% up to 80%, in case of an inflow wind speed of 6 m.s^{-1}. The wind speed reduction is especially noteworthy in point 7 (inside the portico), for an inflow wind speed of 6 m.s^{-1}. For an inflow wind speed of 2 m.s^{-1}, the highest decrease of wind speed is recorded at point 6, also within the portico. Although the overall attenuation of wind speed induced by the mitigation measures, the reduction of wind speed is more effective at the measurement points located within the auditorium and in the north part of the study area. The measurement points from 8 to 11 are registering low wind speed reductions, denoting less effectiveness of the back panels.

COMPARISON BETWEEN CFD AND WIND TUNNEL RESULTS

The normalized mean square error (NMSE) was calculated as an indication of the numerical and physical results accuracy. Only the values measured and simulated at a corresponding height were considered for a direct comparison. Table 1 points out the calculated NMSE for both the reference and the mitigation scenarios.

Table 1. Normalised Mean Square Error calculated from the CFD results and the wind tunnel measurements, for both the reference and the mitigation scenarios.

Wind speed ($m.s^{-1}$)	**north-northwest**		**south**	
	reference	**mitigation**	**reference**	**mitigation**
2	0.15	0.13	0.20	0.25
4	0.18	0.18	0.24	0.35
6	0.18	0.09	0.22	0.29

The NMSE denotes a good correlation between the measurements and the simulations for both the reference and the mitigation scenarios, considering a variation from 0 to 1.5 as model acceptance criteria. However, the NMSE denotes a better correlation between measurements and simulation results for an inflow wind blowing from NNW. The obtained metric confirm the CFD simulations and the wind tunnel experiments as a powerful tool to assess turbulent flow dynamics and to assess the effectiveness of mitigation measures in case of pedestrian wind discomfort.

CONCLUSIONS

In this study, several CFD simulations and wind tunnel measurements were performed in order to understand the local turbulent flow dynamics within and around the auditorium, as well as to assess the effectiveness of a set of mitigation measures. The CFD results and the wind tunnel data confirmed the citizens' perception of wind discomfort within and in the surroundings of the José Afonso auditorium. The highest wind speeds were mainly recorded within the auditorium, and in some specific points in the surroundings of the building. The overall results support the implementation of the mitigation measures to improve the pedestrian wind comfort levels within the area.

In conclusion, the location and configuration of new buildings in sensible areas should be designed and planned considering rules to ensure comfort and safety criteria. Although some urban authorities worldwide already require pedestrian wind comfort studies before grant permits for new buildings, in several European countries there are no legislation or regulatory recommendations. Therefore, the results of this case study, combining numerical and physical approaches, will be very useful to establish a set of guidelines to be disseminated to distinct practitioners, promoting important social, environmental and economic benefits. The combination of both numerical and physical approaches contributes to the development of an effective procedure for pedestrian-level wind comfort assessment studies in urban areas.

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