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Ventilation in a group of courtyard buildings

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Abstract. In the contemporary urban planning, the outdoor comfort is more and more relevant. As a matter of fact, in some Nations the microclimate design, and so, among the others, a quantification of the outdoor comfort is already compulsory, while in many others it is recommended. Various methods to quantify the outdoor comfort can be adopted (e.g., among the others, the PMV-Predicted Mean Vote, or the PET-Physiological Equivalent Temperature), but in every formulation the quantification of the wind velocity, otherwise referred to as ventilation, close to the buildings under study is needed. In this paper, the ventilation inside and outside a group of courtyard buildings is studied via numerical simulations with ENVI-met. ENVI-met is a three-dimensional microclimate model able to simulate the ventilation in an urban environment and the interaction of air flows with surfaces of different materials, with plants and with other typical elements of the built environment in a given climate. Results highlight the relevance of the mutual influence of buildings and of their dimensions in modelling the ventilation inside and outside a courtyard.

1 Introduction

In the contemporary urban planning, the optimization of the outdoor comfort is becoming every day more and more relevant (see, e.g. Santamouris, 2001 [1]). As a matter of fact, in some Nations the microclimate design, and so, among the others, a quantification of the outdoor comfort is already compulsory, while in many others it is recommended (Eliasson, 2000 [2]).

Various methods to quantify the outdoor comfort can be adopted (e.g., among the others, the PMV- Predicted Mean Vote, or the PET- Physiological Equivalent Temperature; see the review of Coccolo et al., 2016 [3]), but in every formulation the quantification of the wind velocity, otherwise referred to as ventilation, close to the buildings under study is needed. In fact, the ventilation (i.e. the wind velocity and direction in the urban environment and its capability to exchange air in it) is the main driver for the air quality and the outdoor comfort ([4]).

Even if the main role of the built environment in the outdoor comfort has been confirmed by several scientific contributions and in various disciplines, most of the legislative guidelines and design activities are related to the optimization of single buildings, even if some studies (e.g. De Pascali, 2008 [5]) have demonstrated that this approach focused on the single building optimization leads to a reduced efficiency, as it is the interaction among buildings that plays the main role. As a consequence, the proper way to deal with the issue of the optimization of outdoor comfort in the urban built environment is to conceive it not as a collection of isolated buildings but as a unique environment, where the interaction among buildings is at least as important as each single building (see, e.g., the microclimate urban design process defined in Chiri et al, 2020 [6]).

The approach to the urban design can follow two main directions: a site-specific approach and a parametric one.

The first one allows to investigate complex built environment (see, e.g., Ouyang et al., 2022 [7], Sedagath and Sharif, 2022 [8], Piedra et al., 2020 [9], Lee et al., 2016 [10]), leading to realistic results on the specific case, but with less generalizable design advices.

On the opposite, in the second approach, the parametric investigation, simple general cases, such single buildings (e.g., Di Bernardino et al., 2017 [11]) or the classical urban canyons (see, among the others, Oke, 1988 [12] for a classification), are investigated via numerical simulations (e.g. Cui et al., 2021 [13], Sun et al., 2021 [14], Badas et al, 2017 [15]) or laboratory experiments (e.g. Badas et al., 2020 [16], Garau et al., 2018 [17], Ferrari et al, 2017 [18]), allowing to extract information about the influence of a single architectural aspect on the outdoor comfort, but without been immediately applicable to the complex nature of urban environment.

Recent studies (Badas et al., 2019 [19], Salvadori et al., 2021-a [20] and 2021-b [21]) has allowed to automatically extract the geometrical features characterizing the urban canyons in real cities, via free online available Geographic Information System (GIS) data, so boosting the potentialities of this last approach to describe the urban canopy for atmospheric Fluid Dynamic purposes.

In addition to the urban canyon, the courtyard building is one of the most employed urban typologies. A courtyard building is a building with an unroofed

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internal area, completely or partially enclosed by walls. Even if the ventilation in courtyard buildings have been extensively investigated, (see, e.g., Sun et al, 2021 [14], Piedra et al., 2020 [9], Subhashini and Thirumaran, 2020 [22]), as well as the ventilation in groups of buildings (see, e.g., Xuyi et al., 2020 [23], Ying et al., 2020, [24]), to the best of the author knowledge, a parametric study on the ventilation on a group of courtyard buildings has not yet been performed.

As a consequence, the target of this work is to perform a parametric investigation of the ventilation inside and outside a group of courtyard buildings, via numerical simulation with the widely employed ENVI-met numerical model (see Section 2). The variable parameter in this work is the length of the courtyard, i.e. the perpendicular-to-the-wind dimension of the internal open space of the building.

The possibility to model the ventilation through the shape, dimension and relative position is relevant for microclimate urban design purposes because, for instance, depending on the specific use of the internal courtyard, it could be more advisable to increase the ventilation (e.g., for recreative uses or in hot climates) or to decrease it (e.g. for storage uses or in windy climates).

2 Materials and methods

The group consists (see Figure 1) of four identical courtyard buildings, with a flat roof, a constant height (10 m), a constant thickness (10 m), a constant courtyard width (W = 5 m; W is the courtyard dimension parallel to the wind direction), a constant width of the streets (or, in other words, a constant distance between the buildings, equal to 10 m) and a variable courtyard length (L = 5 m, 10 m, 15 m, and 20 m; L is the courtyard dimension perpendicular to the wind direction). This configuration was chosen as being typical of some characteristic configurations of family houses in residential areas in many Italian towns. Anyway, it should be recalled that the target of this work is a parametric investigation on the influence of the relative dimensions of courtyard, building and road dimension on the ventilation and not the simulation of a portion of a real town. So, four different configurations were simulated, namely W5L05, W5L10, W5L15 and W5L20. The four courts are named, starting from the South-East one and in anti-clockwise direction, courtyard 1 (or C.1), courtyard 2 (C.2), courtyard 3 (C.3) and courtyard 4 (C.4), so C.1 and C.2 are upstream and C.3 and C.4 are downstream. The parallel-to-the wind street is street 2, while the two perpendicular ones are named street 1 and street 3.

The wind was constant, coming from the East-direction with an undisturbed velocity U_0 of 2.3 m/s, typical of the employed geographical location, the meteorological station of Rome/Ciampino (Italy). The other meteorological data where chosen in the same way, with an air temperature of 19.8°C at the beginning of the simulation, i.e. at 6 a.m. of the 23/06/2018.

The same 24 hours were simulated for each configuration, saving the data every hour.

The simulations ran on a personal computer with a 2,90 gigahertz Intel Core i7-7500U processor and 16GB of an 800 MHz RAM. The duration of the simulations was 78 hours and 27 minutes for W5L05, 82 hours and 26 minutes for W5L10, 84 hours and 22 minutes for W5L15 and 85 hours and 20 minutes for W5L20.

The single cell was a 1m-side cube, with a domain of 250 m in the wind direction, 60 m height and from 150 m (for the W5L5 configuration) to 180 m (for the W5L20 configuration) in the perpendicular-to-the-wind direction. The domain size was chosen, according to Blocken 2015 [25], to left enough space around the buildings to allow the flow reattachment after the detachment due to the presence of the buildings themselves and, consequently, to allow more stability to the numerical codes.

As stated in the Introduction, the numerical simulations were performed via the ENVI-met code (Bruse and Fleer, 1998 [26]), a widely employed software for simulating the urban outdoor microclimate (see, e.g., Ouyang et al., 2022 [7], Binarti et al., 2022 [27], Chiri t al., 2020 [6], Shinzato et al, 2019 [28], Tsoda et al., 2018 [29]). As reported in the review by Fabbri and Costanzo, 2020 [30], ENVI-met is the most widely employed microclimate model: in the quoted paper, a list of 59 recent (from 2013 to 2019) scientific papers where the ENVI-met software was employed to simulate the outdoor microclimate is reported.
ENVI-met is a three-dimensional microclimate model able to simulate the ventilation in an urban environment in a specific geographical location, and the interaction of surfaces of different materials, plants, solar radiation, energy exchanges, etc. with the atmospheric flow and its turbulent phenomena, in a given climate.

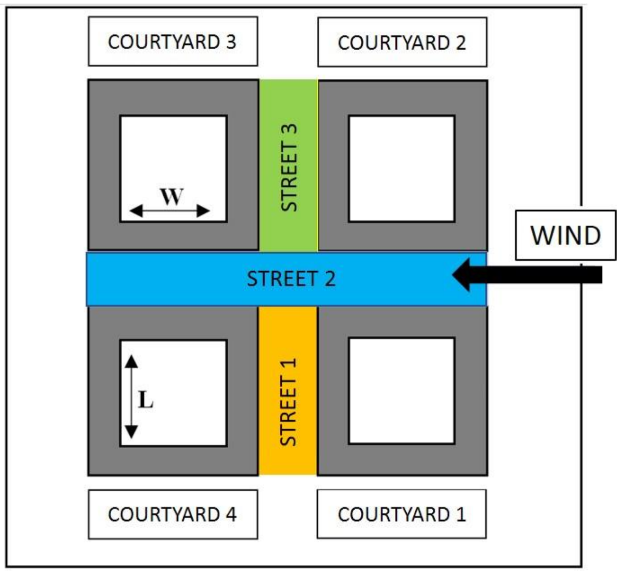

Fig. 1. Sketch of the group of courtyards, with the relevant dimensions, the wind direction, the names of the courtyards and the names of the streets.

3 Results

The data generated by the above-mentioned numerical simulations are in the form of three-dimensional matrices for each variable (e.g., wind magnitude and directions, humidity, temperature, pollutant concentrations, etc) for each hour of the simulated day.

In Figure 2, the horizontal field of velocity magnitude U in m/s, extracted on the plane at the building roof height, is shown: colours close to the yellow point out where the velocity magnitude is the highest, while colours close to the blue indicates that the velocity is almost zero. The white vectors represent the velocity direction (arrow) and magnitude (length). For the sake of clarity, only the closest region to the courtyards where the flow is more biased by the buildings is shown. As above stated, the wind comes from the right, so it is possible to spot the effect of the built environment on the flow. In particular, it is clear that the flow velocity increases in the street 2, the one parallel to the wind direction, due to the reduction of the section encountered by the wind, also called Venturi effect. Streets 1 and 3, the two perpendicular to the wind direction, are instead zones of relative calm, where the wind tends to enter from street 2, as well as the internal courts: these two streets could be consequently considered as a shelter from the wind when it should blow very fast. Moreover, the windward (i.e. upstream the building) recirculation zone and the leeward (i.e. downstream the building) wake are visible.

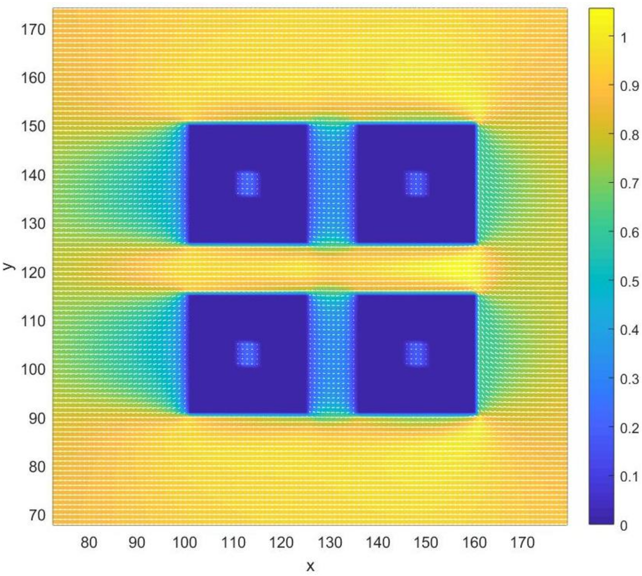

Fig. 2. Horizontal field (colour map) of velocity magnitude U [m/s] at the roof level (the undisturbed velocity U_0 is 2.3 m/s from the right), with the velocity vectors in white, for the configuration W5L05.

In Figure 3, the vertical field of velocity magnitude U [m/s], in colours, as well as the velocity vectors (white arrows) at the middle section of courtyards 2 and 3 are shown. As for Figure 2, it is possible to see that the influence of the built environment on the flow is much larger than the size of the buildings themselves, with the flow separation upstream (with the related recirculation vortex with a horizontal axis), the intrusion of the air inside the inner courts and in the perpendicular to the wind direction street, the downward wake (also here with a recirculation vortex with a horizontal axis), and the acceleration zone above the roof of the first building.

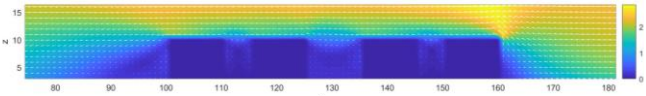

Fig. 3. Vertical field (colour map) of velocity magnitude U [m/s] at the middle section of courtyards 2 and 3 (the undisturbed velocity U_0 is 2.3 m/s from the right), with the velocity vectors in white, for the configuration W5L05.

In order to quantify the effect of the group of four courtyards and of their dimensions in reducing the wind velocity in the inner courtyards or, vice-versa, in allowing their ventilation, the maximum velocity U_{MAX}, as well as the minimum velocity U_{min}, in the volume inside the building have been divided by the wind undisturbed velocity U_0 and plotted for each one of the four configurations, versus the hours of the day on Figures 4 and 5. In this way, the velocity reduction (or nondimensional velocity) U/U_0 is determined. In the x-axis, the hours of the day are from 7 a.m. of the first simulated day to 6 a.m. of the following day. In Figures 4 and 5, the case W5L05 is represented by a continuous black line with black circles, the case W5L10 is represented by a dashed blue line with blue plus, the case W5L15 is represented by a continuous red line with red asterisks and the case W5L20 is represented by a dashed green line with green circles.

In Figure 4, the nondimensional maximum velocity U_{MAX}/U_0 inside the courtyard 1 during the simulated day is plotted. The time dependency, due to the varying sunlight warming during the day, which increases the forcing during the warmest hours, is evident. Moreover, on one hand, the velocity values tend to be the highest for the largest courtyard (W5L20) to then decrease for W515, w5L10 and to find the minimum values or the smallest courtyard (W5L05). On the other hand, the velocity trend and its values tend to be very similar for all the four simulated configurations. For all the courtyards, the lowest values are recorded during the night and the first hours of the morning, while the highest ones are encountered at 17:00 and 18:00. In particular, the absolute lowest value is around 0.17 and it is found at 7 a.m. in the configuration W5L05, while the highest one is around 0.26, found at 6 p.m. in the configuration W5L20.

The nondimensional maximum velocity U_{MAX}/U_0 inside the courtyard 2 during the day is not reported, because, as expected, as it has an identical behaviour as the same quantity in the courtyard 1.

In Figure 5, the nondimensional maximum velocity U_{MAX}/U_0 inside the courtyard 4 during the day is plotted. In a similar manner to the upstream courtyards 1 and 2, the velocity values tend to be the highest for the largest courtyard (W5L20) and then decrease for W515, W5L10 and to find the minimum values or the smallest courtyard (W5L05). Moreover, also in this case in a similar manner to courtyards 1 and 2, the velocity trend and its values tend to be very similar for all the four simulated configurations: as a matter of fact, in all the configurations, the lowest values are recorded during the night and the first hours of the morning, while the highest ones at 17:00 and 18:00. It has to be highlighted that the velocity values for the downstream courtyards 3 and 4 tend to be higher than the ones of the upwards courtyards 1 and 2. In fact, the absolute lowest value is around 0.23 and it is found at 7 a.m. in the configuration W5L05, while the highest one is around 0.27, found at 6 p.m. in the configuration W5L20. These highest values in the downstream courtyards can be explained with the different velocity direction in the two cases: as visible in Figure 3, in the case of the upstream courtyards the velocity is almost vertical due to the flow separation, while in the case of the downstream courtyards the velocity is almost horizontal, in a skimming flow manner (as described in Oke, 1988 [12]), so in this last case it has to modify less its direction to enter the internal volume of the courtyard and, in turns, a larger part of the velocity itself is able to contribute to the ventilation.

The nondimensional maximum velocity U_{MAX}/U_0 inside the courtyard 3 during the day is not reported, because, as expected, as it has an identical behaviour as the same quantity in the courtyard 4.

In all the cases, the maximum values are found close to horizontal open plane close to the building roof.

In summary, we can state that the increase of the internal volume of the courtyard through the increment of the dimension perpendicular to the wind direction contributes to increase the maximum velocity and so, in turns, to improve the ventilation.

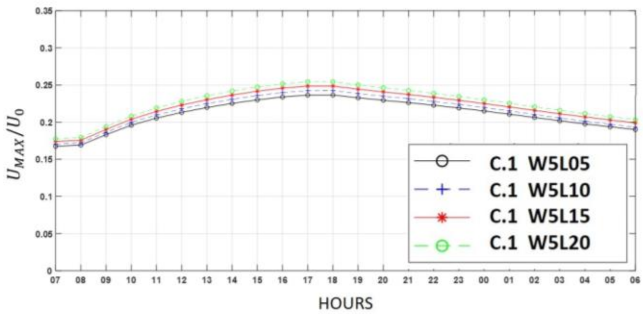

Fig. 4. Maximum nondimensional velocity U_{MAX}/U_0 in the internal court of courtyard 1 versus time (hours of the day), for the different simulated courtyard dimensions (in the legend); U_0 is the undisturbed wind velocity.

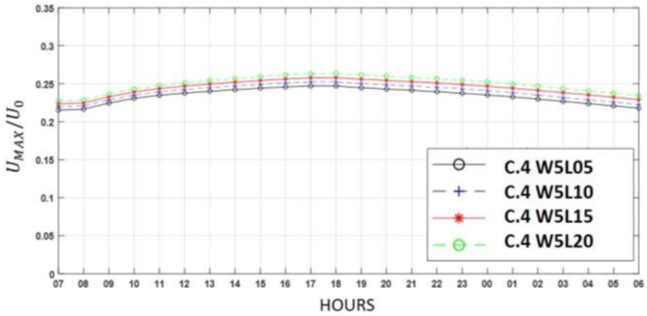

Fig. 5. Maximum nondimensional velocity U_{MAX}/U_0 in the internal court of courtyard 4 versus time (hours of the day), for the different simulated courtyard dimensions (in the legend); U_0 is the undisturbed wind velocity.

Finally, the nondimensional minimum velocity U_{min}/U_0 inside all the courtyards during the day has always a very similar behaviour and, moreover, very low values, so it is not plotted here. Anyway, the minimum velocity inside the internal volume of the courtyards during the hours of the day has almost identical values and trends for all the four simulated configurations, with the lowest value (around 0.002) at 9 a.m. and the highest value (around 0.004) at 10 p.m, meaning, as just stated, that these values are almost negligible.

In summary, we can state that the increase of the internal volume of the courtyard through the increment of the dimension perpendicular to the wind direction does not contribute to increase the minimum velocity and so that all the courtyards have similar capability to isolate the internal open volume from the external wind.

4 Conclusions

In the presented work, the ventilation inside and outside a group of four courtyard buildings was investigated via numerical simulations with the ENVI-met code, a three-dimensional microclimate model able to simulate, among the others, the ventilation in an urban environment and its interaction with surfaces, plants and the atmosphere in a given climate. In this parametric study, the variable parameter is the length of the courtyard L, that is the perpendicular-to-the-wind dimension of the internal open space of the building, while all the other parameters are left constant.

Results highlight the relevance of the mutual influence of buildings and of their dimensions in modelling the ventilation inside and outside a courtyard.

In particular, the flow velocity increases in the street 2, the one parallel to the wind direction, due to the Venturi effect, while streets 1 and 3, the two perpendicular to the wind direction, are instead zones of relative calm, that could be consequently used as a shelter from the wind when it should blow very fast.

Regarding the ventilation in the internal courtyards, an increase of the internal volume of the courtyard through the increment of the dimension perpendicular to the wind direction contributes to increase the maximum velocity and so, in turns, to improve the ventilation. The velocities in the downstream courtyards C.3 and C.4 was found to be slightly higher than in the upstream courtyards C.1 and C.2: this can be explained with the different velocity direction in the two cases, because in the case of the upstream courtyards the wind is almost vertical (due to the flow separation), while in the case of the downstream courtyards the wind approaches the internal courtyard almost horizontally, so it is easier to enter the internal open volume of the building.

Moreover, the increase of the internal volume of the courtyard through the increment of the dimension perpendicular to the wind direction does not contribute much to increase the minimum velocity, meaning that all the simulated courtyard buildings have similar capability to isolate the internal open volume from the external wind.

Eventually, we recall that the presented results can help in modelling the ventilation through the shape, dimension and relative position, and this can be relevant for microclimate urban design purposes.

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