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Recovery of ancient bioclimatic strategies for energy retrofit in historical buildings: the case of the Infants' Tower in the Alhambra

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Abstract

Among Mediterranean historical buildings, the *Andalusí* architecture is the result of an intuitive and experimental process of adaptation to the surrounding environment. The medieval Muslims coped with difficult climatic conditions in *al-Andalus* through passive cooling strategies, paying attention also to the thermal comfort. The paper focuses, in particular, on natural ventilation in the Infants' Tower in the Alhambra of Granada. It has eight mashrabiyas at the top whose performance is investigated through a CFD model, in order to understand their contribution to the improvement of indoor thermal comfort and rational energy use during summer.

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Keywords: cultural heritage; natural ventilation; Andalusí architecture; mashrabiyas.

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1. Introduction

The complexity of historical buildings requires particular accuracy for energy retrofit that represents a huge challenge. Heritage buildings are not suitable to ensure a modern use of the internal spaces in optimal conditions and the typical retrofit interventions are not useful and too invasive and usually damage the architectural artefact and its intrinsic value. For this reason, it does not exist a unique methodology to be applied in historical buildings, but it is necessary to delve deeper into and to study every case in its own context. The starting point has to be the knowledge of constructive techniques and strategies and their recovery aimed at not only at conservative restoration, but also at energy retrofit.

Furthermore, the severe regulations in this field forbids any modification to the facade exterior appearance, i.e. construction materials and architectural features. For this reason, it is usually quite difficult to identify and apply sustainable and effective solutions for improving energy efficiency in these buildings.

The implementation of internal envelope insulation, cool coatings and window retrofit represents the best solution in order to improve the energy efficiency of building envelopes. Additionally, upgraded control systems, lighting, ventilation, thermal storage, and heat recovery are listed as major retrofit technologies to reduce the energy demand of heritage buildings within temperate Mediterranean climate conditions [1-3].

The traditional techniques in heritage buildings are generally the result of a process of adaptation to the dominant climate of its surroundings and lifestyles of inhabitants. For this reason, ancient and vernacular architecture is the origin of the bioclimatic one [4] and represents a rare example of a sustainable building, arisen in response to the geography of a land and the history of its people [5].

Among historical buildings, the case of Andalusí architecture in Granada is one of the most interesting in this point of view because it took place in a particular surrounding environment. In fact, Granada has a continental climate and it is protected from external currents by the Sierra Nevada, Spain's highest mountain, even if some highest areas of the city, such as the Albayzin and the Alhambra, are more exposed to fresh winds.

In this climate context, houses and palaces represent sublime examples of applications of ancient bioclimatic strategies such as protection against solar radiation, well defined orientation, thermal inertia and mass of bearing masonries and rammed earth walls, clear and reflective coating materials, small openings and screens on exposed facades, porticoes, vegetation. In addition, the presence of patio, that is the heart of the house, is a fundamental bioclimatic device, as well as the attention to the openings and buildings' orientation and to the use of shading systems. If we consider that these architectures are located in a climate with hot summer and they originated during the so-called Warm Medieval Period, it is possible to recover these strategies to improve their energy performance, especially during summer.

The Infants' Tower, in the Alhambra, represents a significant example in this sense and the ideal use of passive strategies reaches the peak in this historical building [6].

2. The Infants' Tower

The Infants' Tower was built during Muhammad VII (1392-1408) reign, according to the interpretation of the inscription about the honorary title of sultan in the Tower by Luis Seco de Lucena Paredes [7]. It is located in the Eastern external wall of the Alhambra, with North-South orientation.

The ancient Tower had both residential and military function and it is the last example of the typological evolution of Alhambra architectures [8].

The spatial distribution is complex (Fig. 1). The entrance door is located exactly in the center of the façade and two floors develop around a central space that acts as a courtyard: it is possible to access to the ground floor through a quadruple bend *zaguán* (entrance), typical of military tower, covered by cross vaults with *muqarnas*. The full-height vestibule covered with a lantern is the most interesting area and is the final evolution of the *qubba* (in *al-Andalus* it was a regal dome over a quadrangular space, normally seen from the inner room).

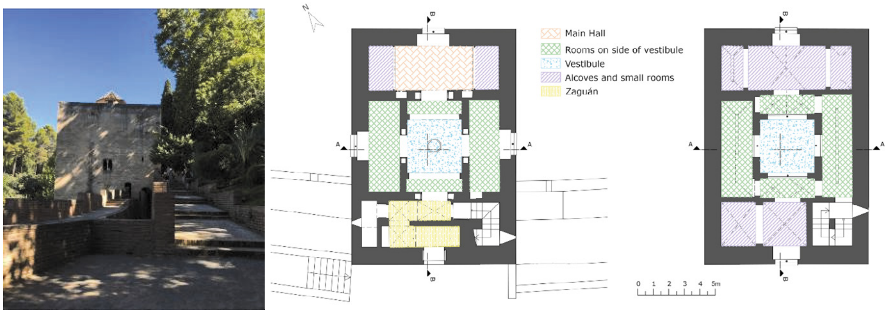

Fig. 1. View of the Infants' Tower and spatial distribution of the ground floor (in the middle) and the first floor (on the right).

It begins with a rectangular area at the ground floor, becomes square at the first floor and ends in an octagon shape at the top. The dome was destroyed during the earthquake in 1806 and the current coverage (Fig. 2) was built by Mariano Contreras with a decorative wooden roof (*ataujerado*), fixed to a load-bearing structure, in place of *mocárabes* dome, and with windows in each of the eight sides of the octagon.

The central vestibule has two rooms on each side: the finely decorated pillars and the arches remind the idea of porticoes, typical of *Nasrid* houses, during the last Islamic Kingdom that ruled a part of Iberia from 1232 to 1492. The rooms, covered by wooden ceiling, are ventilated and lighted up by mullioned windows in front of entrance arches, perfectly aligned along the Tower cross axis. The main north room presents lateral alcoves with decorated arches at the entrance. The central balcony housed the ancient throne and has a *mocárabes* vault with a small central dome.

A staircase with embrasures leads to the upper floor that has a similar spatial distribution of the ground floor. The north and south rooms are covered by cross vaults and overlook the central patio through two big mullioned windows. The east and west smaller rooms, at the other sides of the patio, have small windows with a simple arch. The north room has also the alcoves (*alhanías*) as the lower one, while the south room, placed above the entrance, has a window centered in the facade and is covered by a cross vault as well as the great *alhanía* to the East. The others rooms have smaller windows with a simple arch.

The full height hall influences the indoor microclimate of the whole Tower, especially promoting different airflows. In fact, different natural ventilation typologies coexist in the Tower, like the stack effect, generated through the hall, and the cross ventilation through opposite windows. Moreover, it is interesting the role of the *mashrabiyas* (or *celosías* in Spanish), typical elements of the Islamic architecture in *al-Andalus*. A *mashrabiya i*s a kind of window with carved wood latticework that controls the passage of light and airflow, reducing the temperature and increasing humidity, besides ensuring privacy. During the Middle Age, the *celosías* supposedly allowed a flexible use of windows, opened or closed depending of the sun and ventilation need, as in the case of the Alijares royal palace outside the Alhambra [9]. In Infants' Tower, they have a great influence on indoor microclimate and a fundamental function in natural ventilation.

Fig. 2. Views of the lantern outside and inside.

3. The Fluid Dynamics study of the Infants' Tower

3.1. Methodology

As it is known, only complete and continuous measurement campaigns can guarantee reliable data on ventilation rate, airflow distribution and air speed, both inside and outside of a building. They are expensive in terms of time and costs and it was not possible to realize them in the Infants' Tower.

In spite of this, the Computational Fluid Dynamics (CFD) and numerical simulation methods can help to predict the behavior of airflow and natural ventilation in the Tower.

There has been extensive research dealing with CFD modeling of different strategies of natural ventilation in new and ancient buildings [10-13].

Computational fluid dynamics is based on the resolution of the governing equations, which describe the flow field in the computational domain, namely the continuity equation for mass transfer, the Navier–Stokes equation for momentum transfer and the thermal energy equation for heat transfer [14]. The governing equations are available in [15]. The basic assumptions for the CFD simulation include a three-dimensional, fully turbulent, and incompressible flow.

The most complex step is the numerical model definition, in order to obtain an adequate description of the physical model. The problem is the huge need of time and computer resources for the analysis of complex architecture. For this reason, the software [16] was used: even if the model is simplified, results are reliable either using minor hardware resources.

The CFD module allows us to obtain temperature, pressure and air speed distributions, giving back numerical and graphical results. The only limit is that it is not possible to carry on an un-steady fluid dynamics study, but the CFD provide only a snapshot of fluid dynamics situation of the system, depending on the defined boundary conditions. In the case of natural ventilation, the boundary conditions on the airflow and surface temperatures are obtained from a previous thermal simulation. That is an important issue in case of lack of experimental data. In this way, it is possible to get a valid tool for the study of the Tower's mode of operation.

In order to create an efficient model of the reality, it is important to identify the physics of the problem and to simplify the real object in a right way [17]. For the model set-up, the analysis and the study of the morphological, geometrical and thermal properties are fundamental. The thermal properties of the envelope and its materials have been derived by the existing literature [18] or by the study of plans in the Archive of the Council of the Alhambra and Generalife. For example, the external walls are 1.10 m thick with a U-value of 0.5 W/(m^2 K) [19]. The openings of the ground floor and of the first floor are without glass or screens; since there are not sure data about the shading systems, the actual condition of the Tower was considered in the analysis, in order to evaluate the thermal performance and natural ventilation functioning today.

In the first step, a dynamic thermal simulation was carried out during a typical hot summer day in July, using climatic file of the city of Granada (Fig. 3).

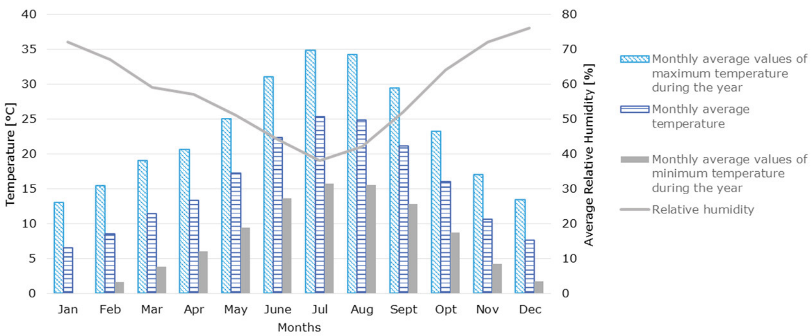

Fig. 3. Temperature and relative humidity in the city of Granada (from www.aemet.es).

It is in the climate zone C_{sa} [20], according to Köppen classification map. The average annual temperature is 15.4 °C. Winters are cold with temperatures between 7 and 10 °C, while summers are hot: the intense solar radiation during the day causes peaks of temperature higher than 40 °C, while night breezes from the surrounding mountain carry cool air. The daily temperature range can reach 20 °C, especially during summer. Although only 50 km separate Granada from the sea, the mountains prevent any breeze of the sea to penetrate inside the city and thus to reduce the extreme temperature fluctuations. Another feature of the city is that it is crossed by the Darro and Genil rivers, which increase moisture in the air, while the rainfall is extremely poor, especially during the dry summer months. The annual mean wind speed is 1.71 m/s mainly arising from the West.

Mesh generation, is one of the most important steps after the definition of domain geometry. CFD requires the subdivision of the domain into a number of cells that are solved numerically, so that the discrete values of the flow properties, such as velocity, pressure and temperature, are determined. Increasing the number of cells improves the accuracy of the solution, generally, even if you have to reach a right compromise between computational resources and accuracy [21].

A Cartesian not uniform structured grid of 7,836,928 cells was used in the Tower.

The boundary conditions (volume airflow, internal and external surface temperatures and mean temperature of thermal zones) were imported as output data of EnergyPlus dynamic thermal simulation. Imposing boundary conditions directly on the internal calculation domain allows to not extending the outside domain to the surrounding environment. That promotes a saving in terms of calculation time because it reduces the dimension of the grid and simplify the model.

The initial condition of velocity was zero with a temperature of 20°C.

The turbulence model, selected for the analysis, was the Constant Effective Viscosity one. It is a simplified model that substitutes the molecular viscosity of Navier Stokes equations with an effective viscosity constant value. Even if this model is unable to describe local turbulence and its transportation, it is less expensive in calculation time and more numerically stable than the k-ε model. This choice is due to the extreme difficulties to achieve convergence in a so complex model, because there are very low air speed of buoyancy strengths and the phenomenon is dominated by convection, as in case of natural ventilation. In fact, it is known that the CFD modeling of natural convection phenomena is particularly complex and presents convergence problems even with high-performance computers. The decision to consider a laminar flow, with natural convection regime, is therefore plausible since the value of the pure Reynolds number is very low. The iterative calculation process ends when the convergence is achieved, that is when the dependent variable values satisfy finite difference equations for every cell. The monitoring of the residues and more than 10000 iterations were used during calculation and the convergence was fixed to 10^{-3} for the mass residual.

It was also verified that the solution was independent of the mesh through a sensitivity analysis, gradually thickening the grid until the stability of solution is reached.

3.2. Simulations and results

The aim of the simulations was to demonstrate the importance of the mashrabiyas to allow proper natural ventilation inside the Tower and to understand their influence on the indoor microclimate.

The model was tested during a typical day of July, the hottest month in the summer of Granada. As it is difficult to evaluate the original ancient conditions of the openings, three different configurations were studied opening or closing the glass windows and the *celosías* at the top of the vestibule.

Boundary conditions related to 9:00 a.m. of 20th July were used. The choice of this hour allows evaluating if the morning fresh air influences passive cooling; instead, during the hottest hours in the day, comfort conditions decreases with natural ventilation because warm air enters the Tower. The surface temperature of walls and openings is constant and was obtained by dynamic simulation. Therefore, an external temperature of 22.2°C was fixed, while surface temperature between 24.33°C and 25.37°C were applied to the ground floor and the first floor, depending on the envelope component (walls, floors or ceiling). The roof has a surface temperature of about 26°C. Lantern walls, characterized by a high degree of shadowing, have temperatures between 23.44 and 23.96 °C, depending on the orientation, while the roof has temperature of 25.91 °C, because of direct solar radiation. Instead, the indoor temperature of the openings is between 21.56 and 22.08° C.

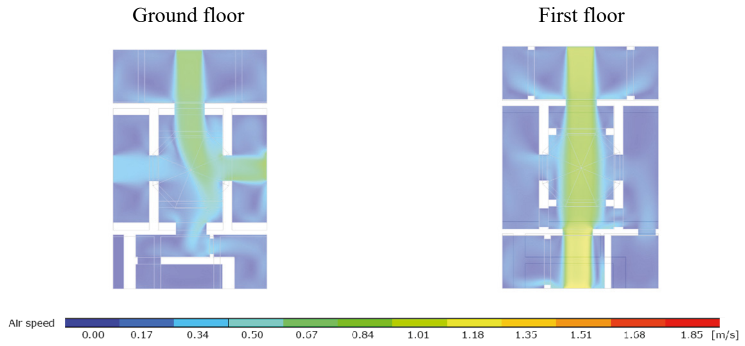

Fig. 4. First configuration (closed windows): air speed distribution on ground and first floor.

The first studied hypothesis is the full closing of windows at the top, through glass and shielding *celosías*. The incoming airflow, equal to the outgoing one, is 4625.75 l/s.

It results that cross ventilation creates a movement of the air in the Tower, thanks to external wind.

On the ground floor (Fig. 4), the external air enters through the openings to the North and West and gets out through the Eastern one. The most ventilated areas are the main room to North and the central patio, in which the air currents meet. On the first floor, the cross ventilation is still more evident and efficient, thanks to the alignment of the openings. Instead, the side areas are less or not affected by the flow.

The longitudinal section (Fig. 5) shows as the wall that divides the *zaguán* from the main rooms blocks the air movement on the ground floor, so that the airflow penetrates from the opening to the North with a speed of about 0.8 m/s and soon decreases, spreading over the inner court.

The air enters through the window to North and go through the entire environment, going out from the opening to South. The air movement does not affect the vaults of the rooms, except the ceiling of the corridor to the South of the atrium. That happened because the air passes from the full height vestibule to the reduced section of the arch of the corridor and the other room, increasing the speed up to 1.27 m/s. In the lantern, the air is still because all windows are closed. The average speed value is 0.21 m/s while the average temperature is 23.42 °C, both calculated on the longitudinal section.

As regards the distribution of temperatures, there is a thermal stratification of the air. Instead, an overheating of the lantern occurs and the temperature reaches about 26.77 °C. Finally, a certain difference of pressure between North and South occurs, in line with the air movement, and there is an overpressure in the lantern at the top.

In the cross section, it can be seen that the air speed is lower: in the rooms in the sides on the first floor and in the lantern it is obviously almost zero, while it is interesting what happens in the patio and on the ground floor.

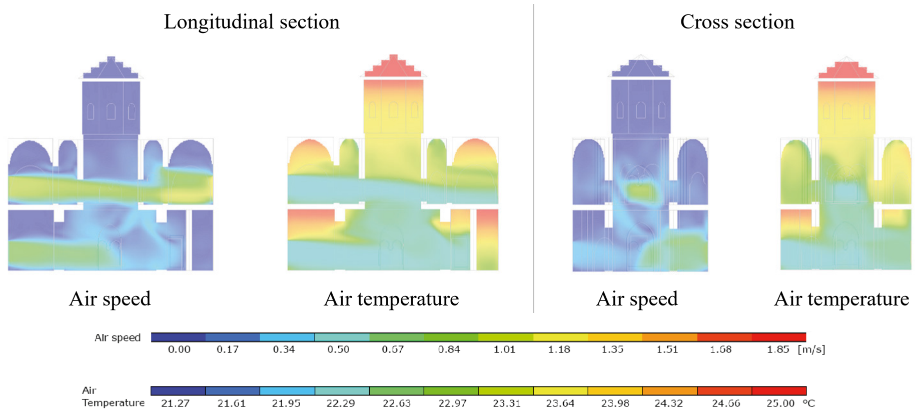

Fig. 5. First configuration (closed windows): air speed and temperature distributions in longitudinal and cross sections.

The wind invests the north and west facades of the Tower, in line with climatic data of Granada. In the vestibule, the inflow from the west window on the ground floor can be summed with the air penetrated from the north mullioned window, increasing the velocity of the air, which is blocked to the south and ejected from the East.

This functioning, as well as the different orientation of the side rooms, affects temperature too: the eastern room, the most exposed to the morning sun, is warmer than the shaded western one.

The study of the distribution of air speed module and temperature along a vertical axis at the center of the atrium reveals that the maximum speed is reached at the height of the first-floor openings (0.91 m/s). However, the average speed is equal to 0.16 m/s and the average temperature is 23.17 °C.

In the second configuration, four mashrabiyas of the lantern on North, South, East and West are opened. In this case, the total input airflow, and, therefore, the balancing output is 5496.95 l/s. The result shows that the cross ventilation prevails on the stack effect, due to the external wind.

On the ground floor, the functioning of ventilation is similar to the first configuration, but the air coming out from the eastern window has a lower speed. On the first floor, the air velocity increases, especially in the full-height vestibule (Fig. 6). This different functioning is due to the opening of windows at the top that generates and promotes the circulation of the air in the atrium.

Once again, the longitudinal section shows how the partition wall that divides the *zaguán* from the main rooms blocks the air movement on the ground floor: the air enters from the opening to the North at a speed of about 0.8 m/s and goes upwards in the full-height atrium (Fig. 7). On the first floor, the cross ventilation prevails: the air enters from northern window, goes through the entire floor and goes out through the South window. Only a part of fluid rises thanks to the suction caused by the *celosías*. However, the three levels have different and independent natural ventilation, depending on the openings of each one.

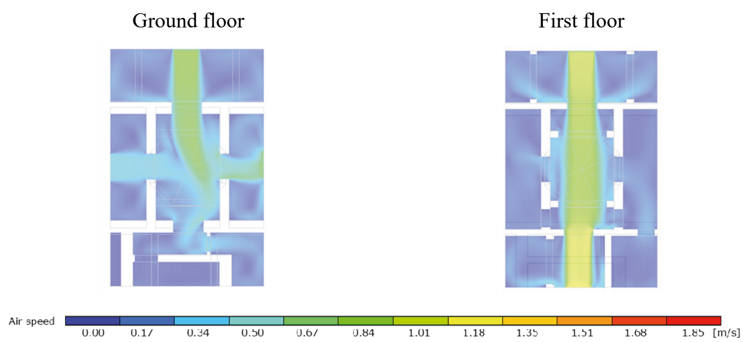

Fig. 6. Second configuration (opened mashrabiyas): air speed distribution on ground and first floor.

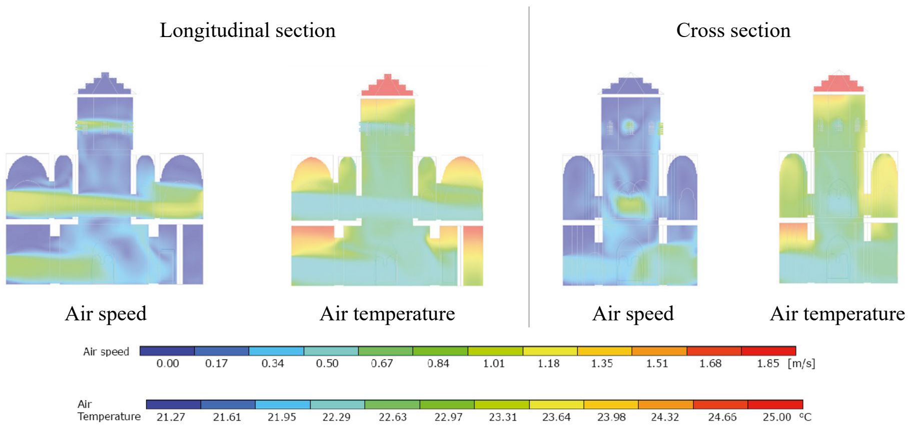

Fig. 7. Second configuration (opened mashrabiyas): air speed and temperature distributions in longitudinal and cross sections.

The module of the average air speed is 0.23 m/s, an ideal value for the thermal comfort, while the average temperature is 23.30 °C, calculated in the longitudinal section. The maximum speed of 0.31 m/s is reached at the windows on the first floor.

In every floor, there is a thermal stratification of the air, in particular on the ground floor, where the air exchange is minimal, in the entrance area and in the areas of stagnation; in the lantern there is no more the warm air accumulation but the temperature is lower than the previous case.

Even the cross-section shows an increase of the ascending air movement inside the central part of the Tower, in addition to a less defined temperature stratification.

The distribution of air speed and temperature along the vertical axis at the center of the atrium confirms what has been said previously: the maximum speed is reached at the height of the first-floor openings (0.93 m/s) and at the height of *celosías* of the lantern (0.82 m/s). The average speed is 0.25 m/s and the temperature is 22.58 °C.

In the third and last configuration, there are not *celosías* and the windows are totally opened. This hypothesis is not real but it is important in order to have a complete knowledge of natural ventilation functioning in the Tower. The inlet and outlet airflow is 7701.38 l/s.

As in the second case, cross ventilation prevails on stack effect, but the air movement is more turbulent because the windows at the top amplify the upward movement (Fig. 8, 9).

The temperature distribution is more uniform and the air change is more efficient than the other cases. The average air speed in longitudinal section is 0.32 m/s (higher than the second configuration) while the average temperature is 23.09 °C.

The maximum air speed of 1.52 m/s is reached at the windows on the first floor.

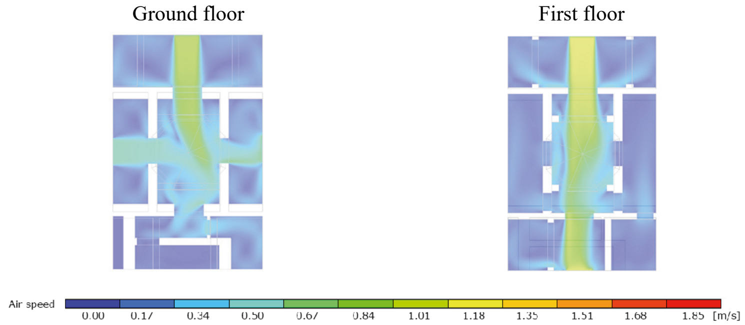

Fig. 8. Third configuration (opened windows): air speed distribution on ground and first floor.

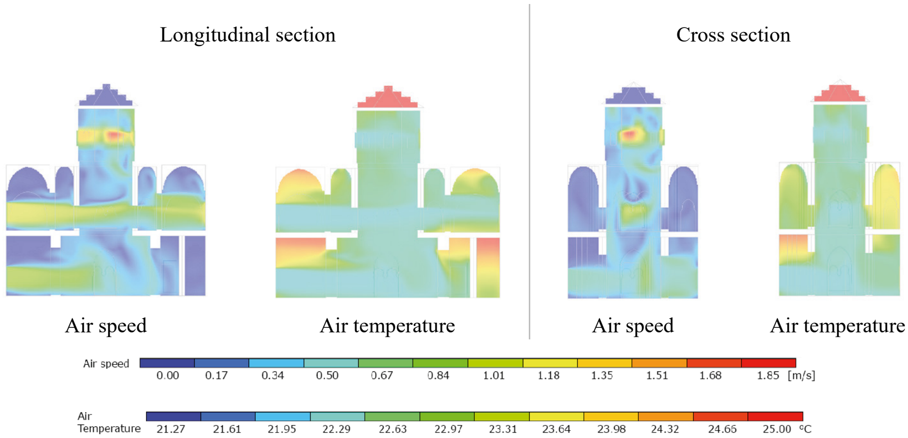

Fig. 9. Third configuration (opened windows): air speed and temperature distributions in longitudinal and cross sections.

As regards the air speed and temperature distribution along the vertical axis placed at the center of the atrium, the maximum speed module is reached at the height of the lantern openings (1.46 m/s), because the air can flows freely through the small cross-section of windows.

The average velocity along the axis is equal to 0.41 m/s and the temperature is 22.56 °C.

3.3. Measurements

Several measurements were carried out in situ. They were done using a hygrometer and a hot-wire anemometer in order to detect the magnitudes of temperature, relative humidity and air speed during different days in September, opening or closing the *celosías* at the top of the roof. For brevity, only an example with the most representative results is reported here. The considered values were measured along the longitudinal and cross axis of the tower, even if several measurement points were analyzed (Fig. 10).

On 1st September, the mean temperature in the Tower in the early morning is about 23.2 °C on the ground floor and 24.1°C on the first floor. The mean relative humidity is about 70%. During the day the temperature reaches peaks of 27.1 °C, maintaining constant the difference between the two storeys, and humidity decreases down to 37.1%

The external wind direction and intensity influences the internal ventilation: in the morning, the wind direction is extremely variable with low wind speed of about 0.12 m/s. During the day, the speed increases.

When the glass windows in the roof are closed (Fig. 11), there is cross ventilation in the tower and the air flows independently in both of the floors, with a constant air speed, except in the point n. 9 where the air gets in and the velocity increases.

In fact, the point 9 is the most ventilated place during the afternoon because the air flows through the west mullioned windows.

In the center of the vestibule, the air speed decreases because of the full height and the increase of the air volume: in this way, the air expands along the three directions.

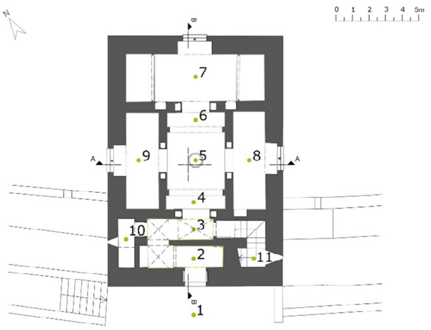

Fig. 10. Individuation of measurements points in the Infants Tower on the ground floor (on the left) and first floor (on the right).

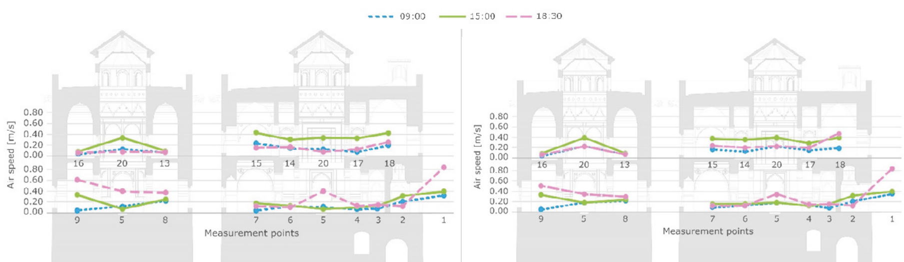

Fig. 11. Measurements in the Infants Tower on 1st September, closing and opening the windows in the roof: air speed in cross and longitudinal section.

Fig. 12. Measurements in the Infants Tower on 1st September: comparison of air speed values between closed and opened windows in the roof.

When the glass windows are opened and only *celosias* remain as shading system, the results are different. Without wind, in the early hours of the morning, in the patio there is an increase of air speed of about 0.10 m/s.

This is due to the stack effect, despite of low wind speed. During the early morning, there is a stratification of the air temperature that increases of 2 °C in the upper floor; the humid air on the ground floor tends to rise, creating pressure differences in the environment. Therefore, that causes an air upward movement inside the tower, also thanks to the suction that occurs at the top through the *celosías*. The stack effect and the Venturi effect coexist with cross ventilation and take advantage from the mashrabiyas. Cross ventilation is free on the upper floor, while on the ground floor the quadruple bend entrance causes a poor air circulation.

An interesting phenomenon happens in the point n. 8, in the east room of the ground floor: during the morning, the humidity rate increases and the temperature decreases. This is probably due to the external little waterfall on the right of the tower: water acts as an evaporative cooling source that affects the indoor microclimate.

The less ventilated rooms are the lateral rooms on the upper floor that overlook the vestibule (point n. 13 and 16) and the alcove on the left of the south room. Finally, when the windows in the roof are opened, the air speed increases from the 10% up to 25% and grows up during the day, proportionally to the wind intensity (Fig. 12).

During the morning on 21st September (Fig. 13), the air speed is near to zero. In the Tower, the air is still, except in the east room of the ground floor, thanks to the humid air that goes up from the waterfall (point n.8). There is no difference if you open or close the windows at the top of vestibule, except a slight increase in the vestibule.

During the rest of the day, the behavior is similar to the 1st September, even if the temperature is 3°C lower.

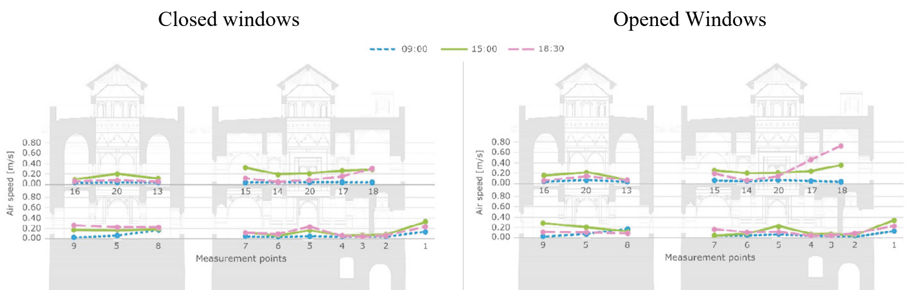

Fig. 13. Measurements in the Infants Tower on 21st September, closing and opening the windows in the roof: air speed in cross and longitudinal section.

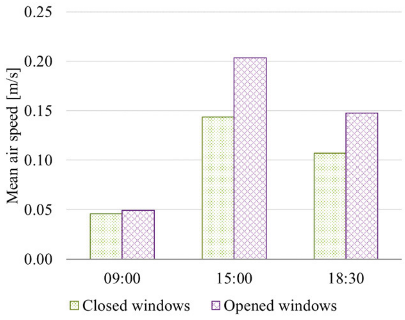

Fig. 14. Measurements in the Infants Tower on 21st September: comparison of air speed values between closed and opened windows in the roof.

When the windows in the roof are opened, the air speed increases from the 8% up to 30% and grows up during the day, proportionally to the wind intensity (Fig. 14).

Even if the measurements suffer of the variability of the wind, they confirm simulation results. Through the comparison between different days and climatic conditions, it is possible to deduce some important considerations about the functioning of the Tower: in the absence of wind, there is a stack effect with stratification of temperature and humidity; when the wind increases, the cross ventilation prevails. Along the North-South axis, the opposite windows allow cross natural ventilation, while the walls thermal mass prevents excessive internal solar gains during the summer.

4. Conclusions

In conclusion, the study highlights the fundamental role assumed by the windows at the top of the Tower: through their opening airflow and the indoor air speed can increase and the temperature and pressure distributions vary. This shows the great possibility of microclimatic control that such architectures offer, thanks to their particular morphological conformation and arrangement of the openings.

Moreover, the *celosías* represent a right compromise between both the needs to ventilate the environment and to protect it from the intense solar radiation, as well as they had the social function to ensure the privacy of the Islamic houses. If you think that also the other windows were equipped with similar shields in the ancient Tower, it is easy to understand how such systems provided shelter not only from sunlight, but also from the intense heat, giving a level of optimum shading in the interior spaces. However, at the same time, the air exchange and better internal microclimate were assured in the point of view of passive cooling.

The morphology of the Infants' Tower is extremely interesting and represents an opportunity to study the complex interaction between shape and ventilation, demonstrating its variability depending on the opening or closing of *celosías* at the top.

Dynamic simulations were carried out for three diverse configurations, in which there is a different use of windows and *celosías*. Simulations demonstrate the importance of these elements for the energy upgrading during summer that can be reached naturally and without a cooling system. The use of mashrabiyas allows for an improvement of the indoor microclimate that is guaranteed not only by shade during the hottest hours of summer days, but also by an increase in air speed and air change rate within the rooms.

Measurement carried out in situ of temperature, relative humidity and speed of air confirm the simulated behavior of the Infants' Tower.

The analysis provides a study methodology for an in-depth knowledge of the natural ventilation strategies applied to the historic buildings. Passive strategies are essential in order to reduce the installation of invasive plant solutions. Moreover, the ancient natural ventilation techniques in the historic buildings are convincing in their simplicity, even if their application involves a number of effects, which need to be considered. They could be advantageous in terms of comfort and air quality but also potentially harmful, for example, to frescoes or fragile objects that need to be adequately protected.

Finally, the study highlights the importance of understanding the historical architecture functioning, especially when the architectural and morphological characteristics of the buildings can naturally improve indoor microclimate and comfort conditions naturally.

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