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Energy Procedia 126 (201709) 289–296

Energy Procedia

www.elsevier.com/locate/procedia

72nd Conference of the Italian Thermal Machines Engineering Association, ATI2017, 6-8 September 2017, Lecce, Italy

Re-interpretation of an ancient passive cooling strategy: a new system of wooden lattice openings.

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Abstract

Traditional passive cooling strategies are a very important tool in Mediterranean architecture to face climate changes and to limit energy consumption, both in new and ancient buildings, toward sustainability and reduction of fossil fuel consumption.
Starting from the traditional architectural culture, the aim of the study is to understand how using and re-interpreting ancient constructive elements that interact with the outdoor environment, in order to assure the indoor thermal-hygrometric comfort. In this regard, the paper proposes the study of a new system of wooden lattice openings to be installed in Mediterranean buildings. It originates from the Islamic architecture and it is used especially to control natural light into the buildings. Actually, it has also the function to regulate the airflow into the indoor environment, mitigating the climate conditions and ensuring the comfort of inhabitants. For this reason, the research proposes the analysis of this system through modern computational tools and demonstrates that it can guarantee better indoor summer conditions, improving wind velocity and air change rate in the room.

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Peer-review under responsibility of the scientific committee of the 72nd Conference of the Italian Thermal Machines Engineering Association

Keywords: lattice windows ; passive cooling strategies ; natural ventilation ; re-interpretation of ancient techniques ; CFD simulations

1. Introduction

In recent years, it is very important to face climate changes and design architectures that are suitable to reduce the energy consumption from non-renewable sources.

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10.1016/j.egypro.2017.08.159

The ideas of bioclimatic architecture and the recovery of traditional knowledge have been extremely popular. The traditional architecture has often a better adaptation to climate than modern architecture. That is due to the materials as well as to the passive strategies used in the buildings.

Moreover, cooling of buildings, obtained with low environmental and energy costs, is now one of the main challenges in hot climate countries.

For this reason, the study of passive cooling systems, starting from traditional architecture examples, is very important in order to reduce the energy consumptions during summer, in the point of view of sustainability.

In particular, natural ventilation is a renowned as an ancient and cost-effective technique to cool indoor environments and manage thermal comfort in buildings [1]. At this regard, different ventilation strategies have always characterized the traditional architecture in the Mediterranean area.

In this context, the “mashrabiya” is a kind of window with carved wooden latticework that controls the passage of light and air flow, reducing the temperature and increasing humidity, besides ensuring privacy. It is a traditional element of the Arabic and Hispano Islamic architecture.

Some researcher studied the window shutters as tool for heat storage [2,3] and others investigated the mashrabiya in the point of view of natural lighting control and visual comfort conditions. Ruggiero et al. [4] affirm that the typical Islamic architectural façade meets two important aspect of vision. On the one hand, there is a physiological aspect, so that light does not cause any contrast, it does not give glare and assures the discernment of details; on the other hand, there is the psychological aspect: the system of holes made on the wall allows a view of the landscape outside and, thus, improves indoor work conditions psychologically.

Nevertheless, the two problems to be solved in hot climate are, at the same time, ventilation and protection from solar radiation. Standard windows cannot provide a solution to these two aspects and, therefore, the system of mashrabiya represents an opportunity to solve both of them. Almador et al. [5] studied similar kind of windows, the “Jaranas”, and demonstrated that they contribute to reduce the indoor temperature of about 1-2°C and are good strategies as ventilation tool. Moreover, the lattice performance improves when the blocked area increases, because air speed rises in the interstice area.

However, the way in which these systems can influence natural ventilation of buildings needs more investigation.

Therefore, the paper proposes the study of natural ventilation through a wooden lattice window to be installed in Mediterranean buildings, deriving the idea from a new prototype of mashrabiya, namely “The shutter”.

It was designed by a research group of Polytechnic of Bari [6] as a system of window inspiring to the examples of modern architectures, like Institut du Mond Arab in Paris by Jean Nouvel and Architecture Studio or Al Bahr Towers in Abu Dhabi by Aedas Architects. Two wooden fixed panels with dodecagonal holes contain wooden dodecagons that can rotate in order to provide natural ventilation or natural lighting control. One of the innovative aspects of this system is the possibility to control the regulation of the openings manually, by wooden levers (Fig. 1).

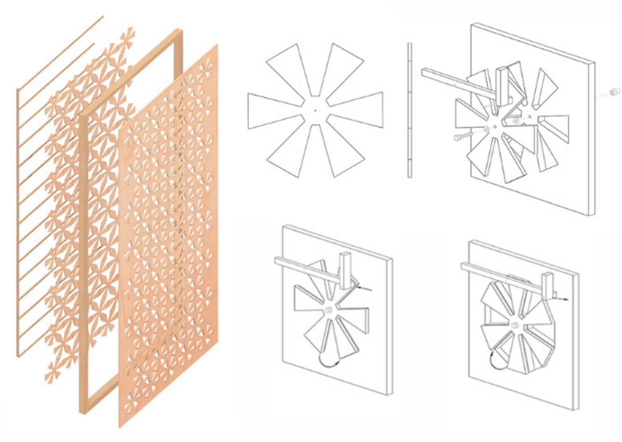

Fig. 1. The Shutter prototype: exploded view of a single module and kinematic mechanism of each mobile dodecagon. [6]

The system offers the possibility to filter the solar radiation and to improve the air change rate at the same time, combining functionality and aesthetic aspects. Consequently, the research tries to quantify the effect of such system on indoor conditions in terms of temperature and air velocity, through a three dimensional Computational Fluid Dynamics analysis.

2. Methods

In order to study the mashrabiya performance in terms of natural ventilation, a simple model of room without heating or cooling system were designed, changing the typology of the inserted window.

Four configurations were studied (Fig. 2).

In the first one, a standard opening, 1.2 m long and 1.1 m high, is installed in the windward south façade; the window surface is bigger than 1/8 of the floor surface, according to the Italian Ministerial Decree of the 5th July 1975 [7], about minimal height and mean health requirement in the houses.

In the other three hypotheses, a mashrabiya substitutes the window opening, with an increasing percentage of voids.

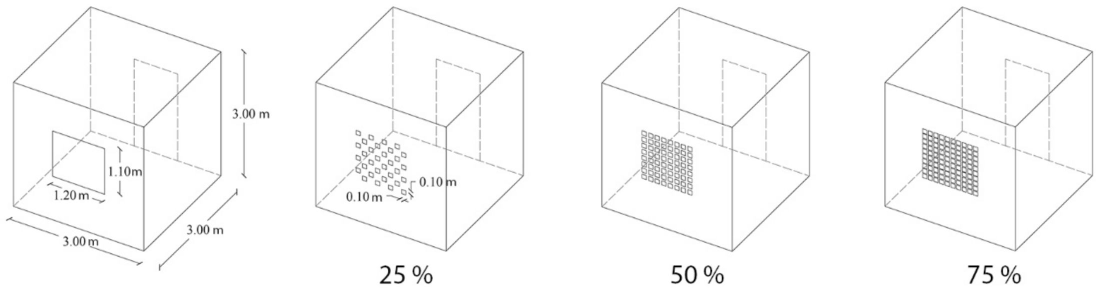

Fig. 2. Test room configurations with an opening or mashrabiya in the windward wall, changing voids percentage, and a closed door in the leeward wall.

The geometry of the mashrabiya was simplified through an equivalent system that has a varying percentage of empty respect to the wall (fraction of open surface), as well as the variability of the openings in the original Shutter. This hypothesis was necessary in order to evaluate the performance of the system through Computational Fluid Dynamics tools in a reliable way and to reduce the calculation time. The considered open surface fractions were 25, 50 and 75%.

The envelope components have high level of insulation, in order to respect the transmittance value according to the DM 26/06/2015 [8]. Table 1 summarizes the data related to thermal transmittance, also known as U-value, of the building envelope components.

Table 1. Features of the studied room

Feature	**Description**	**U (W/m^2K)**
Roof	Reinforced concrete hollow-tile floor, high insulation	0.29
Ground floor	Reinforced concrete hollow-tile floor	0.38
Opaque external wall	Cavity wall, with high insulation	0.32

The openings were considered always open in the models. The energy analysis was carried out through Design Builder software, a graphical interface of Energy Plus building energy simulation engine [9]. A typical summer week (from 27th July to 2nd August) was considered using climatic data of the city of Bari, located in Mediterranean climate zone, which belongs to group C in the Koppen climate classification.

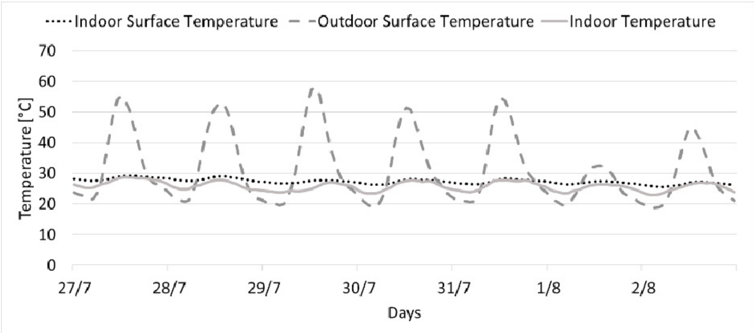

Figure 3. Trends of temperatures during the week of simulation (mashrabiya model).

The use of DesignBuilder software allowed us to combine thermal dynamic analysis with Computational Fluid Dynamics tool in order to evaluate the influence of this system on indoor conditions. Although the DesignBuilder CFD module provides only a snapshot of the fluid dynamic condition of the system, it takes into account the climate data, calculating the balance of fluxes and the surfaces temperature of each component. In this way, we obtained the temperature boundary conditions for the CFD analysis (Fig. 3).

The software imports these boundary conditions from the energy analysis of the model into the CFD module, providing results in terms of natural ventilation.

The continuity equation for mass transfer, the Navier–Stokes equation for momentum transfer and the thermal energy equation for heat transfer are the governing equations in Computational Fluid Dynamics that describe the flow field in the computational domain. [10] The governing equations are available in [11].

A three-dimensional, fully turbulent, and incompressible flow is assumed for the CFD simulation, using the Finite Volume Method (FVM) approach in agreement with many researchers that have studied CFD modeling of different strategies of natural ventilation in new and ancient buildings [12-15].

Among the different types of natural ventilation strategies, such as single-sided ventilation, cross-flow ventilation and stack ventilation [16], only the first one is analyzed in this paper in order to evaluate the performance of the shutter.

The flow path generated by single-sided ventilation is driven by two main effects, namely buoyancy effect and wind effect. Computational Fluid Dynamics (CFD) can be applied to single-sided ventilation in order to obtain detailed information about the flow and to calculate airflow rate for different configurations. In this sense, CFD can be considered as a potential alternative to full-scale experiments, because results can be considered reliable. Comparisons between single-sided ventilation experiments and CFD have shown the good potential of the application of CFD to single-sided natural ventilation, pointing out the influence of the turbulence model on final results [17].

The CFD simulation was carried out at 16:00 of 27th July. The choice of this moment is due to well defined reason: it is known that in the freshest hours of the day, with less solar radiation, the users open the window totally; on the contrary, the mashrabiya, as dynamic shading system, performs its full function during the sunny hours in summer, which are generally those of the early afternoon. In these hours, the windows are generally closed in order to avoid that the hot air comes indoor, but the consequence is a total lack of air change. The mashrabiya, instead, allows the air passage and, at the same time, provides shading against solar radiation.

As regards the boundary conditions, the wind speed is constant and equal to 5 m/s with South-West direction, derived from the climate data.

The average input temperature is of 28 °C, while the surface temperatures are equal to 29.32 °C for the roof, exposed greatly to solar radiation, 28.91°C for the East wall, 28.72 °C for the North one, 28.86 °C for the West one and finally 28.69 °C for the South one. All these boundary conditions are obtained from thermal dynamic simulation.

The adopted grid is structured with 250,000 cells and the internal flow was modeled by using the standard k– ε turbulence model.

It is one of the most widely used and tested of all turbulence models, belonging to the so-called RANS (Reynolds Averaged Navier-Stokes) models family. These models involve replacing the instantaneous velocity in the Navier-Stokes and energy equations with a mean and fluctuating component. The resulting equations give rise to additional terms known as Reynolds stresses and turbulent heat flux components. Reynolds stresses are replaced with terms involving instantaneous velocities where molecular viscosities are substituted for effective viscosities and a similar substitution is conducted for the energy equation. The effective viscosity is the sum of the molecular viscosity and a turbulent viscosity, which is derived from the turbulence kinetic energy (k) and the dissipation rate of turbulence kinetic energy (ε): k and ε are both derived from partial differential equations which are in turn derived from a manipulation of the Navier-Stokes equations.

3. Results and discussion

The CFD simulation reveals that the first studied configuration with a standard window has the worst performance (Fig. 4). The indoor air temperature in the room is greatest than the external one of about 0.65 °C. In fact, from the dynamic simulation, the indoor temperature is of 28.79°C while the outdoor one is of 28.14°C. The airflow in the room is extremely reduced, with a volumetric air flow rate of 43.25 l/s and the average velocity value is equal to 0.022 m/s, even because the wind direction is not perpendicular to the window. The maximum value is reached obviously near the window (0.093 m/s).

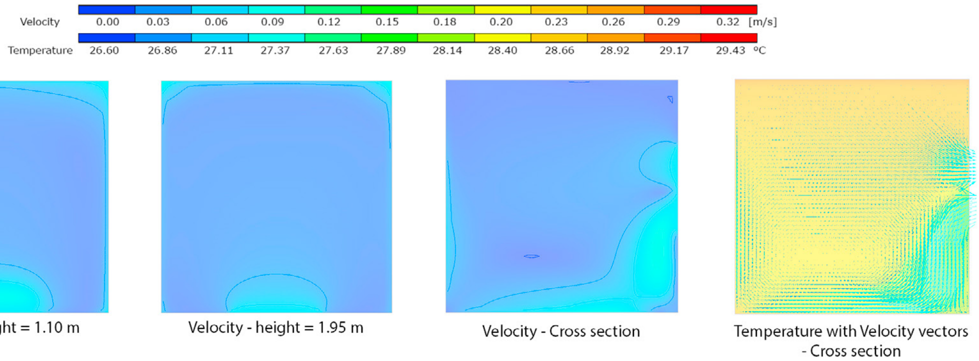

Figure 4. First configuration with standard window: distribution of velocity and temperature in the test room.

In the second configuration the mashrabiya is installed with a percentage of voids equal to 25% (Fig. 5) and the situation changes significantly.

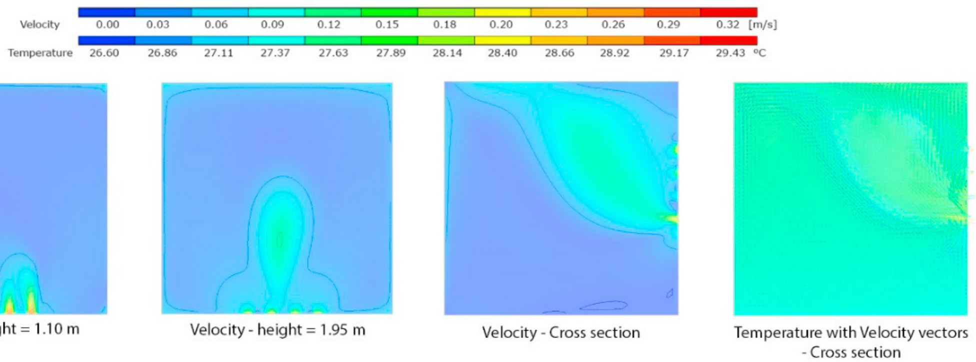

Figure 5. Second configuration with open surface fraction of 25%: distribution of velocity and temperature in the test room.

Even if, at the same wind speed, the input air flow is of 34.90 l/s, lower than the first case, the external air penetrates better in the room, both for the biggest velocity and temperature. The air speed reaches the peak of 0.29 m/s near the openings of the mashrabiya at 1.10 m height from the floor.

That is because the mashrabiya is characterized by a reduced inlet and outlet airflow sections (0.1 x 0.1 m) that contribute to the increase of the air speed.

The rise of velocity and temperature are strictly linked since the mashrabiya, contributing to the shading of the room, determines an internal temperature of 27.59 °C, 0.55°C less than the external temperature of 28.14 °C. Although the entrance of warm air in the room, the indoor temperature is lower than the first configuration (-1.2°C) and, at the same time, the system increases the air change and improves the air quality in the environment. Finally, the warm air from the outdoor goes upward in the room and does not invest the people without worsening the comfort conditions. In this way, the system provides, instead, a better and uniform air change in the room, which is the ideal condition to guarantee thermal indoor comfort.

In the third case, with the empty percentage of 50% (Fig. 6), the air flow rate is of 71.54 l/s and the indoor temperature is equal to 28.05°C, close to the outdoor one. The mashrabiya is less efficient as cooling strategy than the second case, but the air speed increases up to 0.29 m/s, near the lowest small openings of the mashrabiya. The air flow expands itself with a better air change rate, but the average velocity in the room is low, equal to 0.056 m/s.

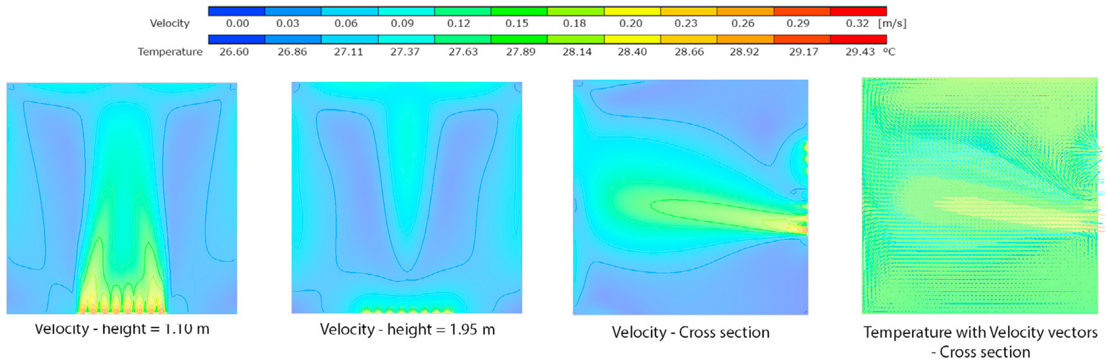

Figure 6. Third configuration with open surface fraction of 50%: distribution of velocity and temperature in the test room.

Finally, in the case of 75% of voids (Fig. 7), the inlet air flow is equal to 112.88 l/s, higher than the other case: the indoor temperature increases and reaches 28.40°C, slightly higher than the outside air of 28.14 °C, but minor than the first configuration.

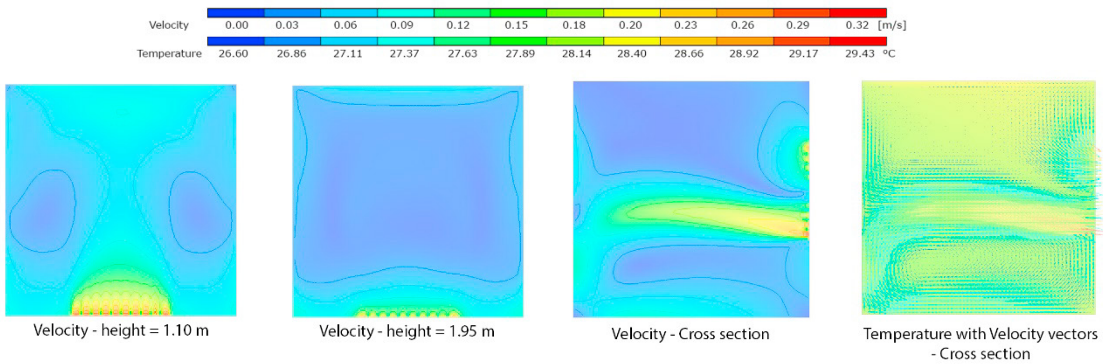

Figure 7. Fourth configuration with open surface fraction of 75%: distribution of velocity and temperature in the test room.

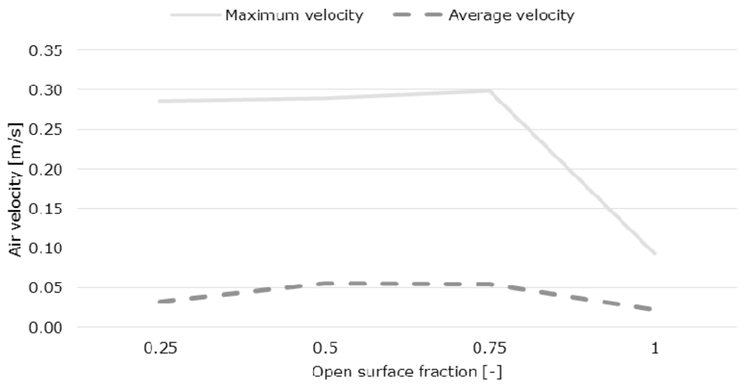

Figure 8. Comparison between the average and maximum air velocities according to the open surface fraction of the four different configurations.

The maximum velocity is of 0.30 m/s and the average one is of 0.054 m/s with a well-defined propagation direction inside the room.

Fig. 8 shows the trend of air velocity in the different cases, depending on the open surface fraction in the mashrabiya. The best values are achieved by the second and third configurations.

It is important to note that not only the velocity, but also the airflow rate change depending on the open surface fraction in the mashrabiya. Moreover, the second parameter seems to follow a parabolic and not a linear law depending on the openings percentage.

In this way, it is possible to optimize the opening of the studied system during the hottest hours of the day obtaining a right compromise from the point of view of natural ventilation.

4. Conclusion

The main goal of this study is to provide a preliminary study of the mashrabiya, derived from “The shutter” prototype, through computational fluid dynamics tools.

The CFD analysis gives the possibility to have an idea of system functioning in three-dimensional domain and considering the boundary conditions derived from a complete energy simulation.

Although, the study is performed for an isolated test room and not for a real situation, considering the windward façade provided of the window, it was demonstrated that this system can guarantee better indoor conditions, improving wind velocity and air change rate in the room.

Future research will study the effect of mashrabiya with more advanced and accurate tools and a measurement campaign will be necessary, in order to validate the model.

The study helps to understand how the mashrabiya can be a powerful tool for natural ventilation in buildings in hot summer, combining this strategy with the need of natural lighting control and shading. It demonstrates that the design principles of the past can be still effective in contemporary project. In fact, passive cooling strategies are sustainable design tools and can fulfill the future objective of limiting the use of plant systems that affect energy demand at local and global scale.

The simulation results demonstrate that the mashrabiya system works well during the hottest hours of the summer days. Generally, during these hours, it would be advisable to close the standard window to avoid that the warm air enters into the buildings. On the contrary, in the case of the shutter there was a different functioning: the geometry of mashrabiya allows protecting the indoor environment from solar radiation and the indoor temperature decreases respect to the case of standard opening.

Moreover, the system permits the entry of external air from the lower holes creating an upward flow movement and increasing velocity that is a fundamental factor to improve the indoor thermal comfort conditions.

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