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Different Strategies for Improving Summer Thermal Comfort in Heavyweight Traditional Buildings

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Abstract

In order to exploit the passive energy potential of the building envelope, it is important to provide a right combination of insulation thickness, heat capacity and night-time ventilation. In this paper, this issue will be tackled with reference to an historic building in Catania (Southern Italy). The building was built at the end of the XIX century, and its opaque envelope is entirely made with lava stones, which is typical of traditional architecture in this area.

Starting from the current configuration of the building, many hypotheses for refurbishment are considered, combined with different strategies for passive cooling, such as night-time ventilation, use of shading devices and adoption of highly-reflective coatings. The effectiveness of each solution in terms of summer thermal comfort is evaluated through dynamic thermal simulations carried out with EnergyPlus.

The results show the synergic effect of these strategies, as well as their individual impact, and allow to draw some general conclusions about the behaviour of heavyweight buildings under moderately hot weather conditions.

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Keywords: thermal comfort; thermal inertia; insulation; natural ventilation; solar gains

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1. Introduction

In summer conditions characterized by wide diurnal temperature variations, as learned from the historic traditional architecture and demonstrated by some studies [1-4], good indoor conditions can be achieved only by

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using a building shell with appropriate thermal mass and insulation level. Moreover, the compliance with the national building codes about thermal insulation is not sufficient to provide energy savings for space cooling [5], and the position of the insulating material in the outer walls represents a key issue [6].

The heat capacity of the building envelope has inspired many studies since dynamic numerical simulation became accessible. For instance, the works referenced in [7-11] report on the thermal behaviour of different heavy walls in simple case studies, under particular boundary conditions and for energy or economic purposes.

However, there are few works that take into account the thermal capacity of the building envelope, and its combination with the level of insulation, under the perspective of thermal comfort. In fact, as long as the building is controlled by an HVAC system, its transient behaviour is under-exploited and its potential for passive cooling masked or distorted. In this context, this paper will analyze the transient behavior of a massive building by looking at thermal comfort in summer, showing the best passive solutions for reducing/avoiding the risk of room overheating.

Nomenclature

ACH	air changes per hour [h^{-1}]
T_{op}	operative temperature [°C]
r	solar reflectance [-]
ITD	Intensity of Thermal Discomfort [°C·h]

2. Methodology

The main goal of this paper is to show how the thermal capacity of the building envelope, its insulation level, the use of blinds and of light colors for the external walls, as well as the adoption of appropriate ventilation strategies, are useful for improving summer thermal comfort in buildings. To this aim, a parametric approach was conducted in order to explore the individual contribution of each technical solution, and possible synergic effects.

The results of the simulations have been interpreted considering not only a classic parameter such as the operative temperature T_{op}, but also taking into account an indicator recently introduced in [12], namely the *Intensity of Thermal Discomfort* (ITD). The ITD represents the time integral of the positive differences between the current operative temperature and a threshold value that defines the upper limit for comfort:

$$ITD = \int_P \left(T_{op}(\tau) - T_{lim}\right)^+ d\tau \qquad (1)$$

In this study, the definition of the threshold value T_{lim} is based on the adaptive approach, as described in [13][14]; in particular, the threshold operative temperature corresponds to the upper limit of Category I, which is the most restrictive one. The threshold value is not constant in time, but it is updated daily as a function of the running mean outdoor air temperature [14]. In order to use this indicator, the building is simulated in a free-running mode to obtain the time profile of the indoor operative temperature. As the building is used for residential purposes, the calculation of the indicator is based on the 24-h profile of the operative temperature.

Moreover, in order to stress the transient behavior of the building envelope, no internal heat gains are considered. Thanks to this approach, the comparison between the different design solutions will be based on physical and measurable parameters, thus allowing an easy but comprehensive identification of the best strategies needed to achieve summer thermal comfort.

3. Case study

The building used as a case study is an historical three-storey building located in the city center of Catania, a hot humid city in Southern Italy (37°28'N, 15°3'E). The building is partially shaded on its northern, western and southern façades (see Fig. 1). As concerns its outer shell, the external walls are made of lava stones (70 cm), covered with a thin layer of lime plaster (2 cm per side); the roof is made of traditional “coppi” clay tiles (2 cm) that lie on a wood structure (3 cm), while the windows are timber-framed (3 cm) and single-glazed. The resulting U-values are 2.0 $W·m^{-2}·K^{-1}$, 1.8 $W·m^{-2}·K^{-1}$ and 5.8 $W·m^{-2}·K^{-1}$, respectively.

As mentioned in Section 2, no internal heat gains are considered, while a constant air change rate of 0.5 h^{-1} is assumed due to air infiltrations through the envelope; the thermal zone considered for thermal comfort analysis during the hottest days is that highlighted in red in Fig. 1. This is exposed due south-east and unobstructed, thus it shows the highest values of the operative temperature. The summer thermal comfort in this room is evaluated through dynamic energy simulations conducted with EnergyPlus. The dynamic behavior of the walls is simulated through the Conduction Finite Difference method, with a hourly time step.

Fig. 1. Axonometric view of the model with highlighted in red the thermal zone considered

4. Results and discussion

In the following subsections, the results of the dynamic simulations will be presented, splitting those concerning actions on the building envelope from those associated with occupant-driven actions, such as natural ventilation induced by opening the windows. Finally, the best combination of these actions for improving summer thermal comfort will be discussed.

4.1 Envelope strategies

A first set of simulations has been carried out to investigate the effect of the thickness and the position of a thermal insulating layer on the overheating sensation perceived by the occupants in summer. To this aim, a layer of extruded polystyrene is considered for simulation purposes, to be applied either to the inner or to the outer face of the external walls, and whose thickness is here assumed to be 4 cm or 8 cm.

The results are shown in Fig. 2a for the three consecutive hottest days of the year (from August 8th to August 10th). As it is possible to observe, the use of an insulating material always leads to an increase in the operative temperature during the central hours of the day; this increase is more evident (about 1°C) when the insulation material is applied to the inner face of the walls. This happens because the thermal mass is “hidden” by the insulation layer, and cannot be involved in the heat storage-discharge process, thus raising up the temperature inside the room. No significant differences are observed when varying the thickness of the polystyrene layer from 4 cm to 8 cm.

The thermal performance achieved by varying the thickness of the layer of lava stones in the external walls (40 cm, 50 cm and 60 cm, respectively) has also been analyzed in terms of operative temperature, but these results are not plotted because they were very close to those achieved by the base case (red dotted line). Indeed, increasing the thickness of the walls beyond a certain extent has almost no effect, as only a limited portion of the masonry is involved in the heat storage process.

Finally, other envelope solutions have been considered, namely:

- the insulation of the roof (4 cm of polystyrene to be applied to the inner face);
- the application of a highly reflective coating to the external walls (*r* = 0.80);
- the use of venetian blinds to shading the windows and reduce the solar heat gains.

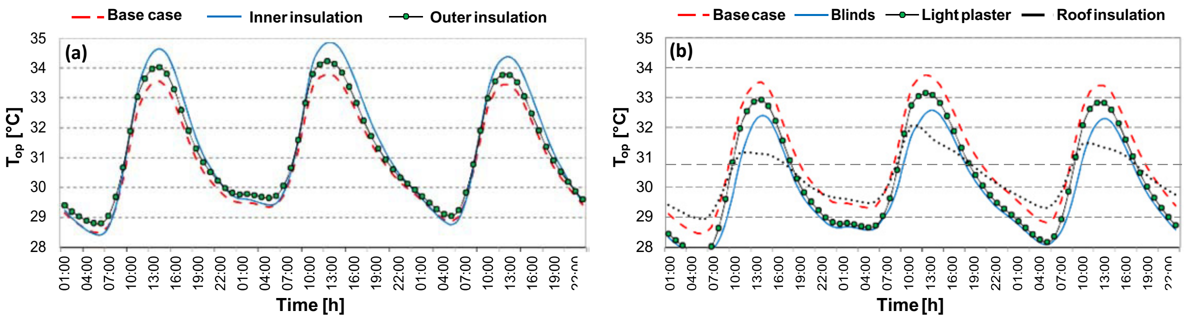

Fig. 2. (a) Operative temperature for different insulation levels; (b) Operative temperature for different envelope solutions

If looking at Fig. 2b, it is possible to observe how the best performing option for cutting the peak values of the operative temperature in the test room is the insulation of the roof, since a peak reduction by about 2°C is expected. This is understandable, since the roof is very lightweight and the zone considered in this study is placed at the last floor. The second choice in terms of effectiveness is represented by the application of venetian blinds to the windows, with plastic-made slats showing a solar reflectance r = 0.70, rotated by 45° with respect to the horizontal axis and separated from each other by a gap of about 12 cm. In this case, the expected reduction in the operative temperature is by about 1°C.

The application of a light-colored plaster to the building façades would only be able to reduce the operative temperature by about 0.5°C, given that the largest amount of the heat flux is incoming through the glazed surfaces.

4.2 Night-time ventilation

It is well-known that night ventilation is a very useful tool for passive cooling purposes when used in buildings with good thermal inertia. Indeed, the capacity of damping and delaying the thermal wave transferred through the outer envelope can be effectively exploited only if the heat accumulated during the day can be discharged at night, when the outdoor air is cool [15, 16]. In this paper, the natural ventilation rate is progressively increased from ACH = 0.5 h^{-1} (base case) to ACH = 4 h^{-1}, which is still considered achievable for the specific climatic and boundary conditions of the building site. The results of the simulations, in terms of operative temperature, are plotted in Fig. 3 and highlight how - when ventilation is active, i.e. from 22:00 to 06:00 - the operative temperature drops down by more than 2°C for ACH = 4 h^{-1}. If the ventilation rate is reduced to ACH = 1 h^{-1}, the beneficial effect on the operative temperature is smaller than in the previous case, but always above 1°C. In any case, natural ventilation at night induces an improvement in the thermal comfort also during daytime, as already remarked in [17].

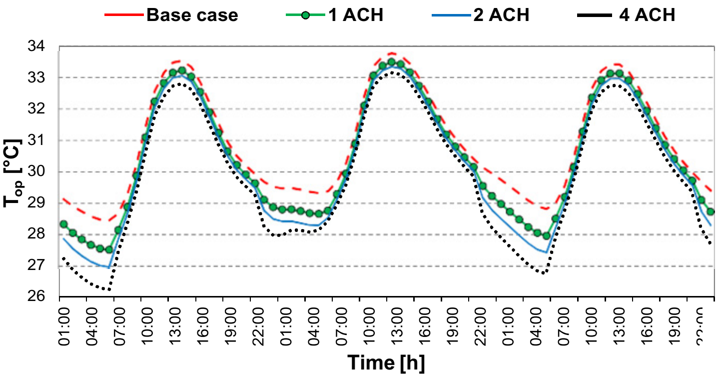

Fig. 3. Indoor operative temperature profile for increasing ACH values.

4.3 Comparison based on a wider perspective

If taking into account the whole summer season, and not only the hottest days, it is useful to refer to the ITD index. In fact, as explained in Section 2, this parameter considers the discomfort conditions due to overheating according to the Adaptive approach, which is more appropriate when dealing with free-floating conditions.

Figure 4 shows the values of the ITD index for each intervention described in the previous paragraph. This time, the ITD index is calculated for the entire building, thus highlighting the impact of each strategy on the building behavior. It seems that the use of venetian blinds is the best solution to improve summer thermal comfort, since it reduces the ITD by about 50% if compared to the base case, strictly followed by the roof insulation. This result stems from the shape of the building, as the roof surface is a significant amount of the total opaque envelope surface.

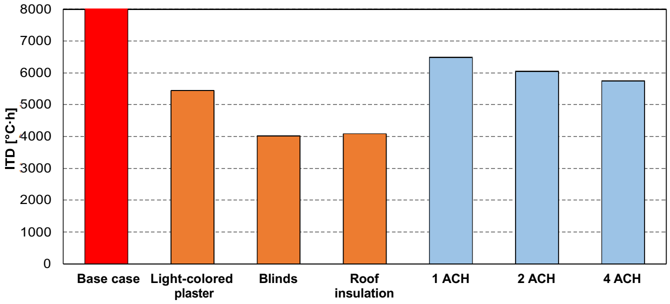

Fig. 4. ITD value for the singular interventions proposed

As concerns night ventilation, this is able to reduce the ITD by about 20% when ACH = 1 or 2 h^{-1}, while ACH = 4 h^{-1} can lead to a more consistent reduction (almost 30%). The application of a light-colored plaster to the outer walls gives results comparable to those achieved by nocturnal ventilation. Anyway, the best potential results obtainable are those deriving from a combination of the previously mentioned interventions, which are independent from each other and well suited for the case study. To this aim, three different scenarios have been compared:

a) roof insulation, application of a highly reflective coating to the outer walls and use of venetian blinds;
b) as in solution (a), but with the introduction of nocturnal ventilation (ACH = 2 h^{-1});
c) as in solution (a), but with the additional use of an external insulation layer (4 cm).

Fig. 5.b shows that, for each day in August within the room highlighted in Fig. 1, the hourly operative temperature – represented by the black circles – keeps within the range corresponding to comfort Category I, as defined in the EN Standard 15251. Similar results are obtained for scenario (a) and (c). This situation is far different from what observed in the base case (Fig. 5.a), where the operative temperature is very frequently higher the comfort threshold for Category I. Consequently, in terms of ITD the three proposed scenarios are very effective: the best results pertain to solution (b) (ITD = 0 °C·h), followed by solution (c) (ITD = 10 °C·h) and solution (a) (ITD = 22 °C·h).

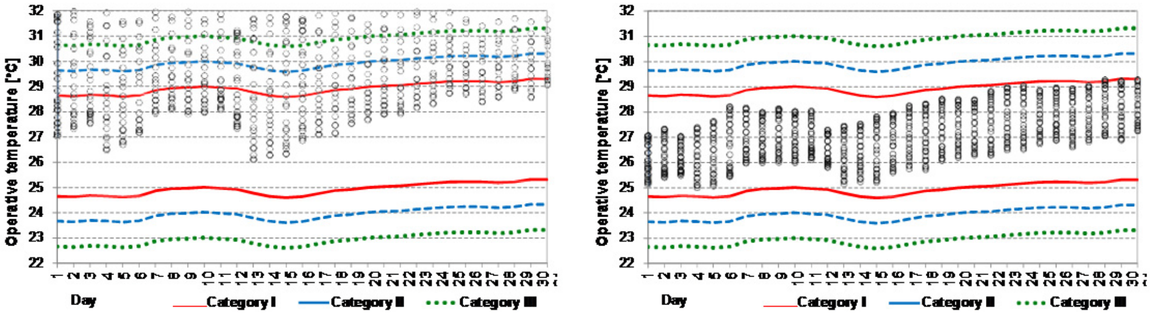

Fig. 5. Compliance to comfort categories of EN Standard 15251 in August for the Base Case (left) and for Case (b) (right)

5. Conclusions

The exploitation of the building thermal mass and of appropriate ventilation strategies have been often treated in an energy saving perspective, while few studies have been made in order to understand their individual and synergic effect on thermal comfort. In the present work, the effect of ventilation strategies, insulation thickness and thermal capacity of the envelope on thermal comfort is investigated by means of dynamic simulations for an existing heavyweight traditional building in Mediterranean climate.

As concerns the thermal capacity of the building envelope, in this case study this seems to have a slight effect on thermal comfort if not assisted by an appropriate ventilation strategy; in addition, a heavy structure seems more effective for improving thermal comfort when coupled with a small insulation layer. In fact, an excessive thickness of the insulation layer, despite being very effective for reducing energy needs in winter, is a cause of overheating and thermal discomfort in summer. In any case, the thermal capacity of the outer opaque envelope cannot be split from the exploitation of natural ventilation: the results of the dynamic simulations underline that night natural ventilation is essential to discharge the heat stored by the opaque envelope. The exploitation of natural ventilation is more effective than other passive cooling techniques, such as the use of reflective coatings. Anyway, a large part of the heat gains penetrates through the glazed surfaces, thus a good compromise between external shadings and night ventilation strategies should be found, with the support of dynamic simulations, to optimize the benefits achievable.

Further investigations are ongoing for predicting in a more accurate way the performance achievable by natural ventilation strategies and solar shadings in reducing both room overheating and building energy needs, also comparing the performance of traditional massive buildings with modern lightweight ones. The results will be reported in future papers.

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