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Influence of natural ventilation on the thermal behavior of a massive building

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Abstract

The aim of this paper is to evaluate the thermal behaviour of a massive building during summer period. Experimental investigations were carried out on "*Caserma Gaetano Abela*", an historical building located in Siracusa (Italy). The researchers have investigated the variation of both walls and indoor air temperatures in two rooms located on the east and west-facing sides. Two different experimental set-up were conducted, the first without allowing nocturnal ventilation, while the second with nocturnal ventilation obtained by opening the windows from 8:00 pm to 8:00 am. Based on the measurements of several physical parameters, the thermal lag and the decrement factor were calculated for the two ways of building ventilation management. The thermal comfort in the two offices was evaluated using the PMV and PPD indices. Results show that the high thermal inertia mass combined with natural ventilation reduces the indoor temperature during the nocturnal period, however the passive strategies resulted insufficient to obtain thermal comfort conditions during the following daytime hoursic correction. Globally it is possible to obtain an improvement of RT_{60} from 7.3 to 2.5 s at 1 kHz and *STI* increases from 33.0% to 40.0%, at 1000 Hz.

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1. Introduction

Traditional buildings were designed with features and thermal properties which took into account site-specific conditions through the adoption of passive strategies. In fact, the traditional buildings have historically proved to adapt to the external environment conditions with limited or no recourse to HVAC systems [1-5]. In particular, in the Mediterranean area, traditional buildings were commonly built using load-bearing massive masonry walls. This kind of envelope, characterised by a high thermal mass, guaranteed high thermal inertia and limited temperature

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swings. In recent years, many researches about the potential of natural ventilation in historical buildings located in different climate zones have been conducted. Axley and Emmerich proposed a method for assessing the suitability of natural ventilation in commercial buildings [6]. Roucoult et al. proposed a simplified characterization of thermal inertia, as part of the installation of a cooling system through night-time ventilation [7]. Yao et al. have carried out an investigation of the natural ventilation cooling potential of office buildings in five climate zones in China using the thermal resistance ventilation model [8], which is a coupled thermal and airflow model based on the British natural ventilation method with a four-node thermal resistance network model. Stazi et al. have studied the effect of high thermal insulation and high thermal mass over the dynamic behaviour in Mediterranean climates [9]. In all these studies, it is evident that the natural ventilation cooling potential is greatly influenced by the combined effect of the local climate, the thermal properties of the building, and the ventilation strategy. In this paper, an experimental survey conducted on the "Caserma Gaetano Abela", a massive building located in Sicily (Italy), is presented. This building was chosen because of the possibility to investigate the thermal inertia parameters in both East and West facing rooms. Moreover, since this building is located close to the sea, it was possible to evaluate the effects of the sea breeze. This study reports the results of the measurement campaign conducted during June and July 2014. The thermal lag and the decrement factor of the external walls were calculated considering two different ways of natural ventilation management. The indoor thermal comfort achievable exploiting the combined effects of thermal mass and nocturnal ventilation were finally discussed.

2. Material and Methods

Night ventilation consists of cooling the building through natural ventilation during the night, using the lower outdoor temperature as a heat sink. As a consequence, the cooled fabric can absorb more heat in the following day, and provide more comfort thanks to reduced indoor and wall superficial temperatures. It is common experience that the efficiency of night ventilation is enhanced by the building thermal inertia. In fact, the cooling loads of a building are closely correlated to the building thermal mass, as this facilitates an attenuation of the outdoor temperature peak, while maintaining the indoor conditions by absorbing the excess heat [10]. Buildings with high heat capacity show a reduction and a time delay of the peak cooling load [11,12]. In order to investigate the possibility to maintain thermal comfort conditions in the case study building by exploiting nocturnal natural ventilation, a campaign of measurements of several parameters was done. The parameters included inner and outer wall surface temperatures (Tsi, Tse), indoor air temperature (Ti), mean radiant temperature (Tr), relative humidity (RH), external air temperature (Te), and solar radiation (R). Two conditions of building management were investigated: the first with windows closed all the day, while the second with the windows opened from 8 pm to 8 am. The window opening strategy was selected considering that night ventilation cannot be combined with daytime ventilation as the last will reduce the temperature differences between indoor and outdoor, decreasing the effect of the mass heat sink. The measurements were conducted using a Babuc LSI-Lastem station (equipped with the air temperature sensor, black globe thermometric sensor, thermo-hygrometric sensor, and anemometer), and a heat-flux-meter Thermozig. The outdoor temperature and solar radiation were obtained by a local meteorological station. The two main parameters used to define the inertial behaviour of the wall were the thermal lag (φ) and the decrement factor (f). These two parameters were evaluated using the following equations [5]:

$$\varphi = \mathrm{t}(\mathrm{Tse}_{\max}) - \mathrm{t}(\mathrm{Tsi}_{\max}) \tag{1}$$

$$f = \frac{\mathrm{Tsi}_{\max} - \mathrm{Tsi}_{\min}}{\mathrm{Tse}_{\max} - \mathrm{Tse}_{\min}} \tag{2}$$

Other dynamic properties of the envelope were also calculated according to the international standard EN ISO 13786 [13], and compared with the results obtained by equations 1 and 2. In order to evaluate the thermal comfort, the authors adopted the PMV and PPD indices according to the International Standard ISO 7730 [14]. The Predicted Mean Vote (PMV) is the mean vote expected to arise from averaging the thermal sensation vote of a large group of people in a given environment. PMV is derived from the physics of heat transfer combined with an empirical fit to sensation. PMV establishes a thermal strain based on steady-state heat transfer between the body and the environment and assigns a comfort vote to that amount of strain. The PMV may be expressed by the equation:

$$PMV = \left(0,303xe^{-0,036M} + 0,028\right)L \quad (3)$$

In which M is metabolic rate (W/m^2) and L (W) is thermal load defined as the difference between the internal heat production and the heat loss to the actual environment for a person hypothetically kept at comfort values of skin temperature and evaporative heat loss by sweating at the actual activity level. The Predicted Percentage Dissatisfied (PPD) is a quantitative measure of the thermal discomfort of a group of people at a particular thermal environment. The PPD is related to the PMV as follows:

$$PPD=100-95e^{-\left(0,03353PMV^4+0,2179PMV^2\right)} \quad (4)$$

The software, PMV calc v2 was used to calculate the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied occupants (PPD) after [15] using data recorded by Babuc . In this study, the values used to assess the thermal comfort conditions refer to a sedentary activity (met = 1.2) and a set of light clothing (clo = 0.6).

3. The case study

The experimental measurements were conducted in the "Caserma Gaetano Abela", which was built in 1735. The building is located in Siracusa, on the coast of the island of Ortigia (37° 5'N; 15°16' E). It has a rectangular plan, 75 m x 54 m, with a floor area of about 2340 m^2, and an inner courtyard 46 x 38 m of about 1740 m^2. The building has three floors above the ground, with a total height included the pitched roof of 16 m. The walls are made of hard limestone bound with mortar of lime and sand. The thickness of the external walls decreases with height: being about 0.81 m at the ground floor, 0.73 m at the first floor, and 0.54 m at the top. Bricks or plasterboard are used for the interior partitions, which have an average thickness of 0.18 m. The measurements were performed in two rooms, located on the top floor of the building, with the external walls facing respectively the East and West directions (Fig. 1).

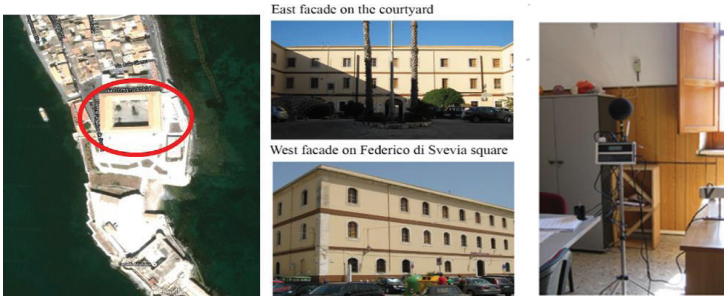

Fig. 1. The case study building Caserma GaetanoAbela: location (left); building façade (center); measurement equipment (right)

Table 1. Wall material composition and thermal transmittance

Layers	Conductivity [W/mK]	Thickness [m]	Density [kg/m^3]
Lime and gypsum plaster	0.700	0.020	1400
Extra soft limestone	0.850	0.500	1600
Lime and gypsum plaster	0.700	0.020	1400
Calculated U-value	1.226 [W/m^{2}K]		
Measured U-value	1.340 [W/m^{2}K]		

The first monitored room has dimensions of 4.60 m x 3.84 m and height of 3.95 m, it overlooks the East side of the courtyard. The second monitored room has dimensions of 5.10 m x 3.95 m and height of 3.95 m, and faces the square in front of the building on the West side. Each room has one window located in the middle of the wall, with dimensions 1.50 x 1.84 m. The windows have single 2 mm glass with inner wooden shutters. Table 1 shows the walls material composition and thermal transmittance (U-value) calculated and measured through the heat flux meter. The rooms were unoccupied during the campaign of measurements and, the doors were closed for all the periods of measurements to avoid interference and reduce the airflows from others zones of the building.

Consequently, a single sided ventilation was generated. In the preliminary phase, thermography testing was performed in order to identify homogeneous zones. As prescribed by UNI ISO 9869, the process to acquire data through temperature sensors and heat flux sensors lasted several days.

4. Results

Figures 2 and 3 display some of the results of the measurements campaign for the two rooms without nocturnal ventilation. The meteorological conditions during the periods of monitoring were substantial similar, with clear sky, maximum value of global horizontal irradiance of about 3.3 MJ/m^2; outdoor air temperature ranging between 18.0 to 28.0° C, which are typical values of the summer period. The comparison of the superficial outer temperatures (Tse) on the East and West walls evidences a substantial difference between them. Indeed, the Tse on the East reaches its maximum value at about 10:00, coherently with the highest solar radiation on this façade, while the Tse on the West wall reaches its maximum value at 19:00, with the highest values solar radiation on this façade.

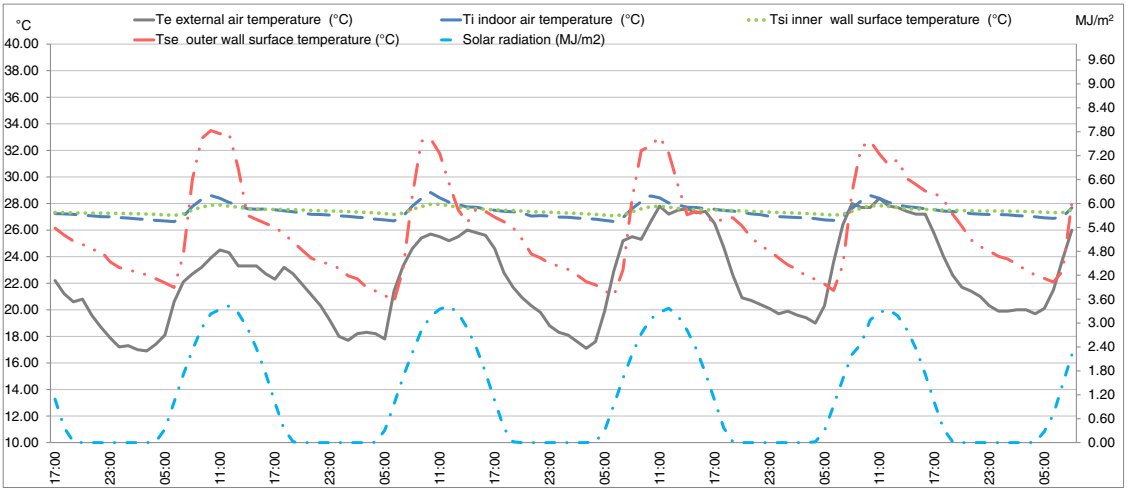

Fig. 2. East room measurements (19/06 – 24/06) - no nocturnal ventilation.

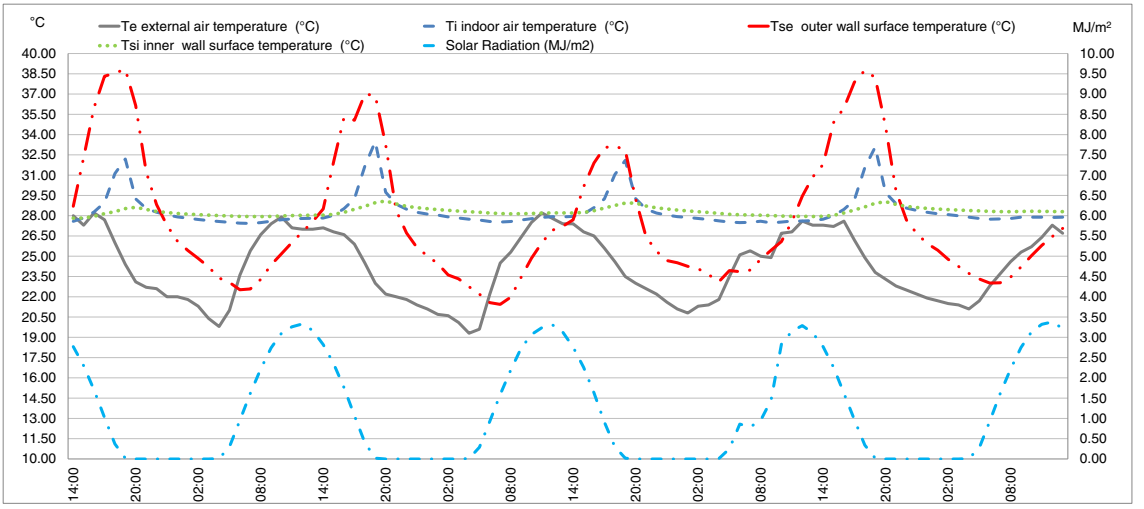

Fig. 3. West room measurements (1/07– 04/07) - no nocturnal ventilation

Moreover, Tse reaches the highest values on the West façade, of about 38.5 °C, versus 33.5 °C on the East façade;

this means that a 5° C temperature difference between the two façade. This results confirm the well-known criticism of the façade toward West. Instead, the minimum values of Tse are comparable for both the orientations. The superficial inner temperatures (Tsi) pointed out very little variations, limited within a range of about 1°C that is an evident consequence of the high thermal inertia of the walls. The max value of Tsi is reached more or less one hour later the peak of Tse, for the two walls (East and West) and, on the West wall is about 1°C higher than Tsi on the East wall. Therefore, through eq. (1) the thermal lag results of about 25 h, while the decrement factor results of about 0.06. As regard the indoor air temperature, it reaches its maximum value almost in concomitance with Tse. This is due to the effect of the solar radiation that hits and warms the internal partition, which has low thermal capacity. Even if the thermal lag and decrement factor are the almost the same for the East and West faced, a greatest discomfort is registered inside the West room from 8:00 a.m to 6:00 p.m (PMVmean value=+3.9; PPDmean=80) respect to East room (PMVmean=+1.6; PPDmean=56.3%).

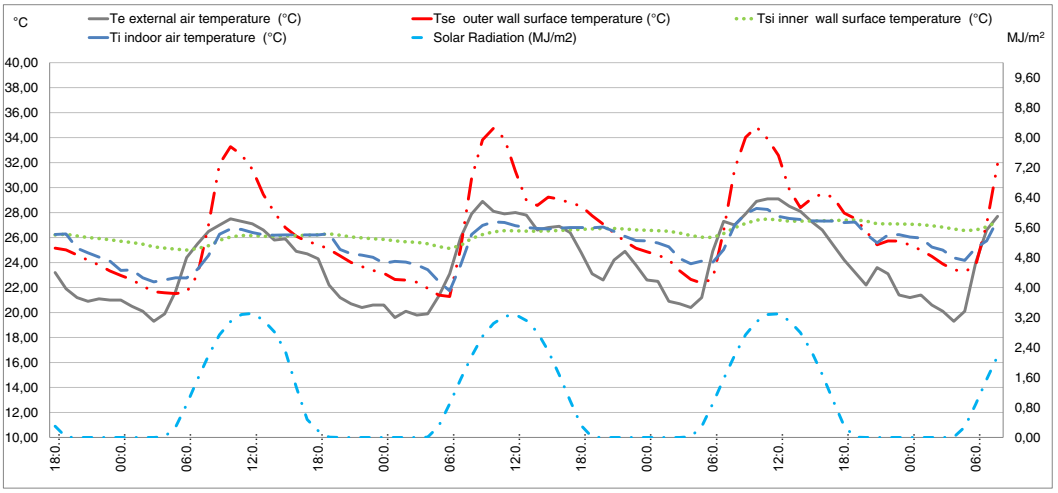

Fig. 4. East room measurements (9/06 – 13/06) - nocturnal ventilation.

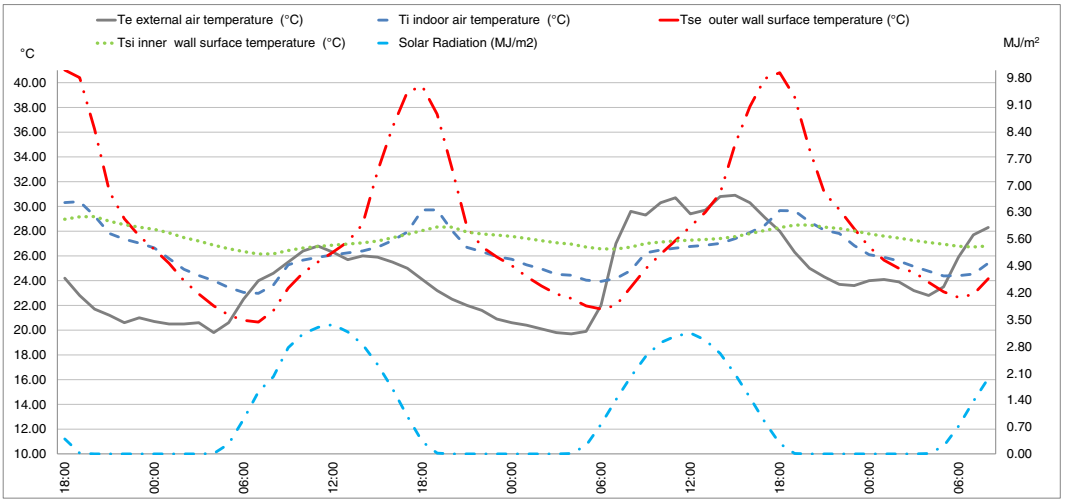

Fig. 5. West room measurements (27/06 – 01/07) - nocturnal ventilation.

Figures 4 and 5 illustrate the results of the measurements for the two rooms when the nocturnal ventilation was allowed. The outdoor conditions during the periods of monitoring were almost the same registered during the other periods of survey. The comparison of the superficial outer temperatures (Tse) on the East and West confirms the

substantial difference between the two orientations. The figures show that the nocturnal ventilation influences mainly the variation of Tsi and Ti and its effect is different on the two rooms. The max value of Tsi on the East wall is reached more or less at 8:00 pm in concomitance with the beginning of the nocturnal ventilation, which cools the inner surface of walls and interrupts its heating. The thermal lag results around 10 h, while the decrement factor results around 0.08. As a result, the nocturnal ventilation interferes with the thermal inertia of the wall and causes the reduction of the thermal lag. This is correlated with the beginning of the nocturnal ventilation. The cooling effects related to the ventilation can be better highlighted observing the profiles of the indoor air temperature. Indeed, Ti decreases quickly when the outdoor air enters into the room. The maximum value of Tsi on the West wall is reached at 8:00 pm, in concomitance with the beginning of the nocturnal ventilation. Therefore, through eq. (1) the thermal lag was of about 1 h, while the decrement factor was of about 0.12. From the point of view of the energy needs, it is possible to observe that the nocturnal ventilation allows maintaining the indoor temperature lower than 26° C from 8:00 pm to 8:00 am within the East room and from 11:00 pm to 9:00 am in the West room. Once more, the West façade confirms its worst performance although mitigated by means the natural ventilation. During daytime hours, it was not possible to guarantee adequate comfort conditions. Finally, the following indexes were calculated in the two rooms from 8:00 a.m to 6:00 p.m : PMV_{mean}=+1.4 and PPD_{mean}=45.5% in the East room, and PMV_{mean}=+3.3 and PPD_{mean}=70% in the West room.

5. Conclusions

The objectives of the present research is the characterization of the thermal behavior of massive buildings by exploiting both the contribution of thermal inertia and natural ventilation. With this aim, an experimental survey was conducted during the hot period in an historical massive building situated in Southern Italy. The results of measurements have allowed calculating, in both at West and East-facing sides, the thermal lag and the attenuation factor allowing or not nocturnal ventilation. It can be noticed that the ventilation interacts with the thermal response of the building modifying the thermal lag. This study has confirmed that high thermal mass and nocturnal air ventilation allowing cooling the indoor space in the case study maintaining the indoor temperature lower than 26°C during nighttime. However, high thermal inertia and nocturnal ventilation are not sufficient for guarantying well-being conditions during daytime hours.

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