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Assessment of the dynamic thermal performance of massive buildings

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ABSTRACT

The aim of this paper is the evaluation of the thermal behavior of a massive building under the synergic combination of natural ventilation and thermal inertia. In particular, an experimental study has been carried out on Villa San Saverio, which is a massive historical building located in Catania (Italy), in order to characterize its thermal performance under dynamic conditions, and to evaluate the potential decrease of the indoor overheating by exploiting natural ventilation and limiting both internal and solar gains.

The analysis of the transient behavior of this building permits to highlight the possibility of diversifying the time lag in relation to the wall orientation. A time lag of 12.00–14.00 h can be suggested for the walls due East. On the other hand, a time lag of around 8.00 h can be suggested to achieve the same result for the walls due West.

Time lags higher than the values suggested above could be not fully functional, since delaying further the heat transfer from the wall to its inner surface, reduces the useful time for exploiting the cooling effect of the nocturnal ventilation.

The results of both measurements and simulations indicate that high thermal inertia mass combined with natural ventilation prevents phenomena of overheating and ensures good comfort levels in occupied buildings, reducing the needs of cooling systems during summer period.

1. Introduction

Strategies to optimize the building envelope have become of outstanding importance as they can help to minimize heating and cooling energy demand and may lead to the downsizing of heating and cooling systems, or even almost eliminate the energy needs. Moreover, energy performances of building also depends on the degree of protection from solar gains, the internal heat sources and the way the natural or forced ventilation is organized and controlled [1].

As an example, the overheating that often occurs in hot periods may be reduced by controlling the heat load due to solar radiation through an appropriate building orientation, solar shadings, smart windows, ventilated structures [2], thermal inertia factors, nocturnal ventilation and so on.

One well known strategy for reducing the energy needs of ACs consists in cooling the structural mass of the building by means of nocturnal ventilation. Many studies have investigated the effect of night ventilation for building cooling in summer [3–8].

Actually, the thermal behavior of the building envelope strongly depends by the interaction between thermal inertia, insulation and ventilation strategies [9].

Cooling loads are extremely variable during the day and closely correlated to the building thermal mass. Structures with higher heat capacity contribute to the reduction and the time delay of the cooling peak load [10–12]. However, the effectiveness of the interaction between thermal mass and night ventilation as a passive cooling strategy strongly depends on the temperature swing at the site [13]: the positive effects of thermal inertia are more enhanced in climates where the diurnal variation of the external temperature is above 10 K, as the mass of the building would help to reduce the outside peak of temperature and to keep the internal conditions within the comfort range by absorbing the excess of heat [14]. However even lightweight construction could benefit from natural night-ventilation [15]. The energy saving potential associated with the use of an adequate inertia ranges from a few percentages to more than 80% [14,15,16,17].

Thermal inertia of buildings has a positive effect on the indoor conditions also during winter period. In fact, the energy available from the solar gains and internal gains during the day is stored and then slowly released into the indoor environment at a later time, when there is a need for it, thus satisfying part of the heating load [18]. The higher is the thermal inertia of a building, the slower is the rate at which its indoor temperature rises and drops.

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Nomenclature

A	amplitude of the heat wave (K)
a	volumetric thermal capacity (J m^{-3} K^{-1})
a_t	thermal diffusivity (m^2 s^{-1})
b	effusivity (J m^{-2} K^{-1} $s^{-0.5}$)
C	specific heat (J kg^{-1} K^{-1})
F	view factor (–)
f	decrement factor (–)
G	solar irradiation (W m^{-2})
h_c	convective heat transfer coefficient (W m^{-2} K^{-1})
h_r	radiant heat transfer coefficient (W m^{-2} K^{-1})
h_0	equivalent heat transfer coefficient (W m^{-2} K^{-1})
I	solar irradiance (W m^{-2})
N	cloud cover (okta)
Q_m	amplitude of the specific heat flux (W m^{-2})
Q_{in}	heat flow between the wall and the indoor environment (W)
Q_{ex}	heat flow between the wall and the external environment (W)
Q_{Wst}	heat stored (lost) (W)
q_r	radiant component of the heat flux (W)
q_c	convective component of the heat flux (W)
T	temperature (K)
U_{value}	thermal transmittance (W m^{-2} K^{-1})
Y	periodic thermal transmittance (–)
V_{w}	parallel component of wind velocity (m s^{-1})
V_{f}	free-stream wind velocity (m s^{-1})

Greek letters

α	absorption coefficient (–)
ε	thermal emissivity (–)
λ	thermal conductivity (W m^{-1} K^{-1})
θ	amplitude of temperature fluctuation (K)
ρ	density (kg m^{-3})
φ	time lag (h)
σ	Stefan–Boltzmann constant (W m^{-2} K^{-4})
τ	time (h)

Subscripts

as	sol–air external temperature
e	outdoor
i	indoor
l	long wave radiation
m	mth thermal zone
max	maximum
min	minimum
mr	mean radiant
n	nth thermal zone
s	short wave radiation
si	inner surfaces of the wall
se	outer surfaces of the wall
sky	sky temperature

Although natural ventilation is apparently the simplest and cheapest option to cool buildings, it is also very difficult to control, since the driving forces, and thus the air flow rates, vary constantly with the weather [19,20].

In this paper, the thermal behavior of Villa San Saverio, an historical building located in Sicily and characterized by a massive envelope, has been investigated.

This particular building was chosen because its wall structure is typical of many historic buildings built in the period we between the nineteenth century and the mid-twentieth century. Moreover the building has the peculiarity of having the facades exposed both versus East and West. In addition, this building was not occupied during the period of survey, thus it was possible to make all the experimental investigations in absence of internal loads and solar gains, as well as to control the period of room ventilation.

Actually, one of the objectives of the study is to evaluate the capability of historical massive buildings to maintain, thanks to their inherent thermal inertia, adequate internal comfort conditions, thereby avoiding to perform invasive interventions of energy retrofit. Such objective is a crucial issue, especially in the Mediterranean climate [21,22].

The study reports the results of the experimental measurement campaign conducted during summer, which permitted to determine the time lag and the decrement factor of the envelope, and to evaluate the benefits on the indoor thermal comfort deriving by the combined effects of thermal mass and nocturnal ventilation of this historical massive building.

The novelty of this work is that allows to highlight the different thermal response of facades having the same configuration, but with different orientation, and how this may induce different ventilation strategies for free cooling.

2. Thermal inertia factors

Thermal mass can be regarded as a passive conditioning system (heating/cooling), which is able to temporarily keep the excess of heat, thus allowing it to be removed during the night.

The main thermal properties correlated to the process of heat storage are: thermal conductivity (k), specific heat capacity (c), density (ρ) and thermal diffusivity (a_t).

The thermal diffusivity is a function of the other three above mentioned properties, and it is defined by the thermal conductivity divided by the volumetric heat capacity:

$$a_t = \frac{k}{\rho c} \tag{1}$$

Materials with high thermal diffusivity rapidly adapt their temperature to the surrounding temperature, because they conduct heat quickly in comparison to their volumetric heat capacity or 'thermal bulk'. Periodic swings of the environmental temperature (thermal excitation) during a 1-day period generate a heat wave that flows through the wall from outside to inside. The depth that the diurnal heat wave reaches within the storage material mainly depends on the thermal diffusivity.

In order to characterize the thermal inertia of the building envelope some *dynamic factors* can be used, namely the *time lag* (φ) and the *decrement factor* (f) [23,24].

Their definition in relation to a heat wave propagating through a wall, with a period $P = 24$ h, is schematically depicted in Fig. 1: the time lag is the time differences between the peaks of the temperatures at the outer and inner surface, whereas the decrement factor is the ratio of decrease of the amplitude during the process above mentioned. In this study, the time lag (φ) and the decrement factor (f) are computed by the following equation [25]:

$$\varphi = \tau(T_{\text{si\_max}}) - \tau(T_{\text{se\_max}}) \tag{2}$$

$$f = \frac{A_{\text{si}}}{A_{\text{se}}} = \frac{T_{\text{si\_max}} - T_{\text{si\_min}}}{T_{\text{se\_max}} - T_{\text{se\_min}}} \tag{3}$$

where $\tau(T_{\text{se\_max}})$ and $\tau(T_{\text{si\_max}})$ represent the time when the outer and the inner surface temperatures reach their peak value, respectively, within a period of 24 h.

Furthermore, A_{si} and A_{se} are the amplitudes of the heat wave measured at the inner and the outer surface of the wall, respectively.