Journal of Sustainable Development of Energy, Water and Environment Systems

http://www.sdewes.org/jsdewes

Year 2020, Volume 8, Issue 3, pp 508-519

The Effect of a Naturally Ventilated Roof on the Thermal Behaviour of a Building under Mediterranean Summer Conditions

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Cite as: Ramos, J., Aires, L., The Effect of a Naturally Ventilated Roof on the Thermal Behaviour of a Building under Mediterranean Summer Conditions, J. sustain. dev. energy water environ. syst., 8(3), pp 508-519, 2020, DOI: https://doi.org/10.13044/j.sdewes.d7.0297

ABSTRACT

With the increasing cost associated with energy consumption, climate change and the greater awareness of the population to issues related to energy and environmental efficiency, energy conservation in buildings has been encouraged, along with the development of several solutions based on a more sustainable construction. Building cooling is the most challenging issue in the Mediterranean climate. The roof is one of the main elements of the building's opaque envelope, where the choice of materials and the implementation of appropriate passive technologies determine the thermal performance of a building. The present work aims to assess the impact of natural ventilation of a roof cavity on the thermal environment of a dwelling house under Mediterranean summer conditions. An experimental study was developed in a small-scale prototype of a typical dwelling house, comprising a ceramic tile roof with vented eaves and insulated sub-tile panels according to the construction solution of the Humbelino Monteiro SA company. The thermal performance of this roof solution was assessed under real climatic conditions based on continuous measurements of the air velocity inside the air gap, the temperature of the air and the surface temperature of all roof layers. Weather conditions were also monitored continuously. Connected with the heat transfer mechanisms, the obtained temperature and air velocity profiles data were analysed and discussed.

KEYWORDS

Ceramic tile roof, Energy performance of buildings, Natural roof ventilation, Passive cooling, Experimental study, Sustainable construction.

INTRODUCTION

Building cooling is one the most challenging issues in warm weather conditions [1-3] and its demand is expected to increase over the next decades due to the climate change and population growth [4]. Building cooling can be achieved by using active and/or passive solutions with different costs, maintenance and energy consumption [5].

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Nowadays, inexpensive and environmentally sustainable solutions like passive solutions are of utmost importance.

Mediterranean climate is very challenging, especially in summer due to the strong solar radiation and high ambient temperatures. The large daily range of temperature during the summer promotes a considerable potential to exploit passive strategies for building design. The incorporation of passive technologies in designing a roof allows to look at external conditions not as undesirable external agents but as useful resources on curbing the energy requirements for heating and cooling a building [6, 7]. Designing a performing envelope is therefore a key element both to reduce the energy need and to improve occupants' comfort conditions in buildings [e.g. 8-10].

Passive ventilation of a roof or an attic has become one of the greatest interests for building researchers in the last several decades. It is possible to design and construct a roof to act as a passive solar cooling system, that pull interior building air through it to induce natural ventilation [11]. In the cooling of a roof by natural ventilation, induced air movement by solar irradiation must be highly enhanced [12, 13]. Then, in a roof's natural ventilation, the buoyancy of hot air should be considered. This self-induction force acts favourably even when wind force is not available. In order to remove accumulated hot air from an attic, one of the most effective strategy is a combination of ridge and soffit vents [14-16]. Moreover, insulation under the roof or above the ceiling has shown good results in reducing the attic temperature in several passive roof designs [17, 18]. The use of cool materials for roof covering [19-21] or green roofs [22-24] can also provide a great thermal benefit.

Previous experimental and/or numerical studies have demonstrated that the ventilated roof approach is adequate for warm climates. Soubdhan *et al*. [25] tested four small-scale test cells with roofs of corrugated iron sheets. They aimed to understand the effect of using different insulating materials, different roof colors and ventilation of the roof air layer on the heat flux reduction through the roof. Their results showed that 86% of the heat was transferred through the roof by radiation and ventilation was fundamental to evacuate the heat, improving the performance of the insulation material (namely when using a radiant barrier). Campi *et at*. [26] studying roofs with small-sized-thickness duct with laminar air flow concluded that energy saving could be higher than 30% using ventilated roofs when comparing with the same non-ventilated structure. A significant improvement in performance was also achieved in a full-scale ventilated roof component, when compared to a non-ventilated roof component [27]. Athmany and Sriti [2] carried out an experimental study on four test cells during a hot and dry month, where three cells were used to analyze the thermal performance of a cool roof (reflective coating), a ventilated roof and a roof with inverted earth pots. Although the cool roof showed the best results, they concluded that the ventilated roof combined with natural ventilation promotes the fast cooling of the building. Gagliano *et al*. [28], using Computation Fluid Dynamics (CFD) demonstrated that the cooling loads of a building could be reduced up to 50% by ventilation of the roof using insulation under the air layer in respect to a non-ventilated roof with the same thermal resistance. In other numerical analysis, Li *et al*. [29] found a strong delay in indoor temperature using the roof ventilation approach, although the air layer thickness, the roof slope and the exhaust outlet size played an important role in the thermal performance of the ventilated roof. Other numerical studies have shown the benefits of using a ventilated roof [13, 30-32]. Recent recommendations on passive design for hot climates includes the use of reflective cool roof and ventilated roof or openings on the roof to remove the heat from the building [33].

The present work aimed to assess the impact of natural ventilation of a roof cavity with insulated sub-tile panels on the thermal environment of a dwelling house under Mediterranean summer conditions. The performance of the natural ventilation was assessed continuously on a test cell built according to the construction solution and experimental test goals of the Humbelino Monteiro SA company, under summer variable weather conditions. Measurements of the air velocity inside the air gap, the temperature of the air and the surface temperature of all layers of the roof were performed, to characterize this passive technology and its relevance to the improvement of indoor thermal comfort.

MATERIALS AND METHODS

A test cell, based on the construction solution of the Humbelino Monteiro SA company, was built at Campus 2 of the Polytechnic of Leiria, Portugal (+39° 44´, −8° 49´). It is a scaled-down model prototype of a typical dwelling house with a non-ventilated insulated attic and a roof with vented eaves. The prototype was built with a floor area of 4.6 m^2. The structure consists of masonry walls of 0.3 × 0.19 × 0.29 m^3 thermal bricks, with 15.5 kg/piece and 0.7 $Wm^{-2}\,°C^{-1}$ of global heat transfer coefficient, covered by a 15 mm layer of mortar. The indoor test cell space was further divided in two compartments by a 4 cm thick extruded polystyrene board (XPS: 0.04 $Wm^{-1}\,°C^{-1}$ thermal conductivity) to create a non-ventilated insulated attic (Figure 1a).

Afterwards, the roof was supported directly on the masonry walls, with length of 2.5 m and 30% slope and oriented to the south in order to maximize solar gain. The first layer of the roof consists of insulated sub-tile polyurethane panels (Naturtherm, Humbelino Monteiro SA), with a factory global heat transfer coefficient of 0.33 $Wm^{-2}\,°C^{-1}$ (Figure 1b). Naturtherm are 2,500 mm long and 1,100 mm wide panels with a weight of 41.40 kg each. Naturtherm panels are insulated by a layer of 40 kg/m^3 of polyurethane located in the middle each panel. The top of the panels consists of a 100% asbestos-free fibrocement board and the bottom is composed by an aluminium coating. The panels have a maximum thickness of 86 mm and a wavelength of 177 mm (Figure 2).

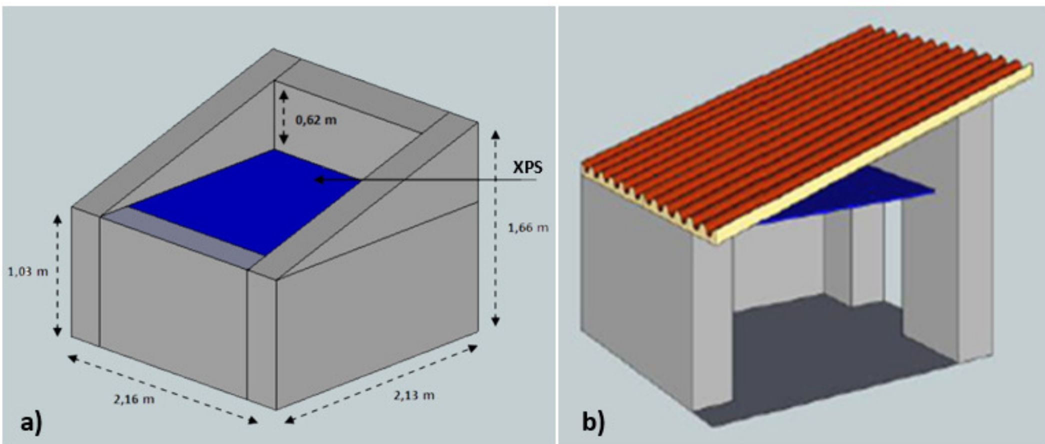

Figure 1. Test cell dimensions with the non-ventilated insulated attic of extruded polystyrene: XPS (a) and Naturtherm panels over the masonry walls (b)

The second layer of the roof is composed by ceramic roof tiles of red color (Advance Lusa, Humbelino Monteiro SA), mounted on battens with 38 cm distance between them, fixed on the Naturtherm panels (Figure 3). The ceramic tiles have 445 mm length, 249 mm width and 3,150 kg of weight.

As consequence, between the two roof layers, the air-gap channels have a maximum radius of 8.7 cm of thickness.

To characterize the dynamic regime of heat transfer in the roof, the temperature on the surfaces of every material of the roof, in the air-gap (between tile and insulated sub-tile panels) and inside the test cell were measured continuously by a set of sensors during summer conditions (from May to July).

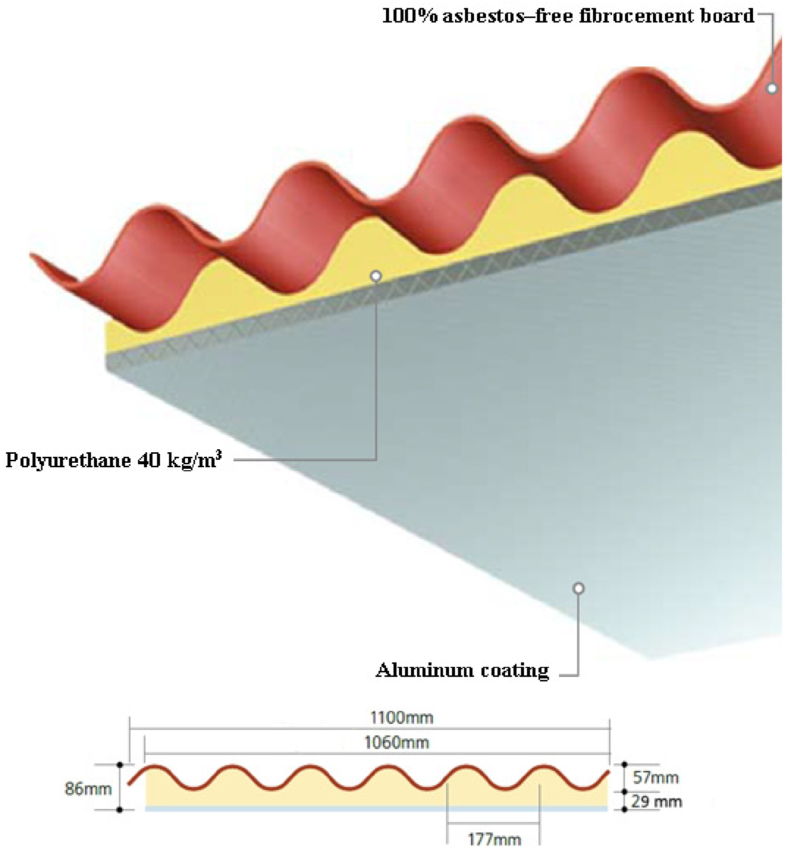

Figure 2. Details of the Naturtherm panels

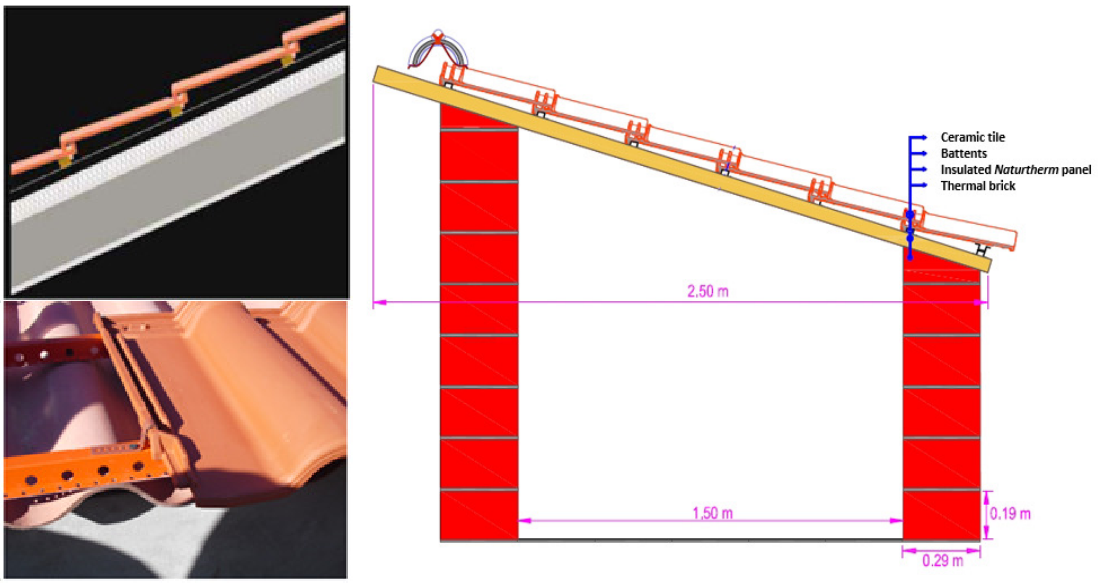

Figure 3. Ceramic tile roof with vented eaves, air-gap and insulated sub-tile panels

The air cavity in the middle section of the roof was equipped with three air temperature sensors (LogTag® TRIX-8 recorders: better than ±0.5 °C accuracy), spaced $\Delta Z = 0.6$ m (Figure 4).

The LogTag® Analyzer software was used to configure the acquisition and download of data from each LogTag® recorder. The air flow velocity in the air cavity (air-gap) of the middle section of the roof was measured by an Airflow meter of 60 mm fan diameter (0.01 ms^{-1} resolution), located at the top of the roof (Figure 5a). Data from the Airflow meter were recorded by a multifunction data logger (Testo 435). The temperatures on the sub-tile panel and tile surfaces were measured by 3 type K thermocouple sensors (±0.3 °C accuracy, 0.1 °C resolution) in each surface (Figure 5b). The average temperature from each set of 3 sensors was recorded in other multifunction data logger (Testo 435).

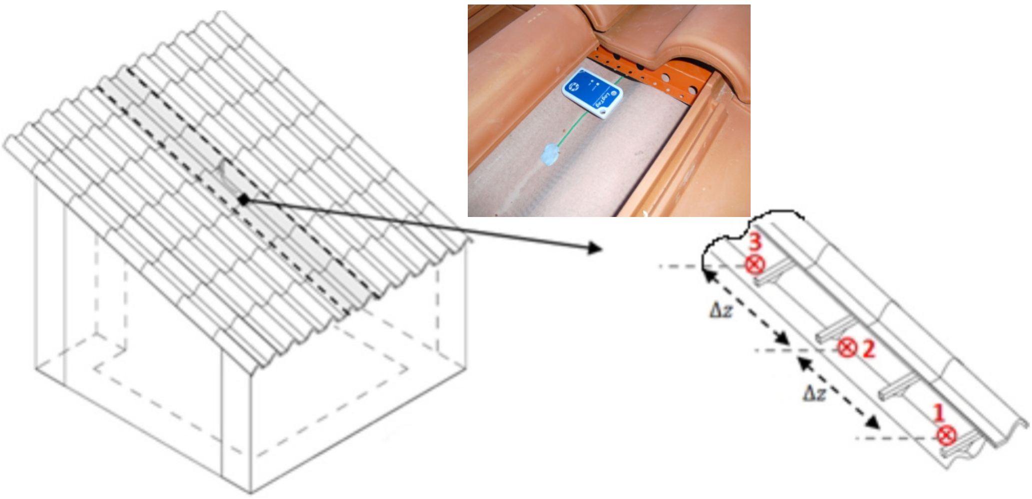

Figure 4. Air temperature sensors (LogTag® TRIX-8 recorders) in the air cavity, between tile and insulated sub-tile panels, in the middle section of the roof, spaced $\Delta Z = 0.6$ m

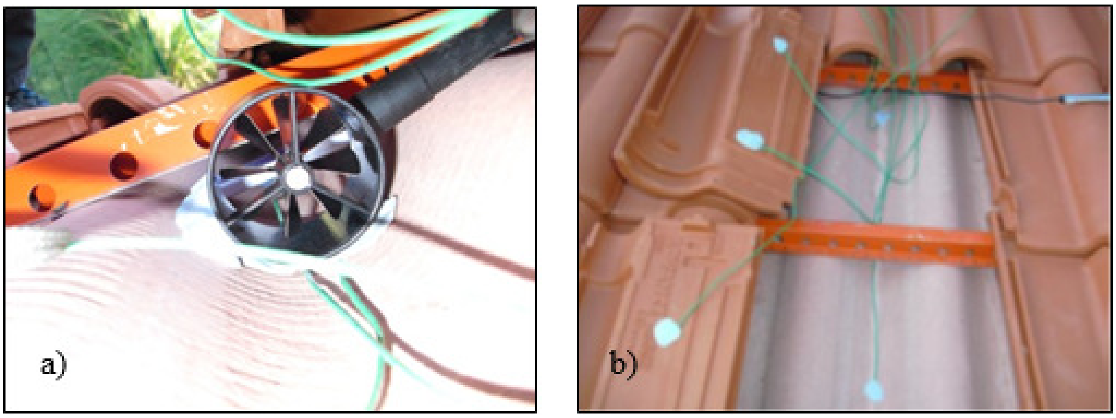

Figure 5. AirFlow velocity meter (a) and type K thermocouple sensors on sub-tile panel and tile surfaces (b)

A LogTag® TRIX-8 recorder was also installed inside the test cell to measure and record the attic air temperature (indoor air temperature), as shown in Figure 6a. Meteorological conditions, namely solar radiation (±5% accuracy) and air temperature (±0.3 °C accuracy), were continuously monitored at a height of 1.5 m above the ground by a weather station (Davis Wireless Vantage Pro2™ Plus, Davis Instruments) located 5 m apart from the test cell (Figure 6b).

The data acquired by the weather station were continuously transmitted by wireless to a console receiver located inside the test cell and stored in its internal data logger. The software Weatherlink (Davis instruments) was used to configure the weather data acquisition and download. All the parameters measured in this study were recorded in 5-min averages and the time of all data loggers was synchronized and adjusted to Coordinated Universal Time (UTC). Data downloaded from each data logger were subsequently sent to an Excel file for further analysis.

The thermal performance of the roof can be analysed in each transversal section *j*, along the cavity length of the roof, in two control volumes, VC_1-Outer tile surface and

VC_2-Inner tile surface, ventilated air-gap and sub-tile panel, as shown in Figure 7. Heat exchanges that occurs in each section are also displayed in Figure 7.

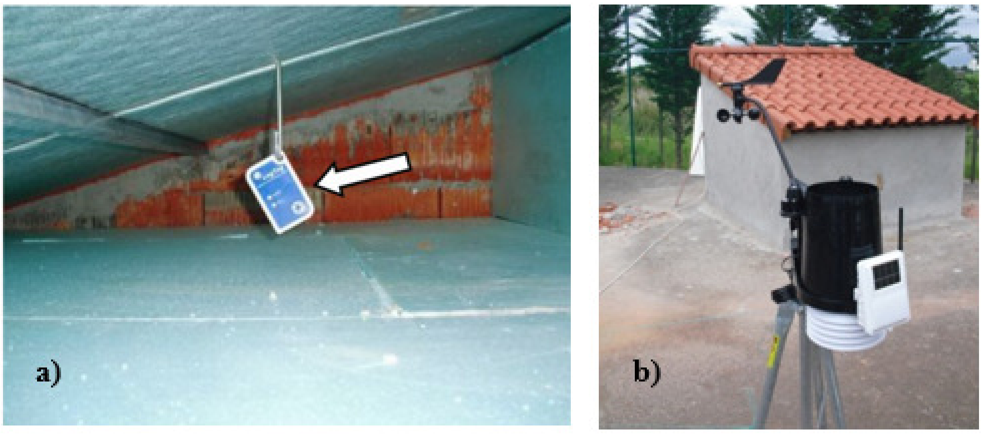

Figure 6. Air temperature sensor (LogTag® TRIX-8 recorder): in the attic (a) and the weather station (b)

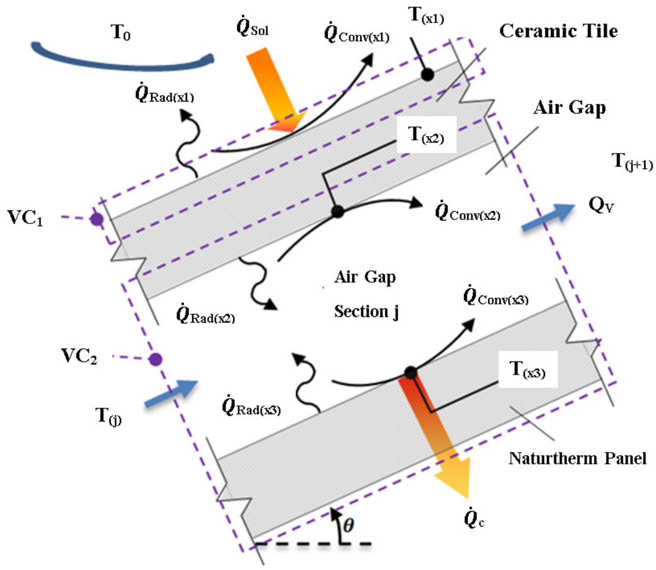

Figure 7. Control volumes VC_1 and VC_2 and the heat transfer mechanisms in a generic ventilated roof section *j*

Heat balance of outer tile surface

The energy balance of the outer tile surface (VC_1), in each transversal section *j*, is based on the absorbed solar radiation flux ($\dot{Q}_{Sol}$), thermal radiation emitted from the outer tile surface to the sky [$\dot{Q}_{Rad(x1)}$], heat flux transferred by convection with the outdoor air [$\dot{Q}_{Conv(x1)}$] and the heat flux conducted inside the tile material [$\dot{Q}_{Cond(x1)}$]:

$$\dot{Q}_{Sol} - \dot{Q}_{Rad(x1)} = \alpha I - \varepsilon\sigma T_{(x1)}^4 \tag{1}$$

$$\dot{Q}_{Cond(x1)} = \alpha I - \varepsilon\sigma T_{(x1)}^4 - h_0[T_{(x1)} - T_0] \tag{2}$$

In Figure 7 and in eq. (1) and eq. (2), I is the solar irradiation flux, T_0 is the outside air temperature, $T_{(x1)}$ is the temperature of the tile on the outer surface, h_0 is the outside superficial heat transfer coefficient and α and ε are tile surface properties, absorptivity and emissivity, respectively.

Heat balance of inner tile surface, ventilated air-gap and sub-tile panel

Relatively to the global energy balance on the inner tile surface, air gap and insulated sub-tile panel volume (VC_2), the heat power transferred from the inner tile surfaces to the airflow ($\dot{Q}_v$), can be estimated by eq. (3), where T_{j+1} and T_j are the temperatures of the air leaving and entering the ventilated air-gap respectively, $\dot{m}$ is the mass airflow rate and C_p the specific heat capacity of the air:

$$\dot{Q}_{\mathrm{v}} = \dot{m}\, C_{\mathrm{p}}(T_{j+1} - T_j) \tag{3}$$

The temperature of the air leaving the section j becomes the inlet temperature of the adjacent section $j + 1$, in the direction of the airflow.

Heat and air transfers in the volume VC_2 can be modelled by one-dimensional steady state energy balance equations, derived from the input of heat flux conducted through the tile material $\dot{Q}_{\mathrm{Cond(x1)}}$, the heat flux conducted through the sub-tile Naturtherm panel ($\dot{Q}_c$) and the convection heat exchanges of the air in the cavity, with the inner tile surface $\dot{Q}_{\mathrm{Conv(x2)}}$ and with the sub-tile panel outer surface $\dot{Q}_{\mathrm{Conv(x3)}}$, which is equal to the heat transported by the airflow in the air-gap $\dot{Q}_v$ [eq. (3)]:

$$\dot{Q}_{\mathrm{c}} = \dot{Q}_{\mathrm{Cond(x1)}} - \dot{Q}_{\mathrm{v}} \tag{4}$$

$$\dot{Q}_{\mathrm{c}} = \alpha I - \varepsilon\sigma T_{(\mathrm{x1})}^4 - h_0\left[T_{(\mathrm{x1})} - T_0\right] - \dot{m}\, C_{\mathrm{p}}(T_{j+1} - T_j) \tag{5}$$

RESULTS AND DISCUSSION

The strategy of building and test outdoors a test cell with a roof with vented eaves and sub-tile insulated panels allowed the study of the thermal behaviour of this passive solution under Mediterranean summer conditions. In this section it is provided a summary of the main results, which highlight the thermal behaviour of the ventilated roof based on the temperature profiles along the air-gap and inside the cell attic (indoor air temperature).

Figure 8 shows the outdoor air temperature, the indoor air temperature, the solar radiation intensity and the air-gap temperature distributions along the cavity, on the 20th of June. The daily thermal amplitude of the outdoor air was 14.3 °C, a normal value for the season. As observed in Figure 8, the temperature inside the attic (indoor air temperature) did not follow the strong nocturnal cooling of the outdoor air and presents a favourable time delay to the amount of solar radiation and outdoor air temperature in the morning. A similar thermal behaviour was reported by Soubdhan *et al*. [25] and Ong [18] on identical roof configurations, i.e. comprising ventilation an insulation in the panel below the air-gap, under warm climatic conditions. Ceramic tiles have the ability to store a significant amount of energy in the first hours of solar incidence. Thus, this roof presents a solution with a favourable and expressive thermal behaviour for thermal comfort. It should be noted the increase in temperature of the air along the air-gap, with a variation from T(1) to T(3) of about 5 °C, reaching a maximum of 30 °C when the outdoor air temperature was 20 °C.

When there is a temporary drop of solar radiation intensity, a reduction of the air-gap temperature is noticed, more clearly in T(3), at the position farthest from the eave, as observed at 15 hours. The increasing temperatures observed in the cavity indicated that the stack effect would work favourably in a cavity with small flow resistance. This self-induced force was the only factor to dissipate the heat accumulated in the cavity, when wind force was not available. The temperature of the air in the cavity was an important indicator to understand the extent of heat transmission to the lower surface.

Figure 9 shows the temperature profile in the air-gap cavity surfaces, between the 22nd and the 25th of June.

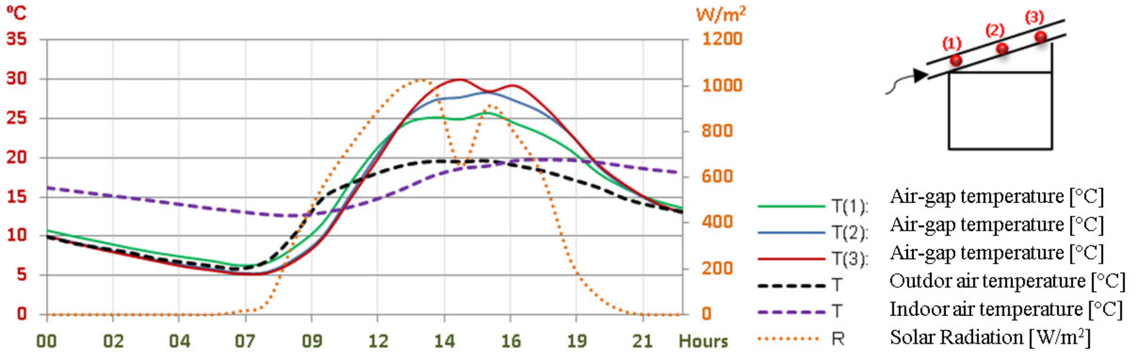

Figure 8. Roof thermal behaviour on the 20th of June

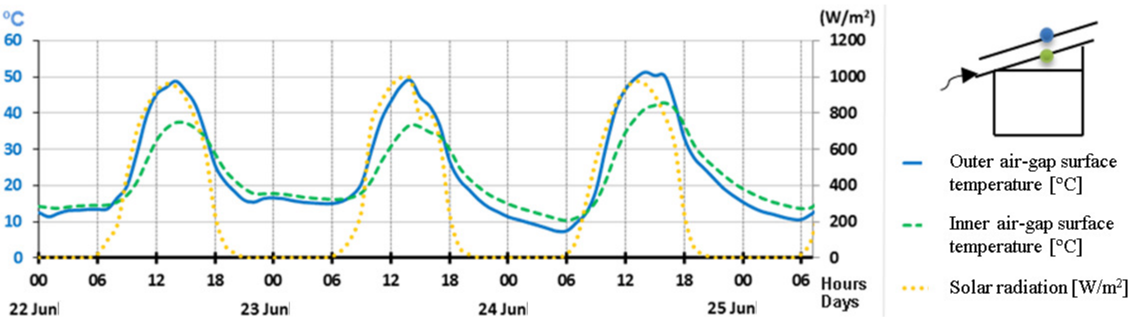

Figure 9. Comparison of the variation of the surface temperatures of the elements in the air-gap according to the incident solar radiation

A progressive variation of the temperature difference between the tile and sub-tile surfaces in the air-gap cavity is observed during the solar incidence time. The highest difference between the inner surface of the ceramic coating and the outer surface of the sub-tile panel (12 °C) occurred around 15 hours and coincided with the daily maximum solar radiation incident on the ceramic coating. During the night, the upper surface temperatures fell slightly below the lower surface temperatures of the cavity.

The study of the air-gap natural ventilation was also complemented with measurements of the velocity profile of the airflow in the air-gap cavity. An example of the effect of solar intensity on the induced air velocity is presented in Figure 10. The incident solar radiation correlated positively with the velocity of the air flow. The highest air velocity occurred at 14:30 h, with an elapsed time of 2-hours delay regarding the strongest solar radiation intensity, due to the thermal inertia of the all system and to the strong transient regime of heat transfer from the outer surface of the tile to the air-gap cavity. When the intensity of solar radiation decreased, the induced air velocity weakened. Air velocity which took place at night was likely due to reverse radiation from the tile surface to the sky by thermal radiation.

It is expected that the ventilation of the air layer allows a significant reduction of the heat fluxes through the roof in comparison with a non-ventilated roof with the same materials, as shown in previous studies for similar roof configurations, i.e. ventilation and insulation under the air-gap [e.g. 26-28, 34]. The passive roof solution studied here is an interesting approach for warm Mediterranean weather conditions, namely for south-facing roofs, that may affect significantly the consumption regarding air conditioner use in summer and the overall energy and environmental performance of dwelling houses.

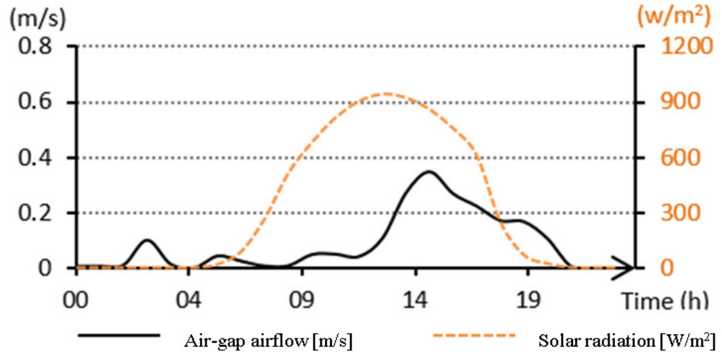

Figure 10. Velocity of the air flow in the air-gap

CONCLUSION

This study aimed to deepen the understanding of the thermal behaviour of a roof with vented eaves and sub-tile insulated panels under Mediterranean summer conditions. The planning of a test cell, built and tested under outdoor conditions, was crucial for recording air temperatures in the unvented attic and in the several surfaces and roof layers, including the air-gap cavity. The analysis and interpretation of the results of the temperature profiles showed that the roof attenuates the indoor air temperature daily fluctuations and presents a favourable thermal time delay. The temperature and air velocity in the cavity indicated that the stack effect worked favourably in ventilating the cavity. This self-induced force created a sufficient rising current of heated air in the cavity and allowed solar heat to be dissipated through the openings at the top of the cavity. It was concluded that natural ventilation is crucial in reducing the temperature of the air-gap surfaces, supposedly leading to reduce the heat transfer by conduction to the roof attic. Thus, this ventilated roof with sub-tile insulated panels could constitute an interesting passive system, namely for south-facing roofs, to decrease the heat transfer from the roof into the building, allowing to reduce significantly the cooling loads of the building. Therefore, in regions with high solar radiation this roof might be considered a good and non-invasive technique to improve the summer energy performance of the building. For future studies it seems fundamental to understand the performance of this solution in the winter time and the effect of geometric characteristics of the air-gap, such as length, thickness, tilt angle and orientation.

ACKNOWLEDGMENT

This work was financially supported by the Associate Laboratory LSRE-LCM-UID/EQU/50020/2019 and by INESCC-UID/Multi/00308/2019, funded by national funds through FCT/MCTES (PIDDAC).

NOMENCLATURE

$h_{(0)}$	outside superficial heat transfer coefficient	[-]
I	solar irradiation heat flux	[W/m^2]
$\dot{m}$	mass airflow rate inside air gap cavity	[kg/s]
$\dot{Q}_{\mathrm{c}}$	heat flux density transferred by thermal conduction mechanism through the sub-tile	[W/m^2]
$\dot{Q}_{\mathrm{Cond(x}i)}$	heat flux density transferred by thermal conduction mechanism through the tile	[W/m^2]
$\dot{Q}_{\mathrm{Conv(x}i)}$	heat flux density transferred by thermal convection mechanism	[W/m^2]
$\dot{Q}_{\mathrm{Rad(x}i)}$	heat flux density transferred by thermal radiation mechanism	[W/m^2]
$\dot{Q}_{\mathrm{Sol}}$	absorbed solar radiation heat flux	[W/m^2]

$\dot{Q}_{\mathrm{v}}$	total heat power transferred to the airflow in the ventilated air-gap section *j*	[W]
T_0	outdoor air temperature	[°C]
T_j	temperature of the air entering in the ventilated air-gap section *j*	[°C]
T_{j+1}	temperature of the air leaving the ventilated air-gap section *j*	[°C]
$T_{(\mathrm{x}i)}$	temperature of the surface *i*	[°C]
VC_1	control volume on the outer tile surface	[-]
VC_2	control volume on the inner tile surface, ventilated roof layers and insulated sub-tile panel	[-]

Greek letters

α	tile surface absorptivity
ε	tile surface proprieties absorptivity and emissivity

Subscripts

x1	Characteristic at the tile external surface
x2	Characteristic at the tile internal surface
x3	Characteristic at the sub-tile panel external surface

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Paper submitted: 22.11.2018
Paper revised: 17.07.2019
Paper accepted: 17.07.2019