Experimental analysis of an innovative tile covering for ventilated pitched roofs

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Abstract

This study investigates the thermal and fluid-dynamic behaviour of two ventilated roofs equipped with a new tile shape in comparison with a standard Portuguese tile. The novel tile shape was designed to improve the air permeability of coverings, thus producing a further above sheathing ventilation (ASV) enhancement as proposed in the ongoing LIFE HEROTILE European project, in which original roof tiles with innovative sidelock and headlock patterns have been designed, produced and are now under testing with real operating conditions. The heat transfer in the different roof layers and the ASV fluid flow have been experimentally analysed by means of a dedicated real scale mock-up. The results of the preliminary testing period are presented in this paper, they are referred to a first period with open eaves and to a second one in which eaves were closed to observe the only effect of tile air permeability. The data analysis shows that the ASV is strictly linked to the external wind conditions and grants better performances in HEROTILE roof. Moreover, the new tile design produces a significant increase of the ASV, so that better thermal performances are achievable in reducing solar heat gain during hot periods. As a consequence, the mock-up with HEROTILE ventilated roofs need less energy for air conditioning and allows high energy saving when compared with the standard one.

Keywords: ventilated roofs; roof tiles; above sheathing ventilation; experimental air permeability

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1 INTRODUCTION

Worldwide, according to the recent environmental policies, much research effort has been made in reducing the energy demand for heating and cooling in residential and commercial buildings. In hot climates, passive strategies, such as the exploitation of natural and forced ventilation by adding a ventilated layer in facades and roofs, are recognized to be effective in enhancing the overall performance of the building envelope, so that significant energy savings are achievable at lower expense. In comparison to other building elements, roofs can play a key role in reducing summer overheating due to their exposure to the sun, if properly designed. In ventilated pitched roofs, the arrangement of battens and counter-battens supporting the tiles allows an air flow below the covering, which is usually recognized as the above sheathing ventilation (ASV). Air flows from the eaves to the ridge, dissipating the excess heat gain due to solar radiation (Figure 1). In the case of discontinuous roof covering (e.g. with roofing tiles), the ventilation is enhanced by the air permeability between the overlapping tiles, which provides an additional and distributed network of airflow paths into and out the ASV.

Several studies have investigated the performance of (ASV) in reducing solar heat gain, following both numerical and experimental approaches. A steady-state numerical simulation of ventilated and micro-ventilated roofs was carried by [1]: a significant improvement in energy savings (up to 30%) was found for the ventilated roof. Comparable results were obtained by means of a computer model of a ventilated roof based on experimental data [2]. The simulated air flow induced by the buoyancy forces within the ventilated space reduces the heat flux into the attic by 30% in comparison to a direct-nailed roof. A numerical model was also developed and validated against experimental data to quantify the thermal benefits of a tiled roof over a traditional shingle roof: a benefit up to 14% was found [3]. A CFD analysis of a ventilated roof performance was carried out in both summer and winter conditions in [4]. The commercial software FLUENT was used to model a simplified

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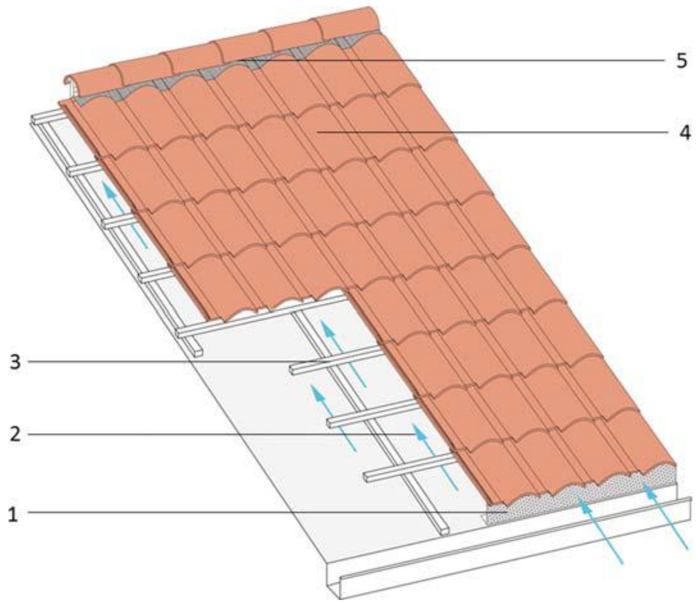

Figure 1. *A ventilated pitch roof with a discontinuous covering: (1) ventilated eaves (bird stopping); (2) ASV; (3) batten and counter-batten; (4) Portuguese roof tiles and (5) ventilated ridge.*

ventilated roof [5], showing that the heat fluxes can be reduced up to 50% during summer. In the previous numerical simulations, the ASV was modelled as an air duct, therefore the air permeability of a discontinuous covering (e.g. with roof tile) was not considered. Recently, the effect of tile air permeability on the ASV was numerically investigated using a 2D CFD [6]. According to the authors, the air permeability of the roof covering can increase the mass flow rate along the ventilation channel, improving also the thermal performance of the roof in reducing the solar heat gain in summer. The effect of roof tile permeability on the thermal performance of ventilated roofs was experimentally investigated by [7].

Real-scale models were prepared to run outdoor tests under real environmental condition in order to evaluate the summer performance of the ASV in combination with a radiant barrier [8]. A significant daytime performance improvement was observed. The effect of wind condition on ventilated and unventilated roofs were investigated in [9]. Different sloped test roofs were tested in a field study, employing a chemical tracer to visualize the air flow patterns. The external wind strongly affected the fluid-dynamic behaviour of the ventilated roof. Laboratory experiments carried out by [10] showed a great decrease of heat gain obtained in ventilated cavities in pitched roofs, a specific focus about envelope and cavity geometry effects is given. Numerical and experimental approaches were combined to investigate the effect of the underlay emissivity on the global thermal response of sloped roof in [11].

In recent years, a good agreement between the results of numerical simulations of ventilated inclined roofs and experimental measurements was found by [12]. In this work, thermal resistances were modelled through circuit transformation theory in order to obtain the radiation resistance, then, a CFD analysis was carried out to calculate the other heat exchange parameters. The model proved reliable in the case of naturally ventilated cavities. Six different types of passive roof were monitored during very hot summer days in India [13]. The ventilated pitched roof with a covering of clay tiles showed the optimum indoor thermal performance. A scale model of a typical dwelling was used to monitor the thermal behaviour of a pitched roof with a covering in ceramic tiles and ventilated eaves by [14], observing a significant heat dissipation capacity. A novel ventilated concrete tile was investigated in comparison with an ordinary corrugated roof tile observing at reduction of solar heat gain through the roof [15].

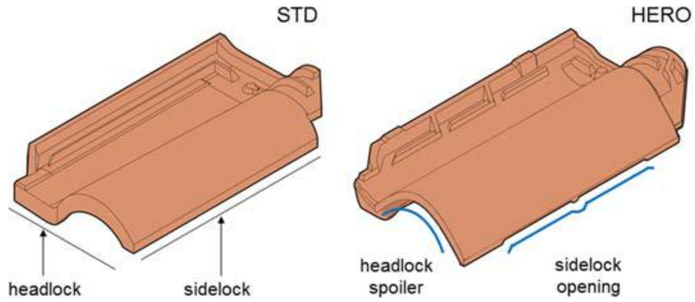

Figure 2. *A comparison between the standard Portuguese roof tile (STD) and the novel design (HERO).*

Several lines of evidence suggest that the ASV can be an effective solution to reduce solar heat gains through roof during summer season. The ASV is mainly dependent on the eaves section opening (which is an intake vent). Moreover, the ASV can be further enhanced by the air permeability of the roof in the case of a discontinuous covering. Therefore, the design of clay tiles can be improved to increase the air permeability of the covering, as proposed in the European project LIFE HEROTILE for two basic shapes: Portuguese and Marseillaise type which both are traditional styles widespread in the market of Southern Europe, easily recognizable for the original shapes with a 'bold roll' and a 'low profile', respectively. The air permeability of a roof tile is a characteristic tied to a specific tile geometry and it is intrinsically linked to the materials, manufacturing process and know-how of individual tile producer. The project combined CFD and experimental analysis to develop and optimize novel tile shapes, which showed a significantly improved permeability to air [16]. The new tile shape (named HERO in the following) is slightly bigger and with a higher roll in comparison with the existing tiles (STD), as shown in Figure 2. In addition, the design involves changes in the side-lock geometry, which has an opening to facilitate air intake when wind blows sideways, and in the headlock pattern, which is equipped with a spoiler to improve the air inlet in front.

The novel tiles shapes were produced and are under testing in comparison with the respective benchmark tiles (already in the market) and other roof typologies (e.g. metal covering, flat roof) on two experimental set-ups, located in Italy (Ferrara) and Israel (Yeruham), respectively. As a part of this effort, the performance analysis of the novel Portoghese tiles is here proposed, in comparison with that of the standard Portoghese tile. Tests were carried out on a real scale gable roof mock-up under the spring weather conditions in Yeruham, in the Negev desert. In order to carry out a comprehensive and detailed experimental analysis, the monitoring system is equipped several sensors, which were also arranged within the ASV to monitor both air velocity and temperature. In addition, the analysis is carried out by varying the permeability to air of the eaves section, which is an air intake and significantly affects the ASV.

2 METHODOLOGY

The performance of a pitched roof equipped with the innovative Portoguese tile (HERO) have been monitored in comparison with a commercial roof tile, which is already available on the market (STD). This was considered as the reference to develop the HERO design towards the increasing of permeability to air of a roof covering. For the purpose of this analysis, a mock-up of a pitched roof was designed and built in Yeruham (Israel). A comprehensive monitoring systems have been installed in the mock-up in order to characterize the dynamic behaviour of the roof. It consists of a network of several sensors aiming to collect data of significant physical quantities such as temperature, air velocity and heat flux in several points of the roof, according to the actual atmospheric conditions (mainly outdoor temperature, wind speed and solar radiation).

The data were collected continuously from the winter 2016/17, during which the experimental system was tested and improved. The present work is a preliminary data analysis, referring to two periods (5 days each one) for the months of March and May, which were run with the vented (as in actual ventilated roof) and sealed eaves section, respectively. According to the weather (spring) and operational conditions during the tests, it has been possible to distinguish the different behaviour between the two ventilated roofs, equipped with STD and HERO roof tiles. Further data collection will be performed during the summer season to obtain more detailed information on long-term performance and hotter weather conditions.

2.1 The mock-up

The mock-up is located in Yeruham (Israel), at the boarder of the Negev desert. It is a real-scale dwelling with a pitched roof, as shown Figure 3. The roof slopes were oriented East-West, according to the prevailing wind conditions of the site (the wind blows mainly from the West), which were identified by means of a previously installed weather station in January 2016. The mock-up is divided into four chambers, two guard chambers at the sides (facing North and South) and two monitored chambers in the central part. The guard chambers have insulating function for controlling the indoor conditions in the monitored rooms, which must be tested in the same conditions. According to this, the roof is divided into four part as follows:

- Guard chamber, unventilated roof, STD Portuguese tile covering (1).

Figure 3. *The mock-up in Yeruham.*

- Monitored chamber, ventilated roof, HERO Portuguese tile covering (2).
- Monitored chamber, ventilated roof, STD Portuguese tile covering (3).
- Guard chamber, unventilated roof, metal covering (4).

Each chamber has a floor area of 10.2 m^2 (1.30 × 7.80 m) and a maximum height of 3 m at roof peak. The volume of conditioned indoor space is 25 m^3. The roof's area is ~5.3 m^2 for each pitch, with 4.3 m slopes in length and a pitch of 20°C. Excepting the roof, the building envelope is composed of insulated sandwich panel (8 cm thick) for exterior and interior partitions as well to reduce the heat gain through the walls and minimize the mutual thermal influence between the chambers. The ventilated roofs are composed by a fir matchboard layer below the tiles (0.03 m thick, thermal conductivity 0.12 W/mK), protected with a vapour permeable sheathing membrane. A counter-batten and tile batten system (0.04 and 0.03 m in height, respectively) is mounted on the roof wooden deck and supports the discontinuous roof covering with STD/HERO terracotta tiles. The STD and the HERO tiles has different design and dimensions (Figure 2), which results in a slightly different weight on the roof: 45 and 49 kg/m^2. On average, the free air cross sections are 0.062 and 0.071 m^2, for STD and HERO roofs respectively; therefore, the HERO ASV flowing area is 15% wider than that of STD roof. The mock-up is equipped with an air-conditioning system consisting in direct expansion units, one per room, which are set in cooling mode (set-point 20°C in the monitored chambers). The electrical consumption is monitored by energy metres.

2.2 Monitoring system

The monitoring system is equipped with several sensors, which were arranged in several measurement points to meet the need for monitoring the main parameters characterizing the energy performance of the roofs: on the tiles, within the ASV, on the upper and lower surface of the roof deck, in the monitoring chamber. In addition, a number of sensors have been dedicated to the monitoring of the heating and cooling system energy demand and of the weather conditions.

Each slope is divided in four transversal monitoring sections, so for each monitored chamber there are eight monitoring sections along the roof slope (A, B, C, D, E, F, G, H), as shown in Figure 4. A monitoring section is divided into four positions across the roof (1, 2, 3, 4) which are set for anemometers installation. The positions are equipped with specifically designed brackets which allows to install different types of anemometers and regulate their height inside the ASV channel. The chosen configuration allows to easily change the location (section and positon) of the anemometers as needed. Sections are also equipped with four thermocouples to monitor the temperature at some points in the structure and a heat flux sensor (only sections C and F).

To monitor the air velocity field within and along the ASV, the monitoring chambers are equipped with 10 anemometers each (5 on the Eastern slope, 5 on the Western). Two types of thermal anemometers have been installed in each chamber: 8 omnidirectional air velocity transducer HD4V3TS2 by Delta Ohm (operating range 0.1–5 m/s, accuracy: ± 0.2 m/s + 3% f.s.) and 2 high precision omnidirectional air velocity transducer Model 8475 by TSI (operating range 0.05–2.5 m/s, accuracy: ±3% of reading + 1% f.s.). The current configuration on the Eastern slopes consists in 2 anemometers in section A (Delta-Ohm, positions 1 and 4), 1 anemometer in C (TSI, positon 2) and 2 anemometers in section D (Delta-Ohm, positions 1 and 4). The arrangements are symmetrical on western slopes. The height of the anemometer's probe was set to be in middle position between deck surface and the lower tile surface (i.e. the middle of the ventilated channel) as shown in Figure 5, according to the shape of Portuguese tiles (V^I, under the bold roll or V^{II}, under the flat part) and the different geometry between STD and HERO tile.

The temperature is measured at different locations (Figure 5) by means of T-type thermocouples (copper–constantan), tolerance class 1 and compliant with ASTM E 230 and IEC 60 584–2. In the monitoring chamber, the temperature is measured as follows:

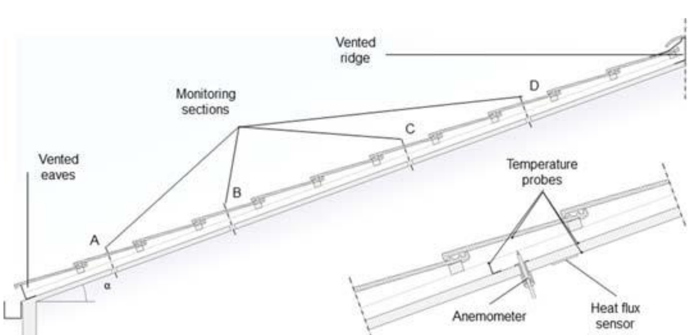

Figure 4. *Longitudinal section of the roof slope in a monitoring chamber with the monitoring sections.*

- T_{ASV}: temperature of the air flowing in the ASV [°C].
- T_{TILE}: underside tile temperature [°C].
- T_{DECK}: external deck temperature [°C], only sections C and F.
- $T_{CEILING}$: ceiling surface temperature [°C], only sections C and F.
- $T_{CHAMBER}$: indoor air temperature [°C].

In order to monitor the diurnal and nocturnal heat flux cycles through the roof, two heat flux sensors have been installed on the ceiling by a special flange in both the East and West side slopes, in sections C and F. Heat flux sensors are HFP01 by Hukseflux, with a range from −2000 to 2000 W/m^2, uncertainty 3% of measured value. Heat flux measurements can be related to the solar radiation data, which are collected by means of SR20 pyranometer by Hukseflux (compliant with ISO 9060, secondary standard). The read out of the sensors is carried out by a commercial data-logger DataTaker DT85 by Thermo Fisher Scientific Inc. connected in the LAN local network, which is a multiplexer datalogger able to read and elaborate analogical and digital signals.

Finally, a wireless weather stations (Vantage Pro2 by DAVIS Instruments) is installed at 4 m height near the mock-up to monitor local weather variable and obtain a correlation analysing the relationship between environmental conditions and the behaviour of the ventilated roofs An overview of the installed sensors is reported in Table 1.

3 RESULTS

The aim of this study is to analyse the thermal and fluid behaviours of a ventilated roof equipped with HERO tile in comparison with a STD tile covering under real weather conditions

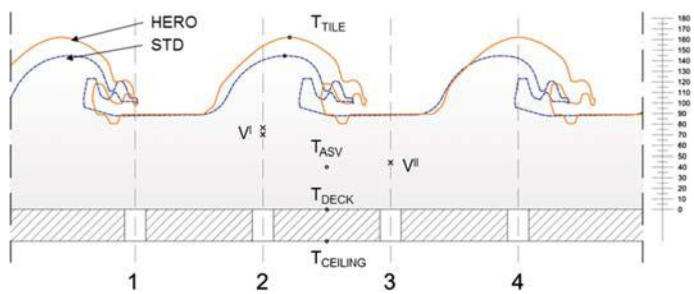

Figure 5. *Cross section of the ventilated roof with STD and HERO covering: monitoring positions and sensors.*

Table 1. *Sensors installed in the mock-up*

	STD roof	HERO roof	Weather variables
Thermocouples	21	21	
Anemometers	10	10	
Heat Flux Metres	2	2	
Pyranometer			1
Rain gauge	1	1	
Electricity counter	1	1	
DAVIS Weather Station			1

of summer season. The results here presented refer to two monitoring periods, in order to observe the exclusive effects of air permeability through the tiles: the first with open eaves and the second one after closing these ones. During the first period (March 2017), the eaves section was open and protected by a grid only (as it should be in a properly designed ventilated roof). On the contrary, during the second period (May 2017) the eaves section was sealed, so that the air could flow into the ASV only by passing through the tiles.

3.1 Above sheathing ventilation

The average air velocity (10 min) within the ASV with STD and HERO tile coverings are compared in Figure 6 for the first period (open eaves section), according to the wind speed and direction. The air flow is higher with HERO tiles; differences are significant in the upwind pitch when the wind blows orthogonal to eaves (which act as air intake vent). Here, HERO tiles shows a 1:10 ratio between the air velocity within the ASV and the wind speed, whereas it is around 1:20 for STD tiles. According the wider cross section of the HERO roof (+15%), the resulting volumetric flow rate is thus 2.3 times higher than that of the STD roof. In the downwind pitch the difference is broadly reduced, even if higher for the HERO solution.

As expected, the air velocity within the ASV decreases in the second period when the eaves section was sealed (Figure 7), but a difference between HERO and STD is still measured. The second period was characterized by a prevailing wind direction from the West, therefore the air velocity is significantly higher in the western HERO slope, contrary to in eastern one where the prevalence is weak. Differences between HERO and STD are likely to be due the improved air permeability which enhances the ASV efficiency.

3.2 Thermal behaviour

The thermal behaviour of the different ventilated roofs is analysed in order to assess the effect of the previous fluid-dynamic

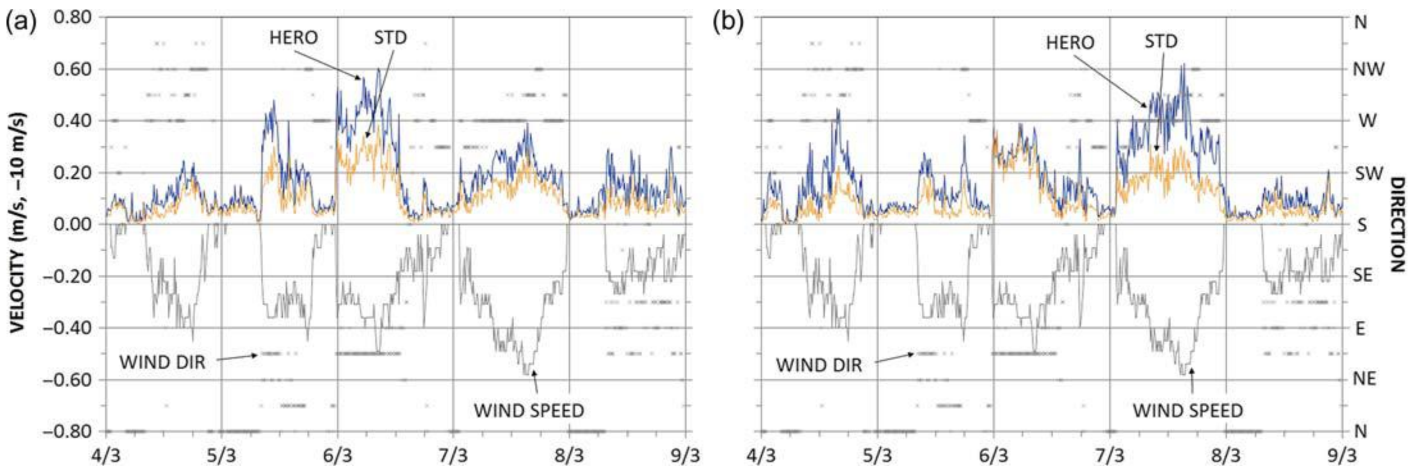

Figure 6. *ASV velocity for East (**a**) and West (**b**) slopes, eaves sections opened (first period). Wind intensity is set negative and scaled with a ratio equal to 1/10.*

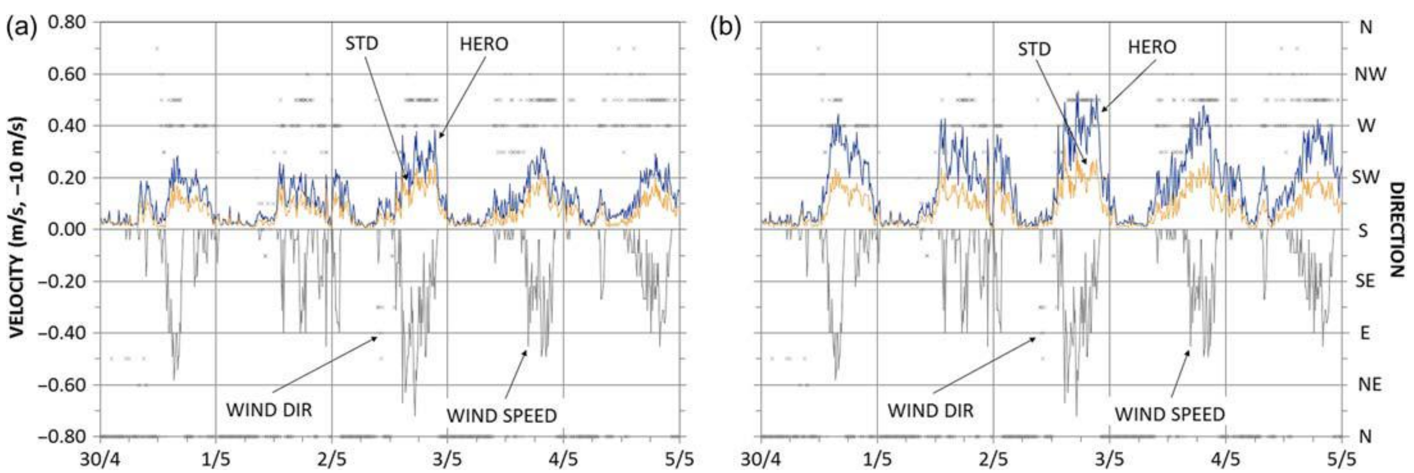

Figure 7. *ASV velocity for east (**a**) and west (**b**) slopes, eaves sections closed (second period). Wind intensity is set negative and scaled with a ratio equal to 1/10.*

remarks. The average temperature of the air flowing along the ASV is shown in Figure 8, for HERO and the STD roofs, according with the outdoor air temperature and the solar radiation during the first period. A relevant ASV air temperature decrease is achieved with the new roof tiles. During the hottest part of the day, an interval of 6 hours with high solar radiation, the air temperature within the ASV is on average 3°C lower in HERO than in STD roof, in both eastern and western slopes. During morning, the ASV air temperature is always higher than that of the outdoor air, up to 5–8°C.

In the second period, the sealed eaves section affects the thermal trend in both roofs, as shown in Figure 9. Overall, the average temperature is lower in western slope than in Eastern one, due to the external wind conditions, characterized by a favourable prevailing Western direction, which helps dissipating excess heat mainly from the upwind slope. Lower ASV air temperatures are measured with HERO tile covering. The temperature trend is similar to the first period and in the Eastern slope, contrary to Western one where a significant reduction of temperature gap between the two cases is visible, in comparison to the first period. This may be related to the airflow passing through the openings between the overlapping tiles: in upwind section the air passing from openings is heated by the tiles and then flows into the ventilated channel. On the other hand, in the downwind slope, a fraction of airflow may flow out from openings because of external pressure differences producing a temperature decrease.

Figure 10 shows the HERO and STD average tiles temperatures, together with the outdoor air temperature and the solar radiation for the first period. The maximum temperature of HERO tiles is up to 4°C lower than that of STD tiles. However, no significant difference between the two tiles is evident in absence of wind. Similarly, Figure 11 shows the tile temperatures during the second period. The temperature trend is consistent with the first period for the first period. On the contrary, similar temperature trend are reported for western slope tile, due to upwind exposure. According to the wind direction, the maximum temperature is higher up to 3°C in the

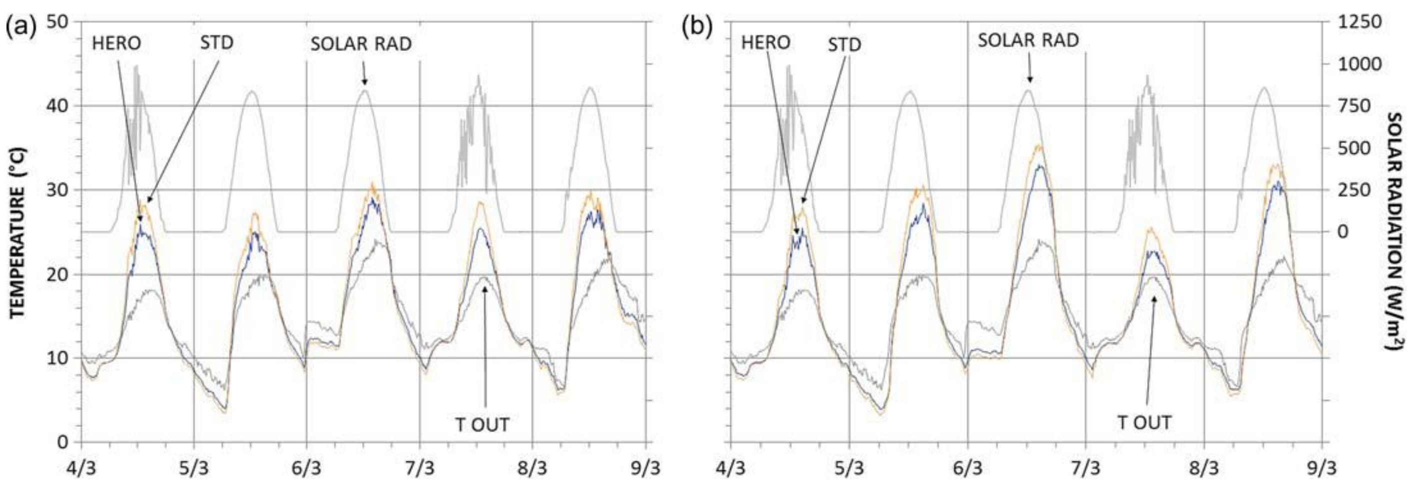

Figure 8. *ASV temperatures for East (**a**) and West (**b**) slopes related to external temperature and solar radiation (first period).*

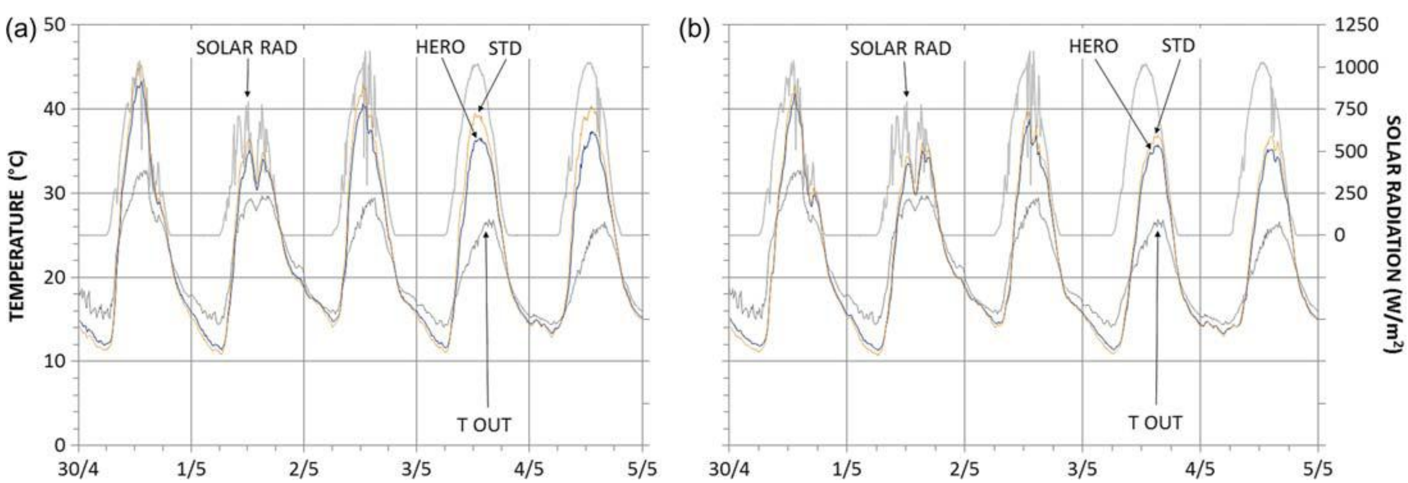

Figure 9. *ASV temperatures for east (**a**) and west (**b**) slopes related to external temperature and solar radiation (second period).*

Eastern side than in the Western one. This should be related to the downwind/upwind exposure of the two sides of the mock-up; the upwind side is more efficiently cooled than that the downwind side, where down-wash effects are present.

In Figure 12, a comparison between the temperature within the ASV and the indoor air temperature is shown, for a single day during the first and second period. The temperature of the air flowing within ASV is the 10 min average of the probes on both Eastern and Western slopes. During the day, the indoor temperature is maintained on a constant set-point (20°C). A lower temperature of the air flowing into the ASV can be observed for the Hero tile roof, and this is reflected on both the indoor temperature and the operation of the air conditioning system, as shown (Figure 13). In the case of Hero Tile roof, the air conditioning unit switching on is delayed of 60 and 30 min in the first and in the second period, respectively. In addition, the system switching off is premature in the HERO chamber. Overall, a significant reduction in the daily operating time is achieved. This could be related to a higher heat removal due to the enhanced ASV with high air permeability tiles, with a resulting decrease in the cooling energy load.

3.3 Heat flux through the roof

Figure 14 shows the trend of heat flux passing through the roof and the accumulative heat gain through the roofs (H) related to the solar radiation for both periods. Accumulative heat gain was calculated by integrating positive heat flux rate (Φ) on entire roof surface and time for selected periods:

$$H = \iint \Phi \cdot dA \cdot dt;\ [\forall\ \Phi \geq 0]$$

A relevant heat flux decrease is achieved by new roof system: during maximum solar peak, differences up to 30% can be observed. As a consequence, a 10% of heat gain reduction is obtained by HERO roof in both periods, this trend has been observed since the starting date (October, 2016).

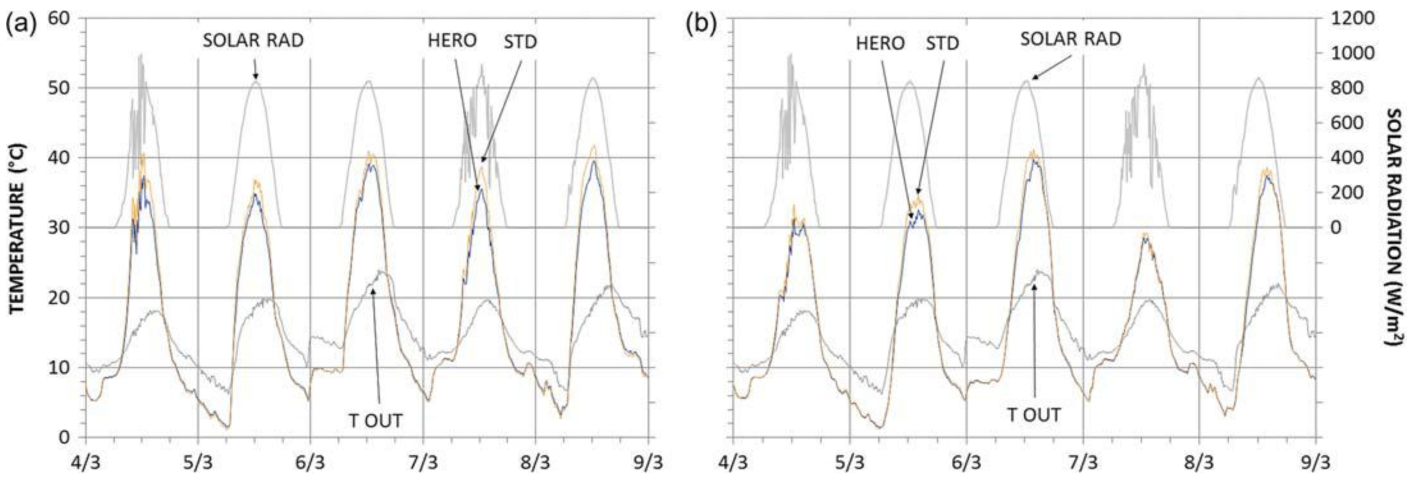

Figure 10. *Tile temperatures for east (**a**) and west (**b**) slopes related to external temperature and solar radiation (first period).*

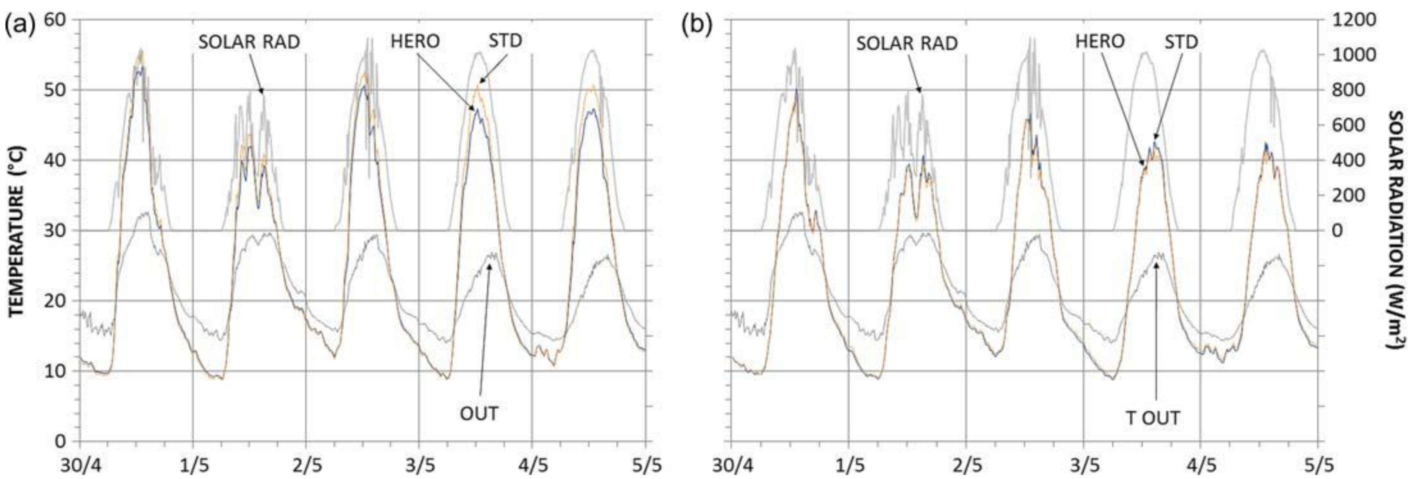

Figure 11. *Tile temperatures for east (**a**) and west (**b**) slopes related to external temperature and solar radiation (second period).*

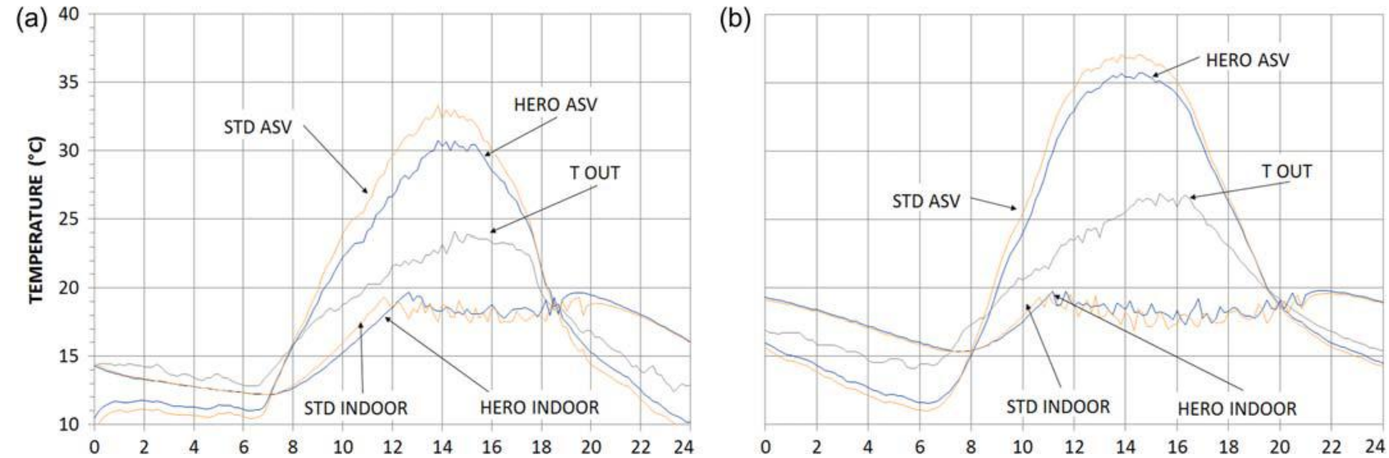

Figure 12. *Indoor temperature for two single days belonging to the first (**a**) and second (**b**) period. ASV temperature are averaged on east and west slopes.*

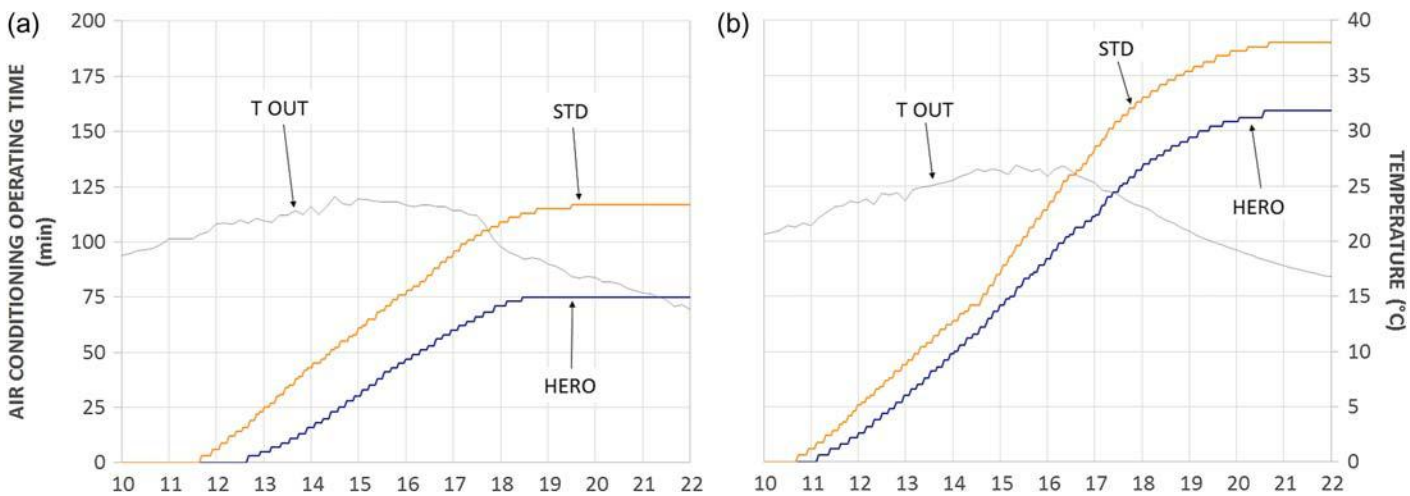

Figure 13. *Air conditioning unit accumulative functioning time for two single days belonging to the first (**a**) and second (**b**) period.*

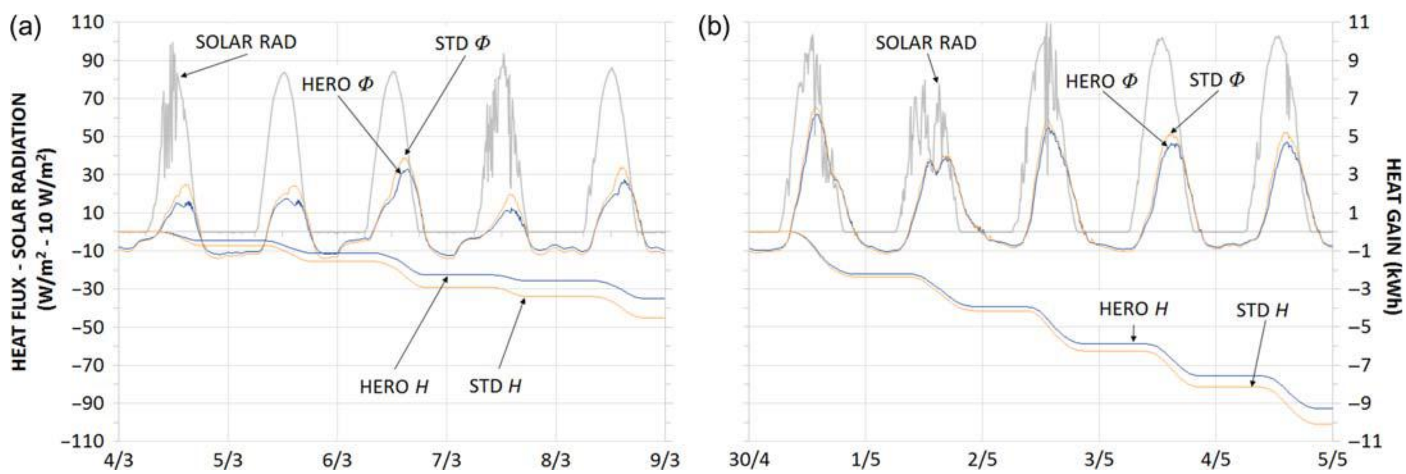

Figure 14. *Heat flux and heat gain for first (**a**) and second (**b**) period related to solar radiation trend. Solar radiation is scaled with a ratio equal to 1/10; accumulative heat gain is set negative.*

4 CONCLUSIONS

This paper reports the preliminary results of a field experimental campaign lead in Life HEROTILE project that aims to analyse the thermal and fluid-dynamic behaviours of ventilated roofs equipped with two different roof tiles: a standard Portoguese tile (STD) and its evolution towards an improved air permeability (HERO). Although data were collected during winter/spring period, the proximity to the Negev desert (Israel) allowed a relative high solar radiation also during this season, as needed to test the cooling requirement. The preliminary fluid-dynamic analysis shows that the ASV velocity achieved by the HERO roof is two times than that of the STD roof. It impacts on the cooling of the roofs overheated by the solar radiation: HERO's ASV temperature is always cooler than STD one. The comparison between the two different configurations having opened or closed eaves shows that the tile temperatures increased in closed conditions, because of the lower ASV velocity and the shorter pitch length for removing heat from the internal duct. The effect of ASV on the indoor temperature is highlighted by a different damping of the solar heat radiation that affects the operating mode of the air condition systems: for the HERO roof a delay of 1 h in turning on was observed. Finally, the global energy performances are proven by the monitored heat fluxes and the cumulative energy calculations; although only a winter/spring season is considered, the 10% cooling energy saving was achieved by HERO roof. Therefore, a further increase of thermal performance should be expected in summer season.

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