Future Cities and Environment

Improving the Air Permeability of Ventilated Roofs

TECHNICAL ARTICLE

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ABSTRACT

In hot climates, ventilated pitched roofs help dissipating the excess heat, thus reducing the cooling energy demand. The key factor is the so-called Above Sheathing Ventilation (ASV) that depends on the air entering and leaving at the eaves, ridge and the gaps among tiles. A strategy for increasing the ASV is the enhancement of the roof air permeability through the development of new tile shapes, as proposed in the European Life HEROTILE project. The performance of a ventilated pitched roof are experimentally analysed by comparing some covering options: the new tile shape designs against the standard ones, available in the market, and a metal cover. A real scale pitched roof mock-up was built and equipped with a comprehensive monitoring system. The air flow and temperature in the different roof layers, as well as the heat flux passing through the roof and the cooling energy demand, were monitored according to the local weather conditions during the summer season. The analysis showed that the new tile design increases the ASV in comparison with the standard ones, and better thermal performance was achieved by reducing the heat gain due to solar radiation.

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INTRODUCTION

According to the latest data, the building and construction sector accounts for more than one-third of the global energy consumption (UNEP, 2020). The European Commission has recently proposed to cut net greenhouse gas emissions in the EU by at least 55% by 2030, compared to 1990 (COM(2020), 2020). Doing this, the refurbishment of existing buildings as well as the construction of new ones require an improvement of the building envelope (De Masi, 2021) to reduce the energy consumption for heating and cooling. Considering the increasing demand for space cooling application due to the rise of atmospheric temperature associated with carbon emission and the consequent rise in the sale of air conditioning appliances that has led to serious environmental issues, the adoption of passive cooling techniques plays a vital role (Bhamare, 2019). Among the possible strategies, there are technologies that exploit natural ventilation, both on the roof and on the façade, which are particularly effective in hot climates, like the Mediterranean one, as the ventilated cavity mitigates the effect of solar radiation (Corrao, 2021). The realization of an air layer allows the prevention of the heat transfer through the building envelope consequently avoiding the cooling down of the building form the penetrated heat, which represents a valid strategy not only from the environmental point of view but also from the economic one (Susanti et al. 2010).

In ventilated pitched roofs, the arrangement of battens and counter-battens supporting the tiles allows an air flow below the covering layer, which is usually recognized as the Above Sheathing Ventilation (ASV), as shown in Figure 1. Air flows from eaves sections (which act as an intake vent) to the ridge, helping to reduce heat gains due to solar radiation. In addition, the ASV is enhanced by the air permeability among the tiles in discontinuous roof covering which provides additional and diffused air intake/exhaust network. The realization of ventilated roofs is possible both on new buildings as well as on existing ones, even in case of height restrictions or refurbishment limitations (Li et al, 2016). Researchers have investigated the mutual relations between air-flows and heat-transfer in ventilated roofs, following both numerical and experimental approaches. A significant energy saving was calculated for a ventilated roof over a micro-ventilated one by means of a steady state numerical simulation (Ciampi et al. 2005). The daytime performance of a ventilated roof can be enhanced by installing a radiant barrier below the tiles (Dimoudi et al. 2006). Laboratory experiments focused on the effects of ASV cavity geometry showed a great decrease of heat gain obtained in ventilated pitched roofs (Lee et al. 2008). A thermal benefit of 14% was estimated to be achievable with a tiled roof instead of a traditional shingle roof when assuming a steady air flow (De With et al. 2009). Simulations showed that the air flow induced by the buoyancy forces within the ASV can reduce the incoming heat flux by 30% in comparison with an unventilated roof (Miller et al. 2007) and up to 50% in summer season (Gagliano et al. 2012). However, the fluid dynamic and thermal behaviour of micro-ventilated and ventilated roofs is strongly affected by environmental conditions, in particular the intensity and direction of the wind incident on the covering (Janssens and Hens. 2006). In recent years, researchers have focused their attention on ventilated roofs with discontinuous covering. Six different types of passive roof were monitored during very hot summer days in India (Madhu Mathi et al. 2014). The ventilated pitched roof with a covering of clay tiles showed the optimum indoor thermal performance. A significant heat dissipation capacity was also monitored for a pitched roof with a ceramic tile covering and ventilated eaves (Ramos et al., 2015). Moreover, real scale tests were carried to evaluate the contribution of discontinuous mantles in ventilated roof, comparing a ventilated roof to one with sealed eaves and ridge line (Baccega et al. 2022). In fact, the mass flow rate along the ventilation channel can be increased by the air permeability of the roof covering (Bortoloni et al. 2017), furtherly improving the thermal performance of the roof.

The European project LIFE HEROTILE started in 2015 to study and improve the design of roof clay tiles towards the increasing of the overall air permeability of the covering. The project combined CFD analysis and experimental tests to develop and optimize novel terracotta roof tiles starting from two traditional shapes which are widespread in the market of Southern Europe: the Portoghese and Marsigliese type, easily recognizable for the original shapes with a “bold roll” and a low and flat profile, respectively. New designs involve changes in the side-lock and head-lock pattern of the tile, producing a significant improvement in the air permeability for both the Portoghese (Bottarelli et al. 2017) and the Marsigliese shapes (Bottarelli et al. 2017). A real scale mock-up of a ventilated pitched roof was built in Ferrara (Italy) to test the novel roof tiles in comparison with the respective benchmark tiles and a metal roof covering. The results of a summer monitoring activity and a comparative performance analysis are here presented.

METHODS

The purpose of this work is the comparative analysis of thermal performance of ventilated roofs with discontinuous covering equipped with novel Portoghese and Marsigliese roof tiles against the corresponding commercial tiles (taken as the references), and metal covering that is not permeable to air. This work follows a preliminary data analysis carried out with a similar mock-up in Yeruham (Israel) in the spring of 2017 (Bottarelli et al. 2018).

The mock-up in Ferrara (Italy) is a real-scale building with a pitched roof, located in the TekneHub laboratory of the University of Ferrara (N44.831, E11.599) in northern Italy. The local climate is continental climate, with hot and humid summer. The roof slopes are oriented in South-North direction. A preliminary analysis of local wind data (weakly ventilated) collected with a Davis Vantage Pro2 weather station did not reveal a prevailing wind direction. In view of this, the performance of the different ventilated roofs have been monitored under various and generally not favourable conditions during the summer of 2017.

The mock-up roof is divided in 7 rooms: 5 rooms in the central part which have ventilated roof with different covering and are equipped with several sensors, 2 guard-rooms at sides to control the indoor conditions in the monitored rooms. Each room is 1.30 m × 7.80 m with a maximum height of about 3 m, corresponding to a volume of 25 m^3. The roof pitch is 20° with a surface area of approximately 5.3 m^2 for each pitch. As shown in Figure 1, the ventilated roof above each room has a different covering laid on the same batten and counter-batten system: standard Portoghese roof tiles (P_{STD} in the following); herotile Portoghese roof tiles (P_{HERO}); herotile Marsigliese roof tiles (M_{HERO}); standard Marsigliese roof tiles (M_{STD}); metal roof covering (MET). A detail of the roof tiles used is shown in Figure 2. The roofing structure consists of a steel truss that the roof sheathing is laid upon. This layer is made of fir matchboard 0.03 m thick (the thermal conductivity is 0.12 W/mK), protected with a vapor permeable membrane.

A wooden counter-batten and batten system (0.04 and 0.03 m side, respectively) is laid upon the roof deck to support the roof coverings, so that the minimum height of the ASV is 0.07 m. According to the tile shape and arrangements, the ASV cross section area for unit of width (1 m) are 0.103 m^2 and 0.118 m^2 in the case P_{STD} and P_{HERO}, respectively, and about 0.090 m^2 in the case M_{STD} and M_{HERO} due to the flat profile; lastly 0.076 m^2 in the case MET. The thermal properties of the main roof materials are reported in Table 1.

	THICKNESS [m]	DENSITY [kg/m^3]	THERMAL CONDUCTIVITY [W/(m*K)]	SPECIFIC HEAT [J/(kg*K)]	SOLAR REFLECTANCE [-]
fir matchboard	0.03	450	0.12	2700	/
roof tiles	0.02	1700	0.7	840	0.3
metal covering	0.0008	8.5 (kg/$m^{2)}$	/	/	0.8

Table 1 Roof materials' properties.

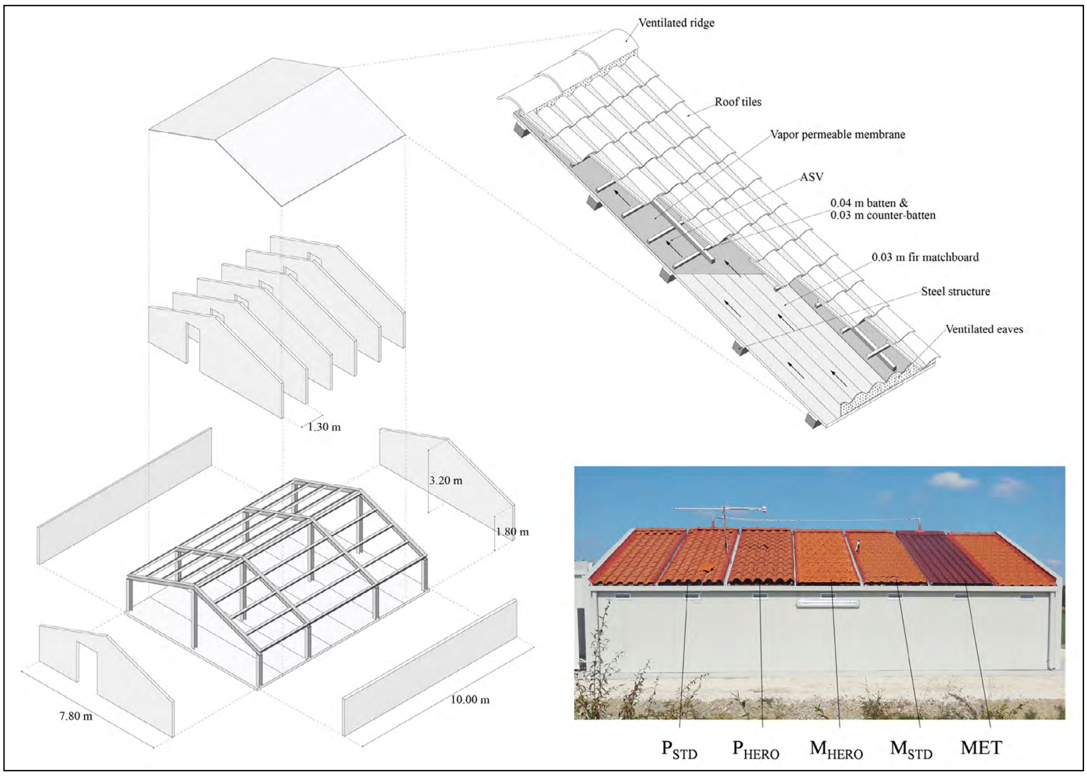

Figure 1 The ventilated roof structure and the mock-up in Ferrara.

The building envelope consists of insulated metal wall panels, 0.10 m thick for exterior (thermal transmittance 0.22 W/m^2K) and 0.08 m for interior partitions (0.28 W/m^2K) to minimize the heat gain through the walls in comparison with that through the roof, and the heat transfer the between the rooms. The temperature in each room is maintained (the set-point in cooling mode is 26°C) by a fan coil unit which is connected to water closed loop water. The cooling/heating power is provided by an air-water reversible heat pump (13.7 kW).

A monitoring system equipped with a network of several sensors was designed and installed in the mock-up aiming to carry out a comprehensive testing activity. The five ventilated roofs were equipped with 4 monitoring cross sections in the south pitch (A,B,C,D) and 2 in the north (E,F), as shown in Figure 3. This layout has been designed to have more measuring points on the south-oriented roof slope, which is directly exposed to the sun.

As shown in Figure 4, a monitoring section consists of 4 slots across the roof (1,2,3,4) that can hold anemometers to monitor the air flow velocity within the ASV. Each section is equipped with 4 temperature sensors (PT100) at some points in the structure. The monitoring roofs were equipped with 6 anemometers each (5 on south side, 1 on north side): 3 omnidirectional air velocity transducer HD4V3TS2 by Delta Ohm (operating range 0.10–5.00 m/s, accuracy: ±0.10 m/s +3% f.s.) and 3 high precision omnidirectional air velocity transducer Model 8475 by TSI (operating range 0.05–2.00 m/s, accuracy: ±3% of reading +1% f.s.). The anemometers were installed so that the sensor was at the average height of the ventilated channel, between the deck and the bottom tile surface. In the MET roof only two TSI anemometers were installed in section C and E, respectively.

The temperature sensors were installed at different locations to measure: the temperature at the lower side of tiles (T_{TILE}); the temperature of the air flowing in the ASV (T_{ASV}); the temperature of the deck upper side (T_{DECK}), only sections C and E; the temperature at the ceiling ($T_{CEILING}$), only sections C and E; indoor air temperature ($T_{CHAMBER}$). The temperature sensor is a PT100 by TE Connectivity (NB-PTCO-011), a platinum resistor on a ceramics substrate (2.0 × 2.3 mm) which complies with DIN EN 60751. It is classified in tolerance class A: ± (0.15 + 0.002*|T|)°C. In addition, a heat flux plate was installed

Figure 2 Roof tiles used. From left to right, standard Portoghese, herotile Portoghese, standard Marsigliese, herotile Marsigliese.

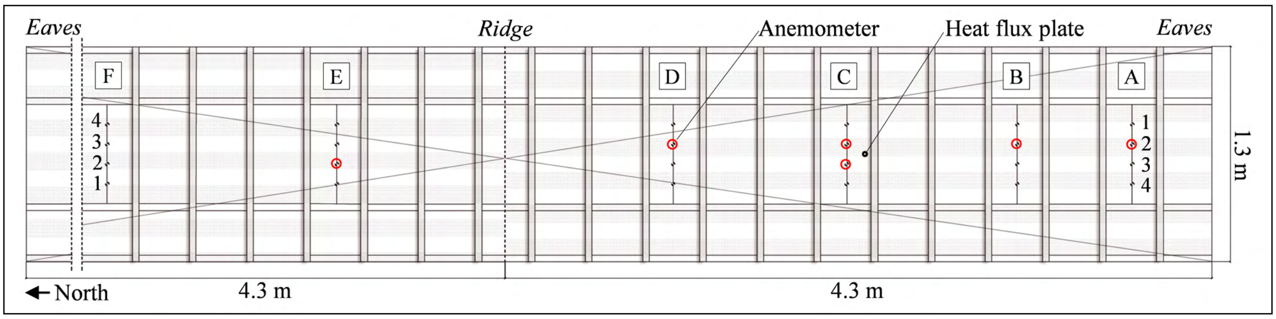

Figure 3 A ventilated roof with the monitoring sections and anemometers configuration.

on the south side ceiling of each roof, in middle position, in order to monitor the diurnal and nocturnal heat flux cycles through the roof. The heat flux plates are HFP01 by Hukseflux, uncertainty 3% m.v.

The analogic signal from the sensors is converted in a digital format by an electronic interface which communicates by means of a ModBus RTU protocol. This was chosen to exchange data between PC supervisor and slaves since it supports a large number of peripherals (up to 247). The PC supervisor polls the installed slaves through an in-house software (developed in LabVIEW environment) with a time interval of 1 min and saves the data on a database.

Finally, an installed wireless weather station collects data of local climate and then analyse the relationship between environmental conditions and the behaviour of the ventilated roofs.

RESULTS AND DISCUSSION

The thermal behaviour of the ventilated roofs is analysed during a sunny and hot day (5th August 2017) with N-E prevailing wind direction; therefore, the South pitch was downwind. The eaves section area was 50% open, similarly to a commercial ventilated roof. The 10 min average of local wind speed, outdoor air temperature and the solar radiation, are shown in Figure 5 together with the mode of wind direction data. According to that weather conditions, Figure 5 shows also the temperature trends (1h average) as measured at different layers in the middle section C of each ventilated roof, and the corresponding heat flux at the ceiling. By integrating the negative values of the heat flux the daily heat gains are: 378 Wh/m^2 in MET, 303 Wh/m^2 in P_{STD}, 251 Wh/m^2 in P_{HERO}, 277 Wh/m^2 in M_{STD}, and 265 Wh/m^2 in M_{HERO}.

In detail, the 10 min average temperatures in the sections of the South roof pitch are reported in Table 2. The values are calculated at 2 PM, when the maximum temperature is reached in the tiles and in the deck below. The air flow rate calculated on a 60 cm width (between two counter-battens) at the same time interval is also reported, according to the measured air velocity and the specific geometry of the tile.

New tile shapes (both Portoghese and Marsigliese types) prove to be effective in increasing the ASV, compared to the respective standard tiles, taken as the reference. Differences are likely to be due to the improved air permeability and may be higher when the wind blows orthogonal to eaves (which act as air intake vent). Among the roofs, the higher air flow rate was measured with P_{HERO} covering, also due to the higher cross-sectional area (+15%, P_{HERO} indeed has a higher bold roll), as well as the more favourable temperature at the ceiling. Although the temperature of the tiled roofs covering is comparable (around 60°C), a reduction in the air temperature flowing within ASV as well as in the deck temperature for P_{HERO} and M_{HERO}. As a

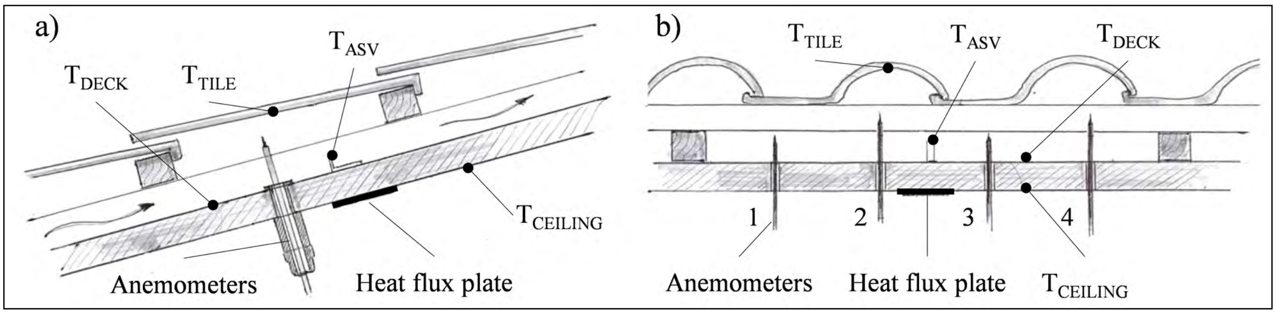

Figure 4 The monitoring section with sensors. **a)** Longitudinal section **b)** Cross section.

	TYPE	A	B	C	D	TYPE	A	B	C	D	TYPE	A	B	C	D
T_{TILE} (°C)	P_{STD}	57.8	57.6	57.1	59.9	M_{STD}	58.2	58.7	60.4	61.3	MET	56.7		67.2	67.4
	P_{HERO}	57.2	58.5	61.4	58.4	M_{HERO}	58.0	59.5	61.2	58.4					
T_{ASV} (°C)	P_{STD}	49.4	50.8	50.1	48.1	M_{STD}	50.0	51.9	51.0	48.1	MET	47.3		52.5	50.5
	P_{HERO}	47.8	48.6	47.7	44.9	M_{HERO}	49.2	51.5	48.5	44.9					
T_{DECK} (°C)	P_{STD}			47.4		M_{STD}			49.6		MET			47.8	
	P_{HERO}			43.4		M_{HERO}			46.5						
$T_{CEILING}$ (°C)	P_{STD}			33.4		M_{STD}			31.6		MET			34.4	
	P_{HERO}			31.0		M_{HERO}			31.8						
$\dot{V}_{ASV}$ (l/s)	P_{STD}	4.3	8.8	4.8	12.2	M_{STD}	2.7	5.7	4.9	6.0	MET			4.0	
	P_{HERO}		8.2	12.3	17.2	M_{HERO}	3.5	6.0	8.7	15.0					

Table 2 10 min average temperature and flow rate at 2 PM.

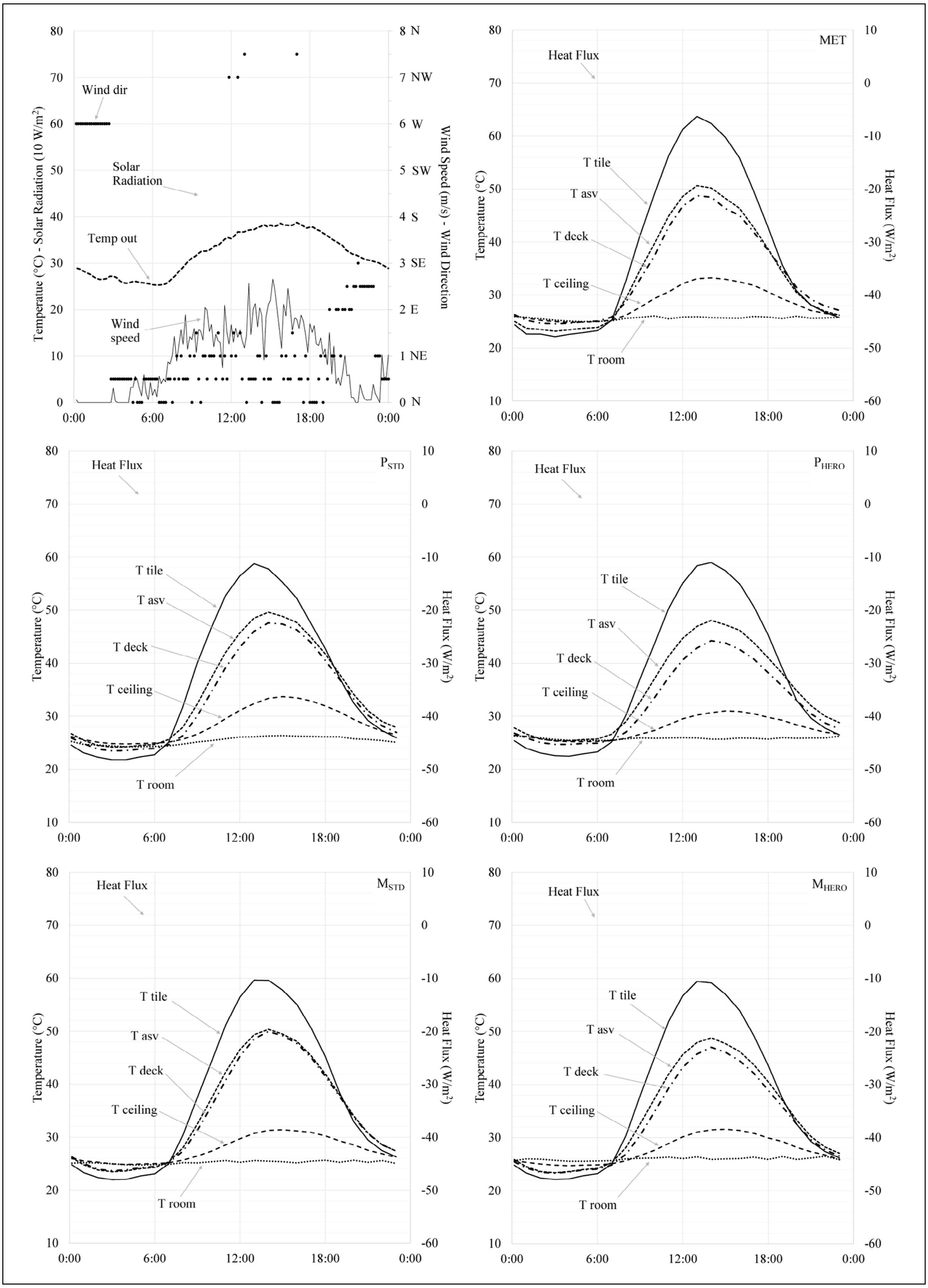

Figure 5 Daily thermal behaviour of the ventilated roofs and local weather conditions.

consequence, a relevant heat flux decrease is achieved by new roof system. The daily heat gain is 17.2% lower in P_{HERO} and 4.3% in M_{HERO} in comparison with P_{STD} and M_{STD}, respectively. Overall, the metal roof covering (not permeable to air) shows higher temperature values than tiled roofs. The temperature peak occurs about an hour earlier than in the other roofs due to the lower thermal capacity of the covering. The energy entering daily at the roof is 50% higher than in P_{HERO}.

CONCLUSIONS

According to previous researches, the use of ventilated roofs is recognized as an effective passive strategy to reduce the cooling energy demand. Their performance can be further enhanced by means of discontinuous covering, which are permeable to air. Basin on the numerical activity carried out in the European project HEROTILE, new roof tiles were designed to obtain higher air permeability, which led to an increase in the ASV in real environmental conditions, as the broad experimental testing revealed. As consequence, even better thermal performance were achieved in reducing the heat gain due to solar radiation in comparison with standard terracotta tiles covering, which are already in the market. This will produce more favourable indoor comfort conditions. In addition, it should be noted that the improvements achieved by the optimization of the tile shape towards an improvement of covering air permeability do not lead to an increase in the cost of the ventilated roof.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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