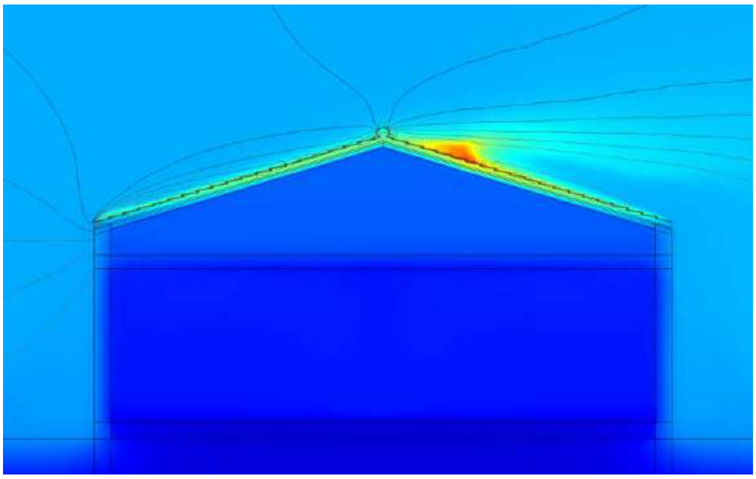
CUNIAL Spa



THERMAL BEHAVIOUR OF VENTED ROOFS IN SUMMER CONDITIONS

CONSORZIO FERRARA RICERCHE
Via Saragat, 1 – Ferrara

Title:	TECHNICAL DOCUMENT
Document n°:	Single
Scale:	-
Date:	April 2013 (resume from Technical document dated December 2012)
Supplement:	-
Scientific head:	Prof. Giovanni Zannoni – Dipartimento di Architettura, Università di Ferrara Ing. Michele Bottarelli – Dipartimento di Architettura, Università di Ferrara
Consulting :	Arch. Marco Bortoloni – Dipartimento di Ingegneria, Università di Ferrara Ing. Mattia Battarra

INDEX

1 INTRODUCTION

The traditional forms of building insulation and their role in energy savings are well recognized in cold climates, while energy performance optimization of the building envelope in hot climates is often misunderstood. Solar reflectance of roof surface, traditional insulation and thermal mass are widespread methods for reducing heat transfer inside buildings. Nevertheless, there are also alternative strategies for improving thermal performance of building envelope, such as the opportunity to have a ventilation layer in pitched roofs. This constructive technology provides thermal benefits thank to an air-flow which move along an air layer usually present at the intrados of the waterproof roof surface. This feature is commonly referred as: Above Sheathing Ventilation (ASV) and it is as an eaves-ridge open cavity present under the waterproof layer, thank to the laying of the tiles over a batten and/or counter-batten support system. Air enters both at eaves section and through the air-permeability of the overlapping tiles, and flows to the ridge, sinking the heat transfer generated by the solar radiation. Several studies have demonstrated the performance of a pitched roof, but it is not well yet investigated the impact of air-permeability of the external waterproof surface over the chimney effect occurring inside the ASV duct, because several factors contribute to the complexity of the problem, such as the increasing mass flow rate and the Buoyancy-driven forces.

This document presents the methodology and the results of a preliminary study about the summer behaviour of a light-structure pitched-roof building in which varies the air-permeability between the elements of the waterproof covering layer (tiles), compared to a concrete flat roof building. The analysis has been approached by means of a numerical model, solving the fluid-dynamic and the heat transfer problems in unsteady state. Time series for wind, solar radiation and indoor space cooling were introduced to simulate realistic boundary conditions, taking into account different air-permeability of the waterproof surface and ASV thickness of the pitched roof.

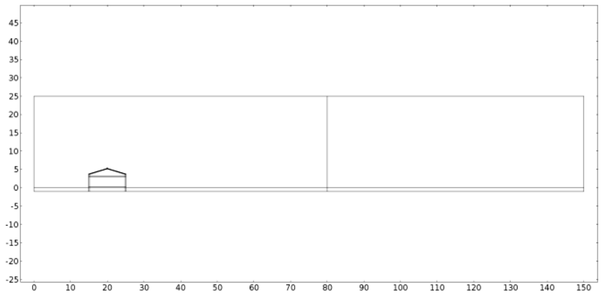
This study was financed by CUNIAL Spa under the agreement signed in July 2012 with Consorzio Ferrara Ricerche (CFR, Italy), to frame the "*Design of pitched roofs with discontinuous waterproof layer in middle-eastern geoclimatic conditions, evaluation of the performance, functionality and architectural image and comparison with other types of roof"*, under the scientific supervision of Giovanni Zannoni and Michele Bottarelli, professors at the Department of Architecture of the University of Ferrara, Italy.

2 METHODOLOGY

A numerical model was applied to analyse the summer behaviour of two different building roofs: flat roof and vented pitched roof.

2.1 MODEL DOMAINS

To compare the roof typologies, two bi-dimensional macro-domains were built (2D model) to include the entire fluid-dynamics phenomenon, according to the turbulence generated by the presence of the building. The macro-domains were also extended to one meter below the ground in order to consider the contribution of the soil in environment cooling.



Because of the need to evaluate the behaviour of the roofs on varying the configuration of specific roof elements (ASV, air-permeability of waterproof layer, air inflow at eaves section), several sub-domains were developed to simulate:

- The micro-ventilation, only obtained by means of the tiles support battens;
- The full ASV, also with different thickness of the air-cavity or with a double ventilation layer separated by a wooden board;
- The presence of an insulating layer (8 cm);
- The impact of waterproof surface emissivity;
- The air permeability of the waterproof surface, obtained by varying the gap between tiles (2.5-9-0 mm);
- The sealing of the air ventilation cavity to prevent the wind action (forced convection);
- The total or partial closure of the eaves section access to the air ventilation cavity to enhance the impact of the air permeability of the waterproof surface;
- Different external wind speed (1.25-2.50-5.00 m/s);
- The hypothesis of total absence of Buoyancy-driven forces, which excludes the contribution of natural convection.

Main sizes of the different domains

Case name	microventilation [cm]	Ventilation (ASV) [cm]	Air-Permeability (gap between tiles) [mm]	Insulation layer [cm]	Double Wooden board
Micro-ventilated	3.0	-	9.0	-	-
Micro-ventilated insulated	3.0	-	9.0	8.0	-
Micro-ventilated insulated, reduced permeability	3.0	-	2.5	8.0	-
Ventilated	3.0	8.0	9.0	8.0	-
Ventilated, reduced permeability	3.0	8.0	2.5	8.0	-
Ventilated, reduced air-cavity thickness	3.0	4.0	9.0	8.0	-
Ventilation, double wooden board	3.0	8.0	9.0	8.0	X
Ventilation, closed eaves section inlet	3.0	8.0	9.0	8.0	-

Thermal-physic properties of the layers

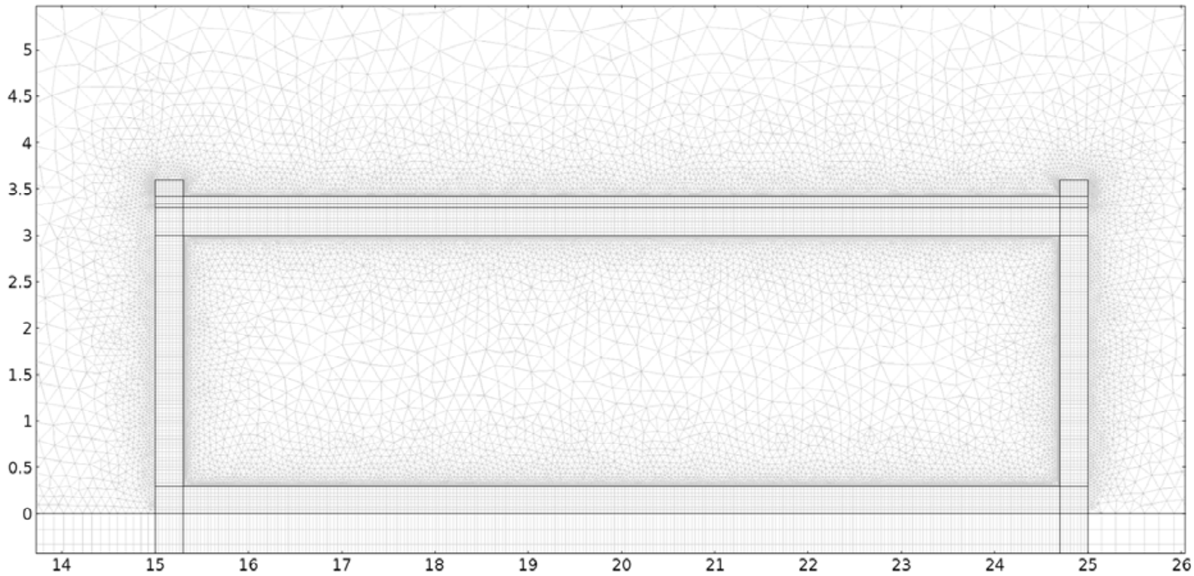
Material	*Density [Kg/m^3]*	*Thermal conductivity [W/mK]*	*Specific heat [J/kgK]*	*Emissivity [-]*
Polistyrene insulation	20	0.040	1340	-
Rockwool insulation	140	0.045	2100	-
Light concrete	1400	1.400	840	-
Autoclaved aerated concrete structure	1400	0.800	850	0.90
Walls	1000	0.800	850	0.90
Wooden board	800	0.120	2100	-
Tiles	1700	0.700	840	0.85
Thermal-reflective membrane	-	-	-	0.05
Slate self-protected membrane	-	-	-	0.60
Ground floor insulating layer	-	0.010	-	-
Ground	1600	0.800	1600	0.92

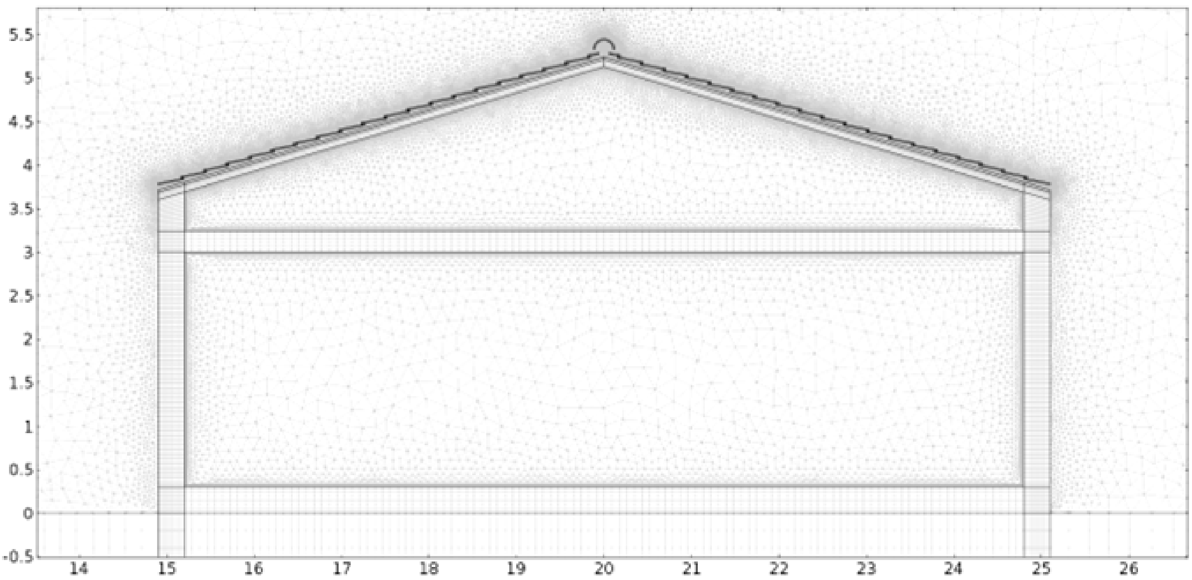
The analysis was carried out in unsteady state, coupling the fluid-dynamic problem with the heat transfer problem, and solving the previous problem with hourly variation of solar radiation and wind temperature. Wind speed was assumed with a variable profile according to the altitude. By regulating the cooling power in order to reach an indoor thermal set point (26°C), the different performances of the pitched roof, varying both the air-permeability between the waterproof elements and the functional layers of the roof, was evaluated.

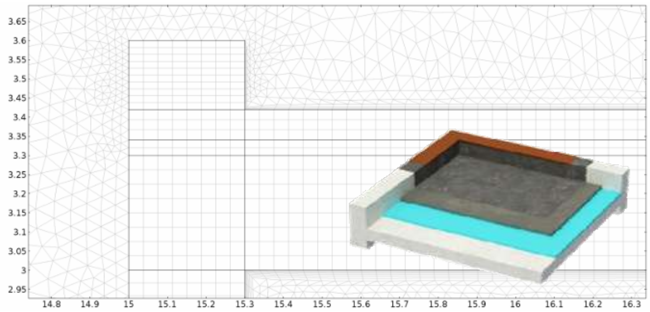
The flat roof domain considers an Autoclaved aerated concrete structure, a polistyrene insulating layer, a filling layer (sloping screed in lightweight concrete) and a membrane.

Each different type of pitched tiled is resulting from discontinuos waterproof surface with tiles, technical air layer below the tiles (micro-ventilation), ASV (ventilation), insulation layer, heat-reflecting membrane.

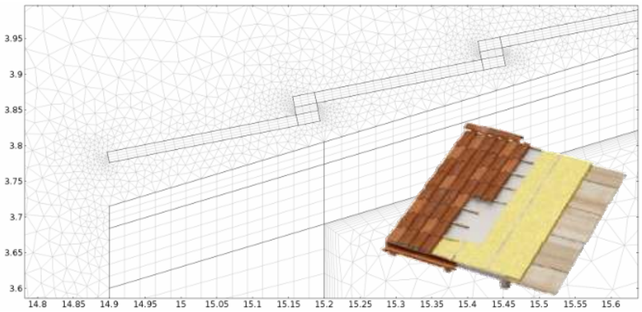
The details of the meshes for the two macro-domains are shown sideways, while the details of the sub-domains and the sketches of the roofs are presented as following.



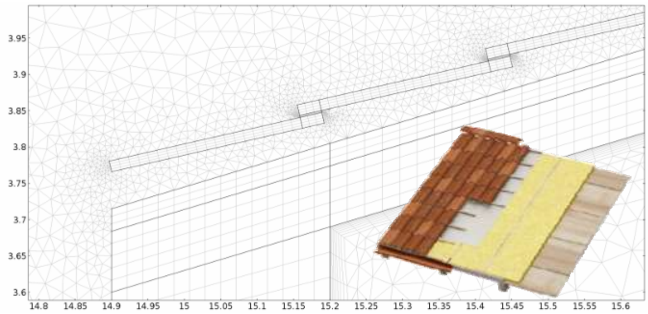




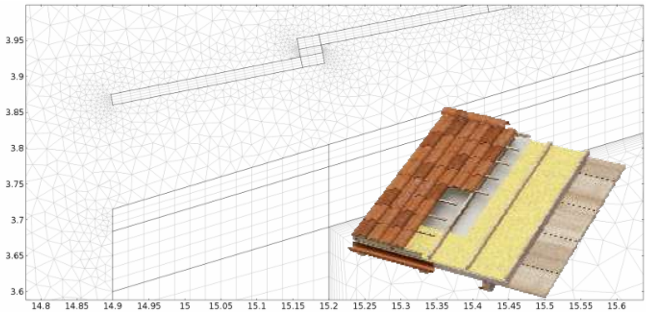
Flat roof



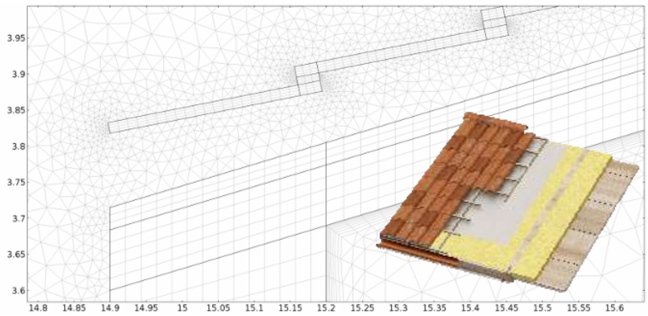
Micro-ventilated roof



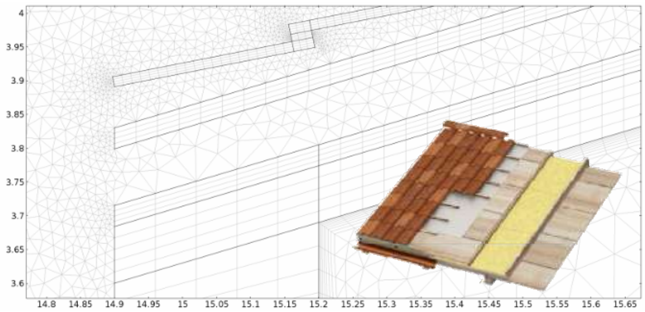
Micro-ventilated roof with reduced air-permeability between tiles



Ventilated roof



Ventilated roof with reduced ventilation layer thickness

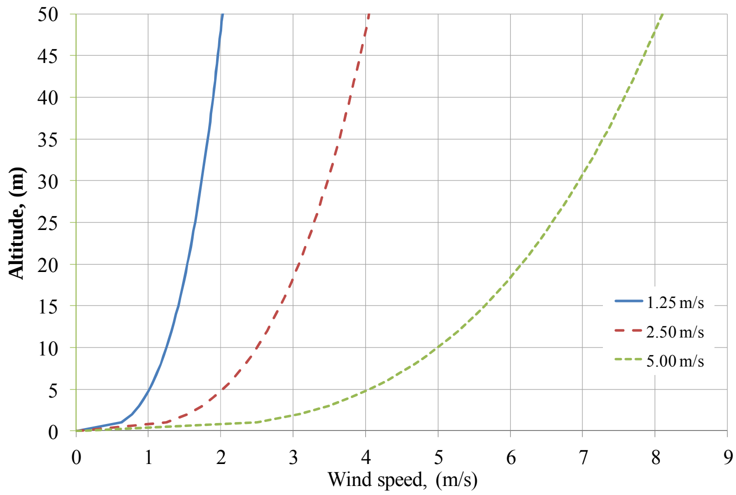


Ventilated roof with double wooden board

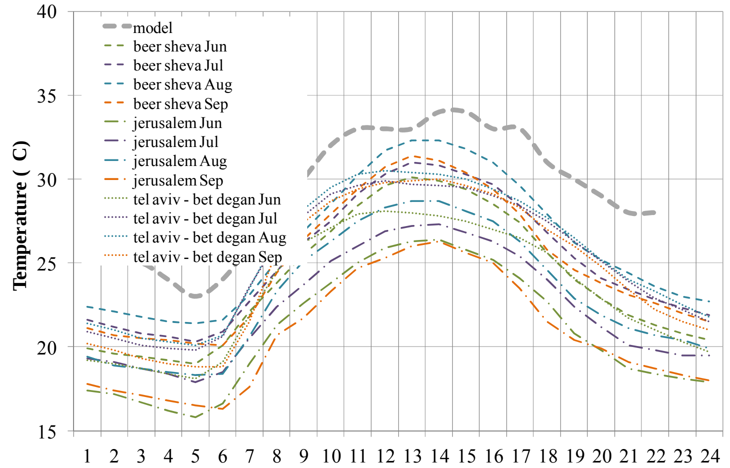
2.2 BOUNDARY CONDITIONS

The overheating of the building is strictly linked to the wind speed, to the air temperature and to the solar radiation, which change significantly during the day and require a hourly timescale to describe the phenomenon.

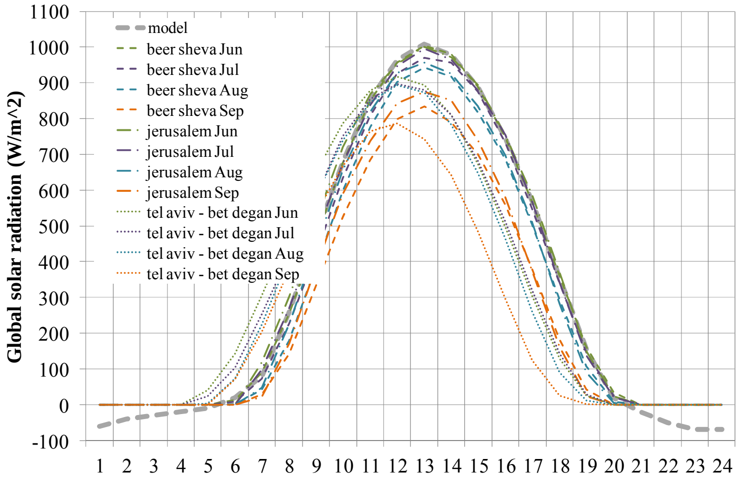
Wind represents the forced convection phenomenon which affects the building and it is defined by the speed and the air temperature. The wind is here assumed independent from time, but variable according to the altitude as showed in the picture, where v_0 assumes three values 1.25/2.50/5.00 m/s and z_0 the value of 10 m. Because the covering of the hypothesized building is on average 5m above the ground, wind speed at this height is respectively 1 and 2 m/s. This is a conservative value, since the average wind speed monitored by the Israeli meteorological service is normally higher.



The time series of the assumed wind temperature is shown sideways, together with the reference temperature reported in the *EnergyPlus®* database, for Be'er Sheva, Jerusalem, Tel Aviv and Beit Dagan in June, July, August and September. The time series constitutes the average in June at the Beit Dagan station in 2011, as acquired directly from: http://weatherspark.com/ and it is 1-2°C higher.



With regards to solar radiation, the assumed time series is reported in the next picture, together with the months from June to September at the Tel Aviv, Beit Dagan, Be'er Sheva and Jerusalem stations, as present in *EnergyPlus®* database. This time series is extracted from the IMS database (http://www.ims.gov.il/) as regards June in Tel Aviv, again traces the maximum values in a conservative way and introducing the night effect as well, that consists in a thermal radiation issued towards the sky by the roof's surface at night. The reported values, albeit being particularly low, partly compensate the absence of night effect phenomenon in the patterns that were used. For the sake of simplicity, solar radiation was set in the model as thermal conduction perpendicular to the ground, with variable intensity.



Considering the functioning of an air conditioning system, located in the ground-floor room of the flat roof building to maintain an enough comfortable temperature of about 26°C, we supposed a cooling-off power of around 150 W/m, that is for each meter deep of the 2D model. Considering the size of the hypothetical building (9.6x2.7 m^2 x 2.7 m height), this translates to a specific power of about 6 W/m^3. This value takes into account not only the heat exchange in the roof, but also what happens along the vertical walls and on the ground slab.

3 RESULTS

The numerical analysis was conducted for several cases with the aim of evaluating the internal temperature of the building, with respect to the variation of the different geometric shapes of the flat roof and pitched roof and a series of other specific conditions.

The final goal was to estimate:

- The effect of the presence/absence of the ASV on the indoor thermal comfort;
- The importance of the "stack effect" with regards to the Buoyancy-driven forces;
- The relevance of air-permeability of the waterproof surface (tiles) on the efficiency of the Above Sheathing Ventilation;
- The impact of eaves section opening on the air-permeability and in the Above Sheathing Ventilation efficiency;
- The energy consumption for space cooling in the main reference cases.

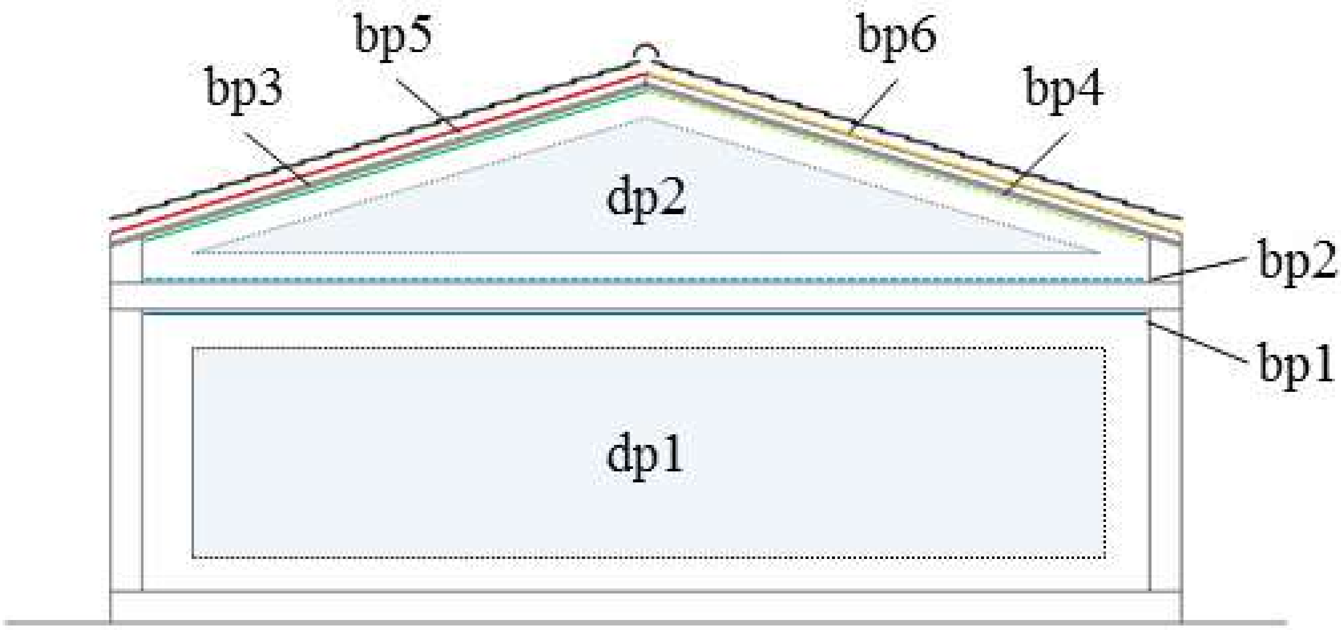
Because of that, the cases match to different ASV sizes, various air-permeability level, presence/absence of the Buoyancy-driven forces, various opening percent at eaves section, low and high wind speed and so on. The next summary table codes all cases that were resolved.

CASE	Roof technology	Insulat. (cm)	Air-duct size (cm)	ε	Air-Permeab. (mm)	Wind (m/s)	Air cond. Power (W/m)	NOTE
P/ε=0.60/p=0.0/w=1.25/P=150	Flat roof	4	-	0.60	-	1.25	150	STANDARD
M_NI/ε=0.85/p=8.0/w=1.25/P=150	Micro-vented	-	3	0.85	9.0	1.25	150	Not insulated
M/ε=0.85/p=8.0/w=1.25/P=150	Micro-vented	8	3	0.85	9.0	1.25	150	STANDARD
M/ε=0.85/p=8.0/w=1.25/P=80	Micro-vented	8	3	0.85	9.0	1.25	80	Lower powered
M/ε=0.60/p=8.0/w=1.25/P=150	Micro-vented	8	3	0.60	9.0	1.25	150	
M/ε=0.85/p=2.5/w=1.25/P=150	Micro-vented	8	3	0.85	2.5	1.25	150	
V/ε=0.85/p=9.0/w=1.25/P=150	Vented	8	8	0.85	9.0	1.25	150	STANDARD
V_DT/ε=0.85/p=9.0/w=1.25/P=150	Vented	8	8	0.85	9.0	1.25	150	Double batten with wooden board
V/ε=0.85/p=9.0/w=1.25/P=60	Vented	8	8	0.85	9.0	1.25	60	Lower powered
V/ε=0.85/p=9.0/w=2.50/P=150	Vented	8	8	0.85	9.0	2.50	150	
V/ε=0.85/p=2.5/w=1.25/P=150	Vented	8	8	0.85	2.5	1.25	150	
V/ε=0.85/p=2.5/w=2.50/P=150	Vented	8	8	0.85	2.5	2.50	150	
V/ε=0.85/p=9.0/w=5.00/P=150	Vented	8	8	0.85	9.0	5.00	150	
V_CR/ε=0.85/p=9.0/w=1.25/P=150	Vented	8	4	0.85	9.0	1.25	150	Low thickness ventilation cavity
V/ε=0.85/p=0.0/w=1.25/P=150	Vented	8	8	0.85	-	1.25	150	No air permeability
V_NFV/ε=0.85/p=9.0/w=1.25/P=150	Vented	8	8	0.85	9.0	1.25	150	no volume forces (NVF)
V_CC_NFV/ε=0.85/p=0.0/w=1.25/P=150	Vented	8	8	0.85	-	1.25	150	Closed channel + NVF+ no perm.
V_IR/ε=0.85/p=9.0/w=2.50/P=150	Vented	8	8	0.85	9.0	2.50	150	Halved inlet at eaves section 50%
V_IC/ε=0.85/p=9.0/w=2.50/P=150	Vented	8	8	0.85	9.0	2.50	150	Closed inlet at eaves section
V/ε=0.85/p=0.0/w=2.50/P=150	Vented	8	8	0.85	-	2.50	150	No air permeability, higher wind

Each case was solved for a simulation period of 4 days, departing from an initial condition of the corresponding unsteady state deducted on the basis of average boundary conditions. The results are here presented as fluid-dynamic solutions for the velocity fields and as maximum/minimum temperatures in relevant observation points of the building.

The relevant points where the temperature was taken are codified as follow:

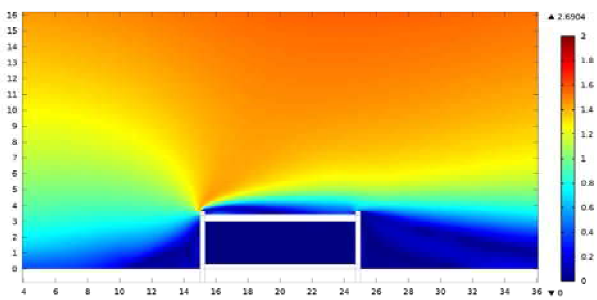
- *bp1:* intrados surface of internal horizontal slab
- *bp2:* extrados surface of internal horizontal slab
- *bp3:* intrados upwind pitch of the roof (ceiling surface)
- *bp4:* intrados downwind pitch of the roof (ceiling surface)
- *bp5:* extrados upwind pitch of the roof (lower surface of above sheating ventilation chamber)
- *bp6:* extrados downwind pitch of the roof (lower surface of above sheating ventilation chamber)
- *dp1:* ground floor room (average volumetric value)
- *dp2:* loft (average volumetric value)

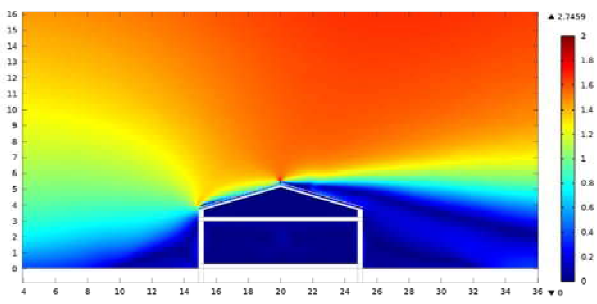


The next table presents the temperatures of all resolved cases, adopting the codes of the previous figure.

	Ground floor room ***dp1***		Loft ***dp2***		Intrados upwind pitch ***bp3***		Extrados upwind pitch ***bp5***		Intrados downwind pitch ***bp4***		Extrados downwind pitch ***bp6***	
CASE	min	max	min	max	min	max	min	max	min	max	min	max
P/ε=0.60/p=0.0/w=1.25/P=150	25.4	26.3	-	-	26.0	26.9	25.7	67.7	-	-	-	-
M_NI/ε=0.85/p=8.0/w=1.25/P=150	26.5	27.9	29.3	40.7	28.8	44.1	26.5	56.7	28.8	45.2	26.7	61.3
M/ε=0.85/p=8.0/w=1.25/P=150	22.8	23.3	25.2	27.9	25.2	28.5	26.1	57.4	25.2	28.8	26.0	62.3
M/ε=0.85/p=8.0/w=1.25/P=80	25.7	26.3	27.4	30.0	27.4	30.7	26.3	57.7				
M/ε=0.60/p=8.0/w=1.25/P=150	22.3	22.7	24.5	26.7	24.6	27.1	25.9	50.5	24.6	27.3	26.1	54.5
M/ε=0.85/p=2.5/w=1.25/P=150	23.0	23.5	25.3	28.2	25.4	28.9	25.7	57.3	25.4	29.1	26.3	66.5
V/ε=0.85/p=9.0/w=1.25/P=150	21.6	22.0	23.7	25.1	23.7	25.4	25.3	41.7	23.7	25.5	26.0	44.1
V_DT/ε=0.85/p=9.0/w=1.25/P=150	21.8	22.1	23.9	25.0	23.9	25.2	25.3	53.0	24.1	25.5	27.9	45.4
V/ε=0.85/p=9.0/w=1.25/P=60	25.6	25.9	26.6	28.0	26.6	28.3	25.5	42.0	26.6	28.4	26.3	43.8
V/ε=0.85/p=9.0/w=2.50/P=150	21.6	22.0	23.5	24.6	23.5	24.7	24.5	36.5	23.6	24.9	25.4	39.9
V/ε=0.85/p=2.5/w=1.25/P=150	21.8	22.2	23.9	25.5	24.0	25.8	25.4	42.4	24.0	26.0	26.3	47.6
V/ε=0.85/p=2.5/w=2.50/P=150	21.9	22.4	23.9	25.5	23.9	25.6	24.6	38.4	24.0	26.1	25.5	47.6
V/ε=0.85/p=9.0/w=5.00/P=150	21.6	22.0	23.4	24.4	23.4	24.5	23.7	34.5	23.4	24.6	24.3	35.9
V_CR/ε=0.85/p=9.0/w=1.25/P=150	22.0	22.5	24.2	26.0	24.2	26.4	25.5	47.1	24.2	26.6	25.9	49.7
V/ε=0.85/p=0.0/w=1.25/P=150	22.0	22.4	24.1	25.7	24.1	26.1	25.5	42.9	24.2	26.4	26.5	50.4
V_NFV/ε=0.85/p=9.0/w=1.25/P=150	21.6	21.9	23.8	25.5	23.8	25.7	25.3	42.4	24.0	26.1	26.8	51.3
V_CC_NFV/ε=0.85/p=0.0/w=1.25/P=150	23.4	23.8	26.4	28.6	26.4	28.8	28.8	51.4	26.7	29.4	32.3	62.3
V_IR/ε=0.85/p=9.0/w=2.50/P=150	21.8	22.2	23.7	25.0	23.8	25.3	25.1	40.4	23.8	25.3	25.3	40.9
V_IC/ε=0.85/p=9.0/w=2.50/P=150	22.0	22.4	24.0	25.7	24.0	26.0	24.9	44.6	24.1	26.0	25.8	45.2
V/ε=0.85/p=0.0/w=2.50/P=150	22.1	22.5	24.1	25.6	24.1	25.7	24.7	38.8	24.2	26.2	25.7	46.9

3.1 <u>FLUID DYNAMICS</u>

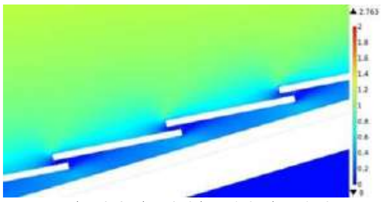




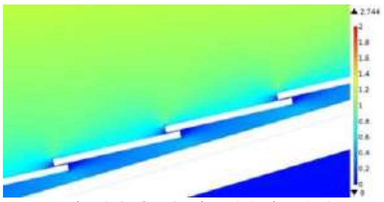
Considering that in each of the numerical cases solved we introduced a variation of the geometry or of the boundary values, the fluid-dynamic solutions vary for each case. Their variation, however, is significant only for a reduced part of the roof, in relation to the different waterproof surface air-permeability, thickness of the ASV and speed of the wind. The two images represent the fluid-dynamic solutions for the two macro-domains (flat roof and pitched roof) at 2pm.
More interesting are the details of the solution at 2/3 of inside the ASV at 2pm, for the pitched roof. The analysis of these graphs show that the air speed inside the ventilation cavity increase towards the ridge, this is evident at least for these cases:

- V/ε=0.85/p=9.0/w=1.25-2.50-5.00/P=150
- V_IR/ε=0.85/p=9.0/w=2.50/P=150
- V_IC/ε=0.85/p=9.0/w=2.50/P=150

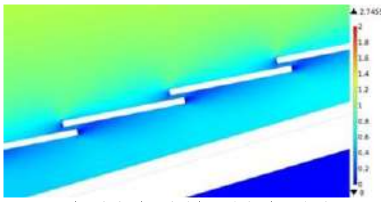
In particular, the partial or total closing of the air entrance at eaves section determines an increase of the air flowing through the air permeability of the discontinuous waterproof layer (overlapping of the tiles). Moreover, the reduction from 9.0 to 2.5 mm of the gaps, that simulate the air-permeability through the overlap of the tiles, clearly determines an excessive restriction which, compared to the assessed pressure, limits the contribution to the above sheathing ventilation. In other words, shifting from an open air-permeability of 2.0% of the overall surface to 0.6%, determines a reduction of the air range entering in the ventilation cavity, and thus a less significant cooling off considering the cooler temperature of the section compared to the roof surface. Finally, the geometry and the overlap of the tiles does not seem to ease the entrance of air in the ventilation cavity.



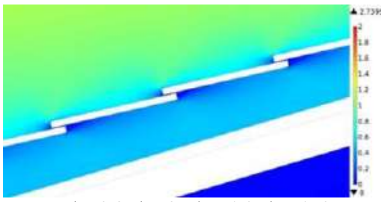
M/ε=0.85/p=9.0/w=1.25/P=150



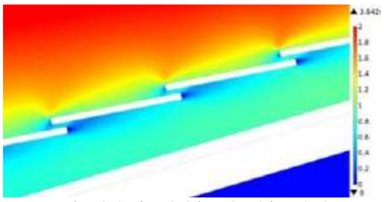
M/ε=0.85/p=2.5/w=1.25/P=150



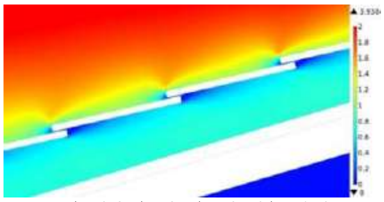
V/ε=0.85/p=9.0/w=1.25/P=150



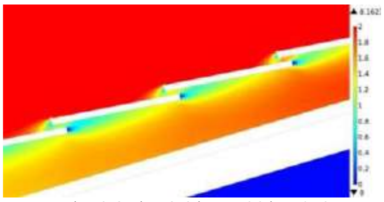
V/ε=0.85/p=2.5/w=1.25/P=150



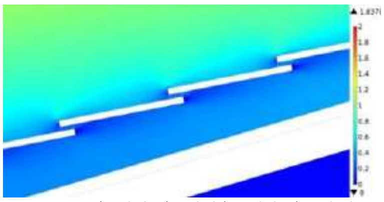
V/ε=0.85/p=9.0/w=2.50/P=150



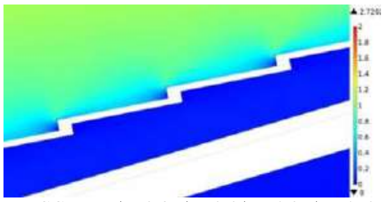
V/ε=0.85/p=2.5/w=2.50/P=150



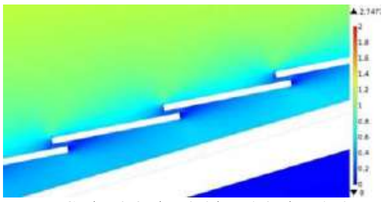
V/ε=0.85/p=9.0/w=5.00/P=150



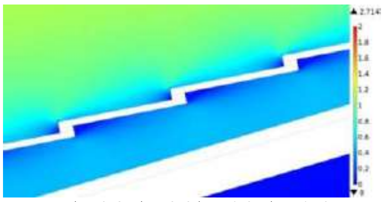
V_NFV/ε=0.85/p=9.0/w=1.25/P=150



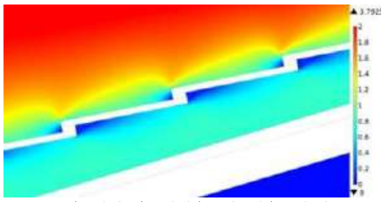
V_CC_NFV/ε=0.85/p=0.0/w=1.25/P=150



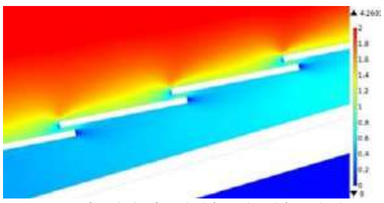
V_CR/ε=0.85/p=9.0/w=1.25/P=150



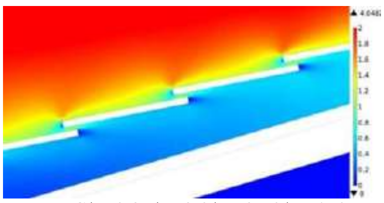
V/ε=0.85/p=0.0/w=1.25/P=150



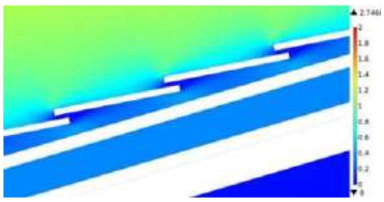
V/ε=0.85/p=0.0/w=2.50/P=150



V_IR/ε=0.85/p=9.0/w=2.50/P=150



V_IC/ε=0.85/p=9.0/w=2.50/P=150

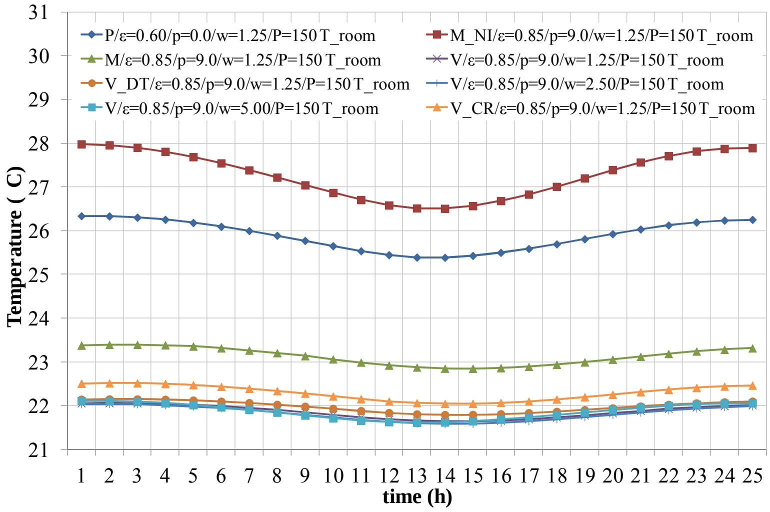


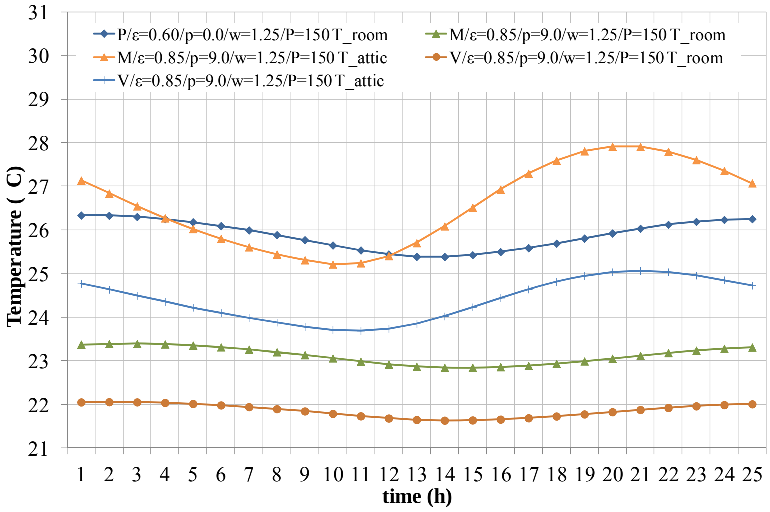
V_DT/ε=0.85/p=9.0/w=1.25/P=150

3.2 HEAT TRANSFER

With regards to the summary table, the following arguments can be done.

3.2.1 Effect of the loft volume and the Above Sheathing Ventilation





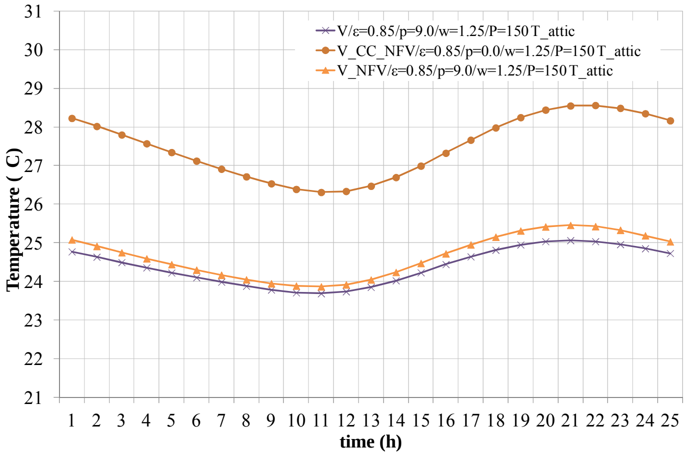
The maximum temperature in the space with a flat roof (P/ε=0.60/p=0.0/w=1.25/P=150) is of 26.3°C, while the minimum temperature is 25.4°C, which means a difference of 0.9°C. These performances were reached in the hypothesis that the air conditioning system generates a cooling power of 150 W/m. For the similar case with micro-ventilated roof (M/ε=0.85/p=8.0/w=1.25/P=150), the temperatures fall down respectively to 23.3 and 22.8 °C. In the extreme unfavourable case with non-insulated, micro-ventilated roof (M_NI/ε=0.85/p=8.0/w=1.25/P=150), the maximum temperature in the ground floor environment rises to 27.9°C, while the minimum temperature rises to 26.5°C. This means that the presence of a "*buffer*" area (loft), between the roof and the living ground floor space with air conditioning, determines a strong abatement of the thermal wave, increasing the overall insulation. In the micro-ventilated roof with no insulation, although it is impossible to compare with the insulated flat roof, the presence of a loft constitutes a barrier to the external thermal load.

Introducing a standard ASV in the tiled roof (V/ε=0.85/p=9.0/w=1.25/P=150), temperatures fall further until they reach a maximum value of 22.0°C and a minimum value of 21.6°C. Consequently, as well as significantly improving the performance in terms of thermal insulation, the ASV further decreases the gap between minimum and maximum temperature, improving the overall comfort of the ground floor environment.

In the case of the standard ventilated roof and with all other conditions being equal, the wind speed does bear any effect on the temperature of the ground floor environment, but only on the temperature of the loft (see the cases: V/ε=0.85/p=9.0/w=1.25/P=150, V/ε=0.85/p=9.0/w=2.50/P=150, V/ε=0.85/p=9.0/w=5.00/P=150).

If the thickness of the ASV was reduced by half (V_CR/ε=0.85/p=9.0/w=1.25/P=150), the temperature would increase both in the ground floor environment both in the loft, with a 1:2 ratio. In the specific case, the maximum temperature in the environment would increase from 22.0 to 22.5°C, while in the loft it would climb from 25.1 a 26.0°C.

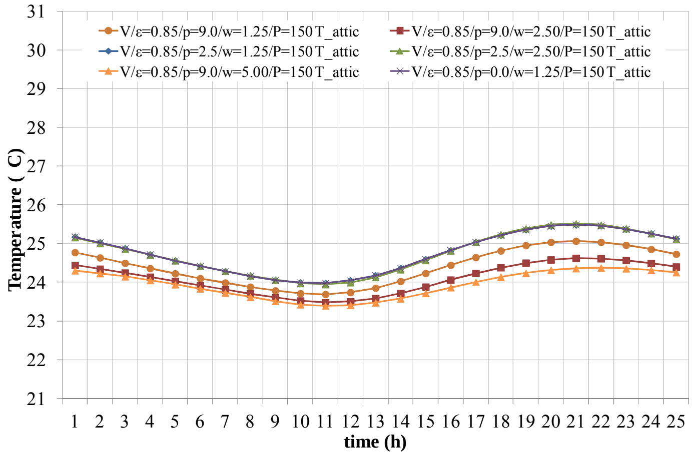
3.2.2 Impact of Buoyancy forces



The impact of volume forces can be evaluated by comparing the temperatures of the standard ventilated case (V/ε=0.85/p=9.0/w=1.25/P=150) and of the similar case but without buoyancy: (V_NFV/ε=0.85/p=9.0/w=1.25/P=150). This second case is obtained by leaving out the relationship between air density and temperature. While the temperatures in the ground floor environment do not change (min/max 21.6/22.0°C), the loft temperatures increase minimally considering the absence of volume forces. In this case the maximum temperature increases from 25.1 to 25.5°C. *Ceteris paribus*, the free convection phenomenon linked to Buoyancy forces is moderate.

Considering the case V_CC_NFV/ε=0.85/p=9.0/w=1.25/P=150, that is the standard ventilated roof case without volume forces and with a completely closed ventilation chamber (immobility of the air in the cavity), a significant increase of the temperatures is observed even in the environment with a maximum of temperature of 23.8°C and minimum of 24.8°C. Combining this argument with what previously pointed out, the ASV ventilation represents an added value of great impact, and how this value is substantially linked to a forced convection phenomenon caused by the external wind, rather than from the volume forces triggered by the different air density.

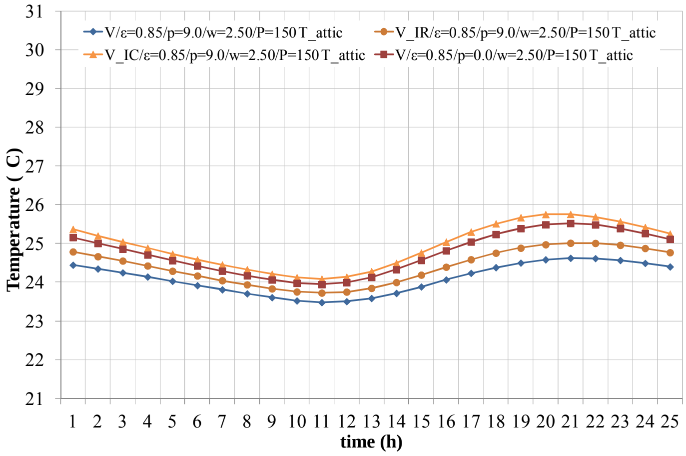
3.2.3 Impact of air-permeability of the waterproof layer



At first, the evaluation of the impact of air-permeability level in the discontinuous waterproof layer is deducted from the comparison of the standard insulated ventilated roof case (V/ε=0.85/p=9.0/w=1.25/P=150) with air permeability between tiles of 9.0mm with the same standard case but with reduced air permeability to 2.5mm (V/ε=0.85/p=2.5/w=1.25/P=150) and subsequently with the non-permeable case (V/ε=0.85/p=0.0/w=1.25/P=150). The gradual reduction to 2.5mm and then to 0.0mm of the air-permeability of the waterproof layer (tiles) determines a significant increase of the maximum and minimum temperatures not only in the loft but also in the underneath ground floor environment. The temperature in the loft increases from 25.1°C to 25.5°C and then 25.7°C. In particular, the first increase of 0.4°C caused by the initial shift from 9.0 mm to 2.5 mm is then halved (0.2°C) as a result of the next decrease, showing that 2.5mm represents a moderate permeability which significantly reduces the inflow of air in the ventilation cavity.

Moreover, while with 9.0mm air-permeability thickness, as wind speed increases, temperatures decrease, in the 2.5mm case as the wind doubles, temperatures are unchanged. In other words, for these geometries and the simplifications that have been adopted, a reduction in the air-permeability from 9.0mm to 2.5mm determines a decrease in performance which almost equates to the decrease assessed with absence of air-permeability. In this latter case, the ventilation is only ensured by the air entrance in the eaves upwind section of the ventilation layer.

3.2.4 Impact of the free passage of air at eaves section



In the numerical model, the wind hits the building on the left side, determining overpressure and, consequently, a depression on the opposite side. This condition affects the Above Sheathing Ventilations upwind and downwind, with an air inflow at the left eaves section (free passage at the eaves section, tiled surface air-permeability) and an extraction effect on the right pitched side. For the standard ventilated roof case with null permeability (V/ε=0.85/p=0.0/w=1.25/P=150) the ASV is only ensured by the free passage of the air at the eaves section of the ventilation chamber. Albeit with null air permeability of the waterproof surface, the free passage through the eaves section alone allows a limitation of the increase of the maximum temperature in the ground floor environment of only 0.4°C, compared to the standard ventilated roof with air permeability of the waterproof surface (V/ε=0.85/p=9.0/w=1.25/P=150).

Comparing the temperatures of the:

- standard reference roof case with wind at 2.5 m/s (V/ε=0.85/p=9.0/w=2.50/P=150),
- with halves opening of the eaves section of ventilation chamber (V_IR/ε=0.85/p=9.0/w=2.50/P=150),
- with no opening of the eaves section of ventilation chamber (V_IC/ε=0.85/p=9.0/w=2.50/P=150)
- with roof case with null air permeability of the waterproof surface (V/ε=0.85/p=0.0/w=2.50/P=150),

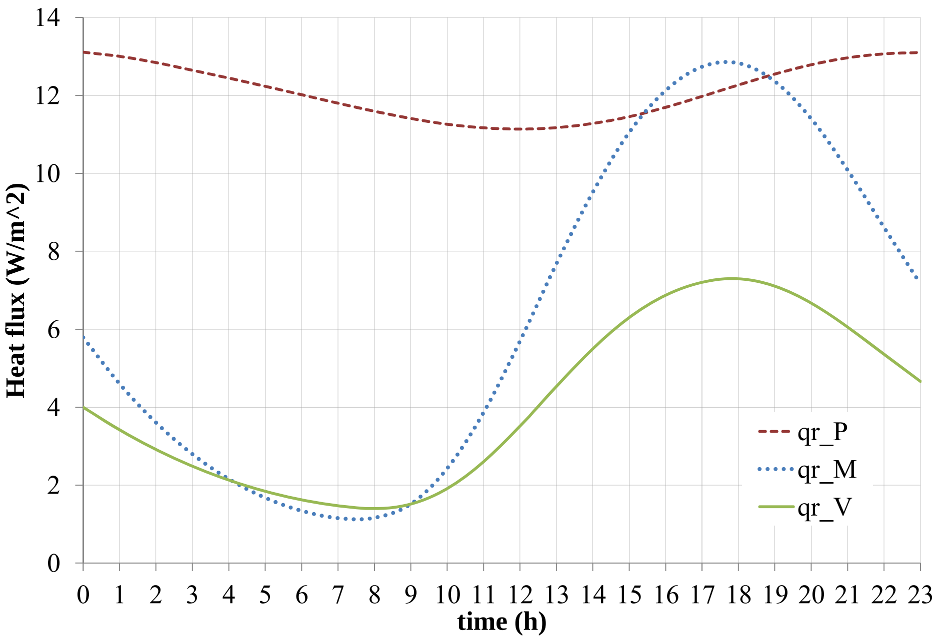
it is possible to observe that, similarly to the previous considerations about the impact of the level of air-permeability of the waterproof layer, these increase significantly at the same rate. The minimum and maximum temperatures are all but similar for the ground floor environment and the loft, in both cases with null permeability and with closed eaves section.

Consequently it can be argued that, in the conditions that we postulated, the impact of the total closure of the eaves section of the ventilation chamber is equivalent to the null air-permeability of the waterproof layer. The only substantial difference is linked to the direction of the wind. Indeed, while for air permeability the wind impact angle on the roof presumably has a limited effect until reaching the direction of the ridge line, the same cannot be said for the air entrance at eaves section. In the case considered, the perpendicularity of the wind to the upwind wall of the building fosters this effect significantly, but this condition degenerates quickly as changes the impact angle. In this sense, the air permeability of the waterproof layer clearly constitutes a more reliable and frequent effect.

3.3 ENERGY BALANCE

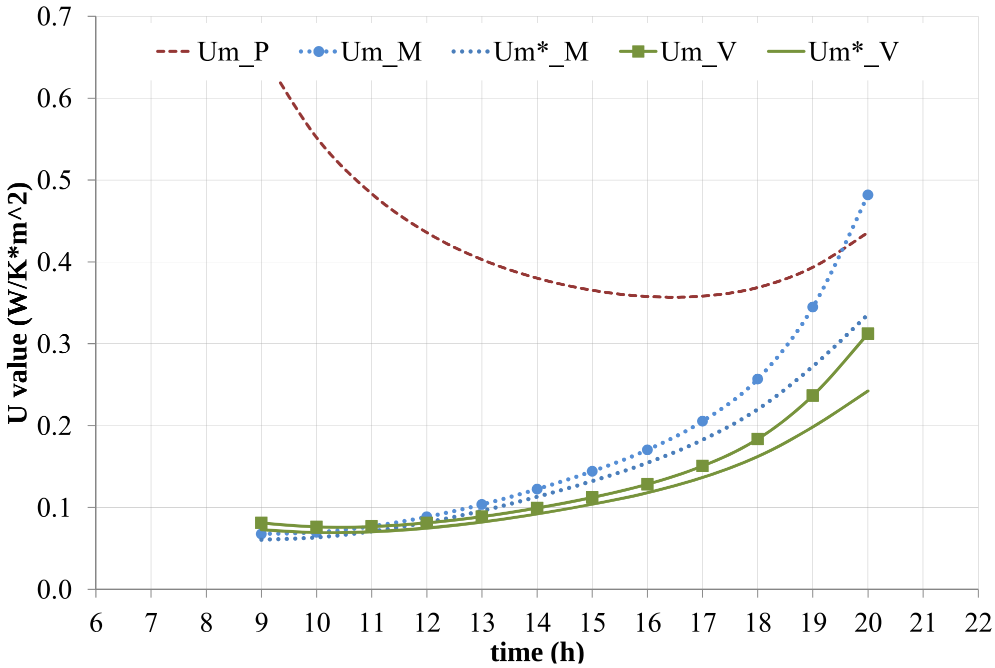
3.3.1 Heat fluxes

For the assumed boundary conditions, the trend of the thermal fluxes that are assessed at the intrados of the standard roof are reported in the follow picture (*bp1* for the flat roof case, average between *bp3/bp4* for the pitched roof case). The heat flux in the flat roof case is 12 W/m^2 on average, in the micro-ventilated pitched roof case it is about 6.4 W/m^2 and in the ventilated pitched roof case it is about 4.0 W/m^2. For the flat roof case, the oscillation is somewhat reduced because of the massive structure, while for the pitched roof cases the oscillation shows a marked increase.



The trend of the equivalent transmittance is reported in the further picture, as determined by an average accumulated from 9am to 8pm, in a different way for the different cases:

- for the flat roof case (*Um_P*), the coefficient is the relationship between the thermal flux and the temperature difference between the ground floor environment (*dp1*) and at the lower surface of the ASV chamber (*bp6*);
- for the pitched roof case (micro-ventilated *_M*, ventilated *_V*), the value is averaged between the following two:
  - *Um*, the average value obtained from the ratio between the windward and leeward fluxes and the respective temperatures of the external waterproof layer and of the loft (*dp2*);
  - *Um**, in analogy to the previous average value, but considering the ground floor environment temperature (*dp1*) instead the loft temperature (*dp2*).



3.3.2 Air conditioning requirements

To maintain a comfort temperature (~26°C) in the room of the building with the flat roof, a cooling power of 150 W per meter of development of the building has to be postualed. This power level covers the energy need not only consequent to the performance of the roof, but also of the rest of the envelope of the building. In particular, the vertical walls are not considered insulated. Because of the size of the ground floor room (9.6x2.7 m^2), the specific power becomes 5.8 W/m^3 (~150/9.6/2.7), without taking into account the latent heat from condensiation linked to air humidity, which is not considered here for simplicity's sake. To evaluate the powers needed to maintain the same temperature in the other standard domains (micro-ventilated and ventilated pitched roof), several attempts were conducted to regulate the power to obtain a similar maximum temperature. These power levels drops to 80 W for the micro-ventilated pitched roof and to 60 W for the ventilated roof case, that compared to the cubic meter of air-conditioned environment become 3.0 and 2.3 W/m^3 respectively. Consequently, the micro-ventilated roof would express a power of 52% of the flat roof and 40% of the ventilated roof.

Assuming an energy cost which includes the electric residential kilowatt-hour of 0.59 NIS/kWh_e and a COP (coefficient of performance) of the chiller equal to 3.0, the thermal kilowatt-hour cost becomes 0.20 NIS/kWh. On average, the volume of a standard building could estimated at about 500 m^3, therefore the complete air-conditioning would cost 69.6/36.0/27.6 kWh_t per day for the flat/microventilated/ventilated roof cases, assuming 24h/day air conditioning. This would translate to a daily cost of 13.9/7.2/5.5 NIS, which means that a hypothetic 180-day cooling season would cost 2502/1296/990 NIS. Overall, one would save 1206 NIS/season by installing a micro-ventilated insulated pitched roof, while with ventilated roof the saving would be 1512 NIS/season.

These arguments should be considered of an explorative nature and a first approximation, in relation to all the simplifications and to the macro numbers adopted to estimate the duration of the space cooling period. However, given the adopted precautions, these numbers should represent a minimum value which, combined to the limted extra-cost of a pitched roof compared to the cost of a flat roof, should result in a limited pay-off period.

4 REMARKES

With regards to the approximations and the simplifications that were introduced in the present study, the results of the numerical approach allow to make the following remarks.

Under similar boundary conditions and similar model domains, the vented tiled pitched-roofs displays indoor temperatures lower than the flat roof (average 2-4°C), which was due to the insulating effect of the under roof added volume, which reduced the thermal wave caused by solar radiation. This is reflected in the indoor comfort in terms of radiation temperatures and thermal stability.

Analysing the behaviour inside the above sheathing ventilation of the ventilated pitched roof, the convective effect, in its natural and forced components, determines and overall 2°C reduction of the temperatures in the ground floor environment. The share related to the volume forces, however, becomes irrelevant even in the presence of a very weak wind, while the reduction of the air-permeability waterproof layer determines a significant decrease of the performance. This leads to believe that the thermal benefit is strictly linked to the naturally forced convection induced by the wind, rather than to buoyancy-driven fluid flow of the free convection.

The thermal benefit of natural convection affecting the above sheathing ventilation is generated by the wind inflowing both through the air-permeability of the discontinuous waterproof layer (2% of the overall surface), both at the entrance of the eaves section (free eaves section of 8 cm, the same thickness of the ventilation chamber). However, because the wind was supposed coming from a direction that is favourable to the opening of the eaves section (perpendicularly to the building facade), it must be that the different benefit coming from these two different functional characteristics (air permeability of the waterproof surface and opening at eaves section) could also be significantly different at different wind direction with respect to the building facade. In particular, while the percentage benefit given by the air entrance at eaves section could reduced drastically, the percentage linked to the air permeability of the waterproof surface may be more independent, in relation to the widespread presence of discontinuities.

In order not to go beyond the maximum internal temperature of the flat roof case (26.3°C), the cooling-off power for a building with standard micro-ventilated pitched roof should be reduced by 48%, while for the standard ventilated roof the reduction would amount to 60%. These values refer to conservative external wind and heat conditions and thus they should represent minimum values, liable to better results.

This represents a significant energy saving, which allows to suppose short payback period of the higher cost of pitched roofs than flat one, however modest.