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Annual thermal performance of ventilated roofs in different climates: an energy analysis

Prestazioni termiche annuali di tetti ventilati in climi diversi: un'analisi energetica

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Abstract

According to the increasing desire and necessity to use all the available indoor spaces, the attics are more and more used as living spaces in buildings. In regions with high level of solar radiation such as Mediterranean countries, the roofs receive large amounts of solar radiation during the summer, and their superficial temperature can reach values between 60 and 70 °C causing unacceptable indoor conditions. As a matter of fact, ventilated roofs have gained more and more interest in recent years due to the possibility to reduce the cooling load and the energy needs of buildings. The paper reports on the effect of ventilated roofs, comparing the annual energy performances of a typical residential building with a ventilated roof with one with a traditional no-ventilated roof. The simulations are carried out by Trnsys coupled to Comis, a multi-zone air infiltration, ventilation and contaminant transport simulation program. The two software are used in a parallel operation strategy to simulate the ventilated roof building in different climates, in order to analyze the energy effectiveness of the different solutions varying the slope of the roof, the thickness of the air layer, the orientation and the thermal insulation level of the building. The results are discussed in terms of cooling and heating energy needs of the reference building.

Keywords:

- Ventilated roof
- Cooling load
- Energy saving
- Mediterranean climate

Sommario

I sottotetti sono spazi sempre più utilizzati negli edifici di tipo residenziale. Nelle regioni con elevati livelli di insolazione come i paesi dell'area mediterranea i tetti ricevono grandi quantità di energia solare durante la stagione estiva, portando la loro temperatura fino a valori attorno ai 70 °C. Ciò comporta condizioni di comfort non accettabili negli ambienti sottostanti. I tetti ventilati rappresentano una soluzione che sta acquisendo sempre maggior interesse negli ultimi anni perché consentono una riduzione dei carichi di raffrescamento dell'edificio.

L'articolo riporta uno studio riguardante l'effetto dell'utilizzo di un tetto ventilato in un edificio di riferimento a confronto con un tetto tradizionale non ventilato. Le simulazioni dinamiche sono realizzate mediante l'accoppiamento di Trnsys con Comis, un software che consente di simulare in maniera dinamica i fenomeni di infiltrazione, ventilazione e trasporto di contaminanti in aria tra zone termiche adiacenti. I due software sono utilizzati in parallelo al fine di simulare il funzionamento di un edificio con tetto ventilato in diversi climi, con lo scopo di valutare le prestazioni energetiche annuali al variare dell'inclinazione della falda, dello spessore dello strato d'aria, dell'orientamento e del livello di isolamento dell'edificio. I risultati vengono presentati e discussi in termini di fabbisogni termici per il riscaldamento e il raffrescamento dell'edificio di riferimento.

Parole chiave:

- Tetto ventilato
- Carico termico di raffrescamento
- Risparmio energetico
- Clima Mediterraneo

Introduction

The European Directive 2018/844/UE promotes the improvement of energy performances of buildings considering local climate conditions and costs, and outlines the common general picture for buildings energy performance calculation. By the end of 2020, only "nearly zero-energy" buildings will be allowed to be built, that is buildings having a very high energy performance and with the very low amount of energy required covered to a very significant extent by energy from renewable sources.

Both public administrations and scientific communities across the world have identified the potential and need for energy efficiency in the buildings, and initiated significant efforts in this direction during the last years. Both active strategies (improvements to heating, ventilation and air conditioning systems, electrical lighting, smart control and monitoring systems, etc.) and passive strategies (improvements to building envelope elements) can enhance buildings energy efficiency. The latter have seen a renewed interest in more recent period due to the increasing pressure of energy crisis, energy cost and environment pollution.

Several studies were carried out on improvements in the building envelope and their impact on building energy utilization. Sadineni et al. [1] made an exhaustive technical review of different types of energy efficient walls such as Trombe walls, ventilated walls, and glazed walls. Performance of different fenestration technologies including aerogel, vacuum glazing and frames were also presented, and advances in energy efficient roofs were discussed. More recently, the same topic was tackled by Amirifard et al. [2]: they concluded that despite the passive techniques feature good performance in decreasing energy consumption, implementing the most effective combination of these passive technologies, with respect to the characteristics of the buildings, remains a big challenge for building designers/managers.

In [3], a design of systems that use novel configurations of existing system components in order to demonstrate their ability to improve the performance of heating, ventilation and air conditioning (HVAC) systems was presented. Yang et al. [4] presented a review of thermal comfort research and issues pertinent to energy conservation in buildings. The objective was to better understand how thermal comfort is related to and affects the broader energy and environmental issues involving social-economic, fuel mix and climate change. Moreover, Cuce and Riffat [5] presented a comprehensive review of the latest developments in glazing technologies, and currently available high performance glazing products and technologies were analyzed in detail with application examples. As a specific case for Jordan, an assessment study for the present Jordanian building codes that directly affect the efficiency of the passive building design has been conducted in residential sector [6], revealing significant influences of some main variables (orientation of building, dimension of setback and size of window) on the thermal performance of buildings. Furthermore, the Authors analyzed in the past the energy impact of buildings' insulation materials in Italy: the analysis was developed from both the energy (taking into account both the savings in the annual climatization and the energy consumed to produce them, Life Cycle Assessment, LCA) and the economic point of view (Life Cycle Cost, LCC) [7]. More recently, Tushar et al. [8] investigated the factors for the selection of appropriate thermal insulations to reduce the excessive electricity consumption and greenhouse gas emissions for heating and cooling of residential buildings situated in different Australian climatic conditions.

In Europe, thermal building regulations were traditionally developed with the aim of reducing the energy needs for winter air conditioning; this often had the drawback of the "over insulation" of buildings that could reduce the effectiveness of traditional passive strategies (thermal mass, air ventilation), creating adverse effects on indoor thermal comfort and making consequently very expensive the cooling of the building [9] [10].

Roofs are a critical part of the building envelopes both from the construction point of view (they are highly susceptible to solar radiation and other environmental changes) and from the energy point of view (they account for large amounts of heat gains/losses). A solution to mitigate the use of air conditioning plants is the reduction of heat fluxes through the building roof utilizing techniques that reduce the cooling load. These include a compact cellular roof layout with minimum solar exposure, domed and vaulted roofs, naturally or mechanically ventilated roofs, micro ventilated roofs, high roofs and double roofs [11]. Other methods are white-washed external roof surfaces, or new cool materials to reduce solar absorptivity called cool roofs: these have high solar reflectance in the solar radiation wavelength range and high emissivity in the near infrared range [12]. Finally, roofs covered with vegetation to provide humidity and shade (green roof) [13]-[15], and usage of high thermal capacity materials such as concrete to minimize peak load demand ([1], [16]) are other interesting techniques.

In this study we concentrate on the benefits that ventilated roof can give with respect to a traditional no-ventilated roof, by means of a coupled Trnsys-Comis transient simulation model [17]. Ventilated roofs have the same structure of traditional pitched roofs (Figure 1). In this study, we suppose they are made by terracotta coverings (i.e. concave brick tiles) over a structure of wooden rafters fixed by riveting to a bearing structure (sheathing, thermal insulation, concrete fool), allowing forming air ducts with 10 cm thickness under the roof tiles. The air flow into the duct is obtained by a continuous opening along the eaves course (inlet) and along the ridge one (outlet), protected by shutters to prevent small animals and dirt to entry the channels. A tilt angle of 30° is fixed.

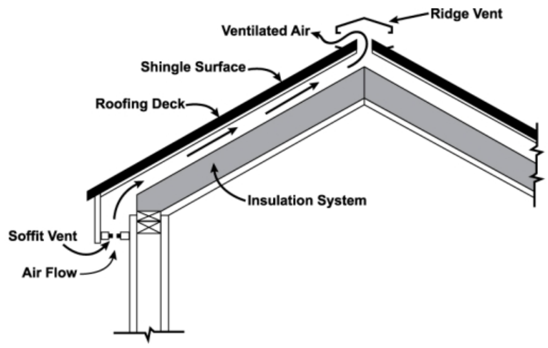

Figure 1 – Scheme of the ventilated roof (www.energyauditingblog.com)

Figura 1 – Schema del tetto ventilato (www.energyauditingblog.com)

The ventilation of the roof may be created by natural (that is generated by difference of temperatures) or forced (generated by mechanical apparatus, i.e. blowers) convection. Here we suppose natural convection (buoyancy effect).

Several studies report that pitched ventilated roofs, in summer period, can achieve an interesting energy saving (in the order of ten per cent) compared to a traditional roof. In [18], a series of tests on advanced ventilated roof components were carried out in full-scale dimensions and under real weather conditions, revealing a better thermal performance of the ventilated roof during daytime and on

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a daily basis compared to a conventional structure. D'Orazio et al. [19] presented the results of an experimental study aimed at analyzing the effects of roof tile permeability on the thermal performances of ventilation ducts. A computational fluid dynamic software was used in [20] with the aim of acquiring a better knowledge of the thermo-fluid dynamic behavior of the air within the ventilated roof (characterized by a different placement of thermal layer insulation respect to the air gap). The results of the study showed that the ventilation of roofs can reduce significantly the heat fluxes (up to 50%) during summer season. Furthermore, Ciampi et al. [21] presented the case of roofs with small-sized-thickness duct in which the air flow was laminar (micro-ventilation). They obtained an energy saving even exceeding 30% by using ventilated roofs in summer, compared to the same non-ventilated structure. More recently, Bottarelli et al. presented an analysis of an innovative tile covering for ventilated pitched roofs, both from theoretical [22] and experimental [23] point of view.

The study of the ventilated structures is a very complex procedure that requires a detailed knowledge of the air flow rate and its thermodynamic properties, thermo-physical properties of materials, the values of convective coefficients, the intensity of solar radiation, the outdoor air properties (temperature and humidity), velocity and wind direction. The aim of this work (by the use of Trnsys coupled to Comis in a parallel operation strategy) is to investigate the thermal performance of a ventilated roof for a typical residential building in function of the slope of the roof, the thickness of the air layer, the resort, the orientation and the thermal insulation level of the building.

METHODS

Description of the building for the case study

In order to implement an easily comprehensible theoretical analysis, the building considered is a parallelepiped detached house, two floors (ground floor and attic) with the dimension of 10 m x 12 m x 6.88 m (Figure 2).

The building is divided in four thermal zones, two per floor. U-values for opaque and transparent surfaces are reported in Table 1; they satisfy the Italian limits for the F zone by the Decree of the President n. 412/93 (the colder one with more than 3000 heating degree days).

Each floor has a surface of 100 m² (net of internal walls and stairs); windows surface is fixed according to compulsory standards (1/12 and 1/8 of floor surface for the attic and the ground floor respectively). Windows are double glazes 4-16-4 mm filled with argon, solar factor 0.59. To simulate mobile shielding it is supposed an annual average external shading factor equal to 0.2 (due to rolling shutter) and

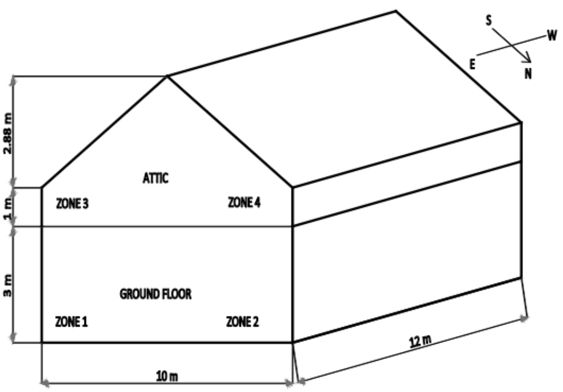

Figure 2 – Schematic view of the simulated building

Figura 2 – Vista schematica dell'edificio simulato

Table 1 – U-values for the opaque and transparent surfaces with respect to the Italian limits for the F zone by the Decree of the President n. 412/93

Tabella 1 – Valori di trasmittanza termica per le superfici opache e trasparenti rispetto ai limiti per la zona F del D.P.R. n. 412/93

Element	U-value (W m^{-2} K^{-1})	
	Model	F zone
External wall	0.254	0.33
Ground floor	0.288	0.32
Roof	0.228	0.29
Window	1.27	1.3
Window (with frame)	1.8	2

a variable internal shading factor (by curtains) equal to 0.38; the latter is considered only in the period May-September with solar radiation on the window greater than 300 W m^{-2}. Natural air infiltration is set at 0.6 vol h^{-1}, internal heat gain to 112 W per thermal zone, and indoor air set point temperature is fixed at 20 °C and 26 °C respectively during heating and cooling season (relative humidity 50% and 60% respectively).

Modelling of heat and air transfer

The ventilated roof is simulated both in Trnsys and Comis by defining three thermal zones, two simulating the cavities on the South and North pitches (CAV_SOUTH and CAV_NORTH), and one simulating the ridge (RIDGE). The air enters the cavities in the eaves lines and goes out by the ridge. Each cavity is simulated by two layers, one made of the terracotta coverings facing the atmosphere (ONLY_COVER in Table 2 as an example for the Southern pitch), and the other made of all the other materials.

Table 2 – Layers constituting the cavity on the South-facing pitch

Tabella 2 – Strati costituenti la cavità nella falda sud

CAV_SOUTH (Volume 6.65 m³)			
Wall type	Area (m²)	Trnsys category	Orientation
PITCH_SOUTH	66.51	Adjacent to zone 3	Slope 30° facing the South
INT_WALL	0.58	External	East
INT_WALL	0.58	External	West
ONLY_COVER	66.61	External	Slope 30° facing the South
BEARING_WALL	0.1	Adjacent to RIDGE	

For example, the South cavity is made by the PITCH_SOUTH wall (made of 2 cm of internal plaster, 20 cm of cement floor, 4 cm of cement screed, 7 cm of cement gradient screed, 12 cm of polystyrene, 3 mm sheathing) adjacent to the thermal zone 3 (attic), and by the ONLY_COVER wall adjacent to the atmosphere. The two small vertical walls (INT_WALL) facing the East and the West determine the dimension of the cavity (10 cm thickness, 5.77 m width and 11.59 m length of the ridge). The BEARING_WALL is a fictitious wall that couples the cavity to the ridge. The latter is modelled as a rectangular section (18 cm x 26 cm) thermal zone with length equal to the ridge, and a further horizontal wall made of an internal steel layer plus an external terracotta covering.

To simulate the ventilation in the cavities, three new inputs (to Trnbuild) are defined: they are the external air infiltration rates in input to the cavities thermal zones, calculated by Comis. Similarly, the coupling air flows between the different thermal zones in input to Trnbuild are calculated by Comis.

In Comis, the same three thermal zones (CAV_SOUTH, CAV_NORTH and RIDGE) are defined. Furthermore, four façades (one per each opening) are defined with different values for the pressure coefficient, and connections between the openings are defined too.

Once the Comis model has run, a.cif file is generated in Simulation Studio. Such a file is pointed by type 157 in the Trnsys model; this type has in input the air temperature and humidity, wind velocity and direction, and the temperature of the CAV_SOUTH, CAV_NORTH and RIDGE thermal zones. In each time step of the simulation, type 157 gives in output the air infiltration values for the three zones (in vol h^{-1}) and the four coupling values (in kg h^{-1}). In order to increase robustness of the model and to improve convergence during the dynamic simulation, type 93 in the Trnsys model is used to pass in input to Comis the air temperatures of the three thermal zones constituting the ventilated roof of the previous time step (Figure 3).

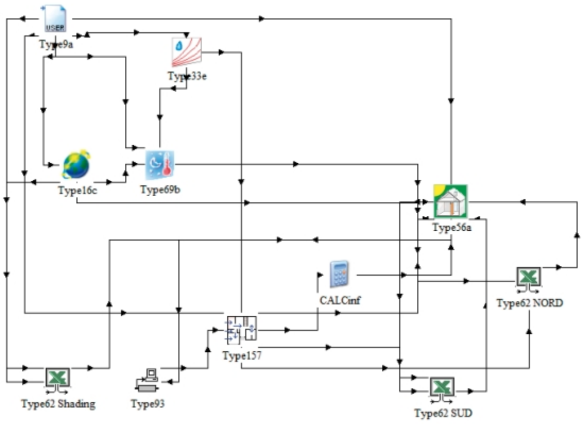

Figure 3 – **The complete Trnsys model**

Figura 3 – Modello Trnsys completo

Figure 3 reports also the presence of type 62 (one per each cavity). For each time step, they open and execute an Excel file that implement the algorithm for the calculation of the convective coefficients for the two cavities, in input to type 56 (the building). As a matter of fact, both natural and forced (that is induced by the wind pressure) convection could be present in the cavity. The calculation of the convective coefficient is different in function of the type of the flow, laminar (*Re*<4000) or turbolent (*Re*>4000) [24]:

a) Natural-forced convection with laminar flow

The Authors use the relations given by Brinkworth [25]. Nusselt number is approximated by Equation 1:

$$Nu = 5.385 + \frac{0.015}{L^+} \qquad (1)$$

The convective coefficient h_c is calculated by Equation 2:

$$h_c = \frac{\lambda \cdot Nu}{D_{id}} \qquad (2)$$

where λ is the thermal conductivity of air (0.026 W m^{-1} K^{-1}) and D_{id} is the hydraulic diameter (given the width *W* and the thickness *D* of the cavity, D_{id} is equal to $2 \cdot W \cdot D/(W+D)$). L^+ is the characteristic length, calculated by Equation 3 that is solved iteratively by Newton-Raphson scheme:

$$\frac{Gr \cdot D_{id} \sin(\theta)}{Pr}(L^+)^3 + \frac{\Delta p_w D_{id}^4}{\rho v^2 L^2}(L^+)^2 - 48L^+ - 0.837 = 0 \qquad (3)$$

where *Gr* is the Grashof number, *Pr* is the Prandtl number, θ is the cavity slope angle, ρ the air density, v the air cinematic viscosity, *L* the cavity length, Δp_w is the pressure difference in the openings of cavity due to the wind (only differences giving an upward flow are considered). *Gr* and *Pr* are calculated using air thermophysical properties (viscosity, density and specific heat) at the mean temperature between inlet and outlet of the cavity.

b) Natural-forced convection with turbulent flow

The relation developed by Gnielinski [26] is used (Equation 4):

$$Nu = \frac{(f/8)(\mathrm{Re} - 1000)\mathrm{Pr}}{1 + 12.7(f/8)^{0.5}(\mathrm{Pr}^{2/3} - 1)} \qquad (4)$$

where *f* is the friction factor calculated by the relation by Swamee-Jain [27] (Equation 5):

$$f = \frac{0.25}{\left[\log\left(\frac{\varepsilon}{3.7D_{id}} + \frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^2} \qquad (5)$$

and ε is the roughness of the cavity, fixed at 0.0005 m.

RESULTS AND DISCUSSION

Energy analysis

A first analysis concerns the study of the air flows in the cavities in some typical days during both winter and summer for the climate of Milan. In order to evaluate the effect of natural ventilation, no wind is supposed initially. Figure 4 and Figure 5 depict the natural air flow in the two cavities during daytime (when air enters in the eaves line and goes out from the ridge line due to the heating of air inside the cavities by solar radiation): air flow in the North cavity is marginal respect to the South one in winter, while it is comparable in summer when the sun is higher on the horizon and so solar radiation is consistent also in the North pitch. During night-time, air inside cavities

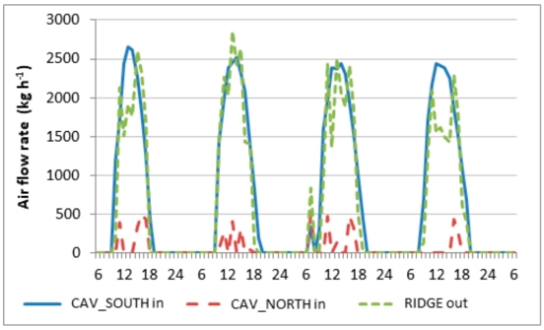

Figure 4 – **Air flows during daytime hours in four winter days**

Figura 4 – Portate d'aria durante le ore diurne per quattro giornate invernali

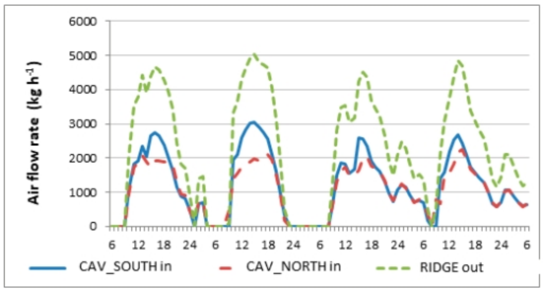

Figure 5 – **Air flows during daytime hours in four summer days**

Figura 5 – Portate d'aria durante le ore diurne per quattro giornate estive

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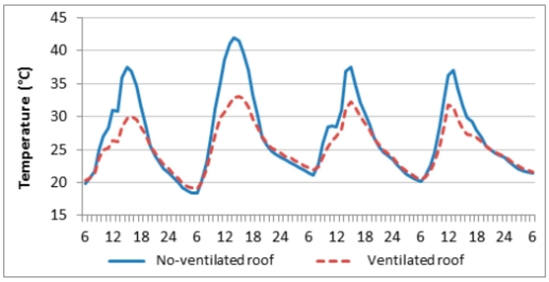

Figure 6 – Temperature of the upper surface of the thermal insulation layer (South pitch cavity): comparison between ventilated and no-ventilated roof (summer)

Figura 6 – Temperatura della superficie superiore dello strato di isolamento termico (cavità della falda sud): confronto tra tetto ventilato e non (estate)

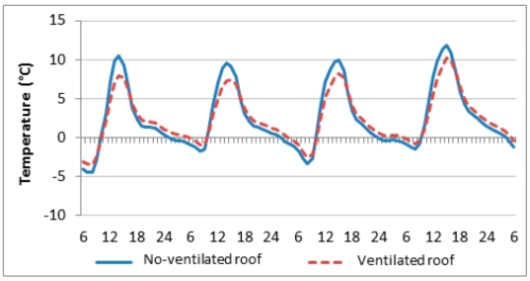

Figure 7 – Temperature of the upper surface of the thermal insulation layer (South pitch cavity): comparison between ventilated and no-ventilated roof (winter)

Figura 7 – Temperatura della superficie superiore dello strato di isolamento termico (cavità della falda sud): confronto tra tetto ventilato e non (inverno)

Table 3 – Energy needs for the two models (ventilated roof and no-ventilated) divided by the two floors

Tabella 3 – Fabbisogni energetici per i due modelli (tetto ventilato e non ventilato) suddivisi tra i due piani

	Thermal zones 1+2		Thermal zones 3+4	
	Heating (kWh)	Cooling (kWh)	Heating (kWh)	Cooling (kWh)
No-vent. roof	4891	975	6408	991
Vent. roof	4893	969	6400	921

Table 4 – Cooling energy needs for the attic thermal zones

Tabella 4 – Fabbisogni di raffrescamento per le zone termiche del sottotetto

	Cooling zone 3 (kWh)	Cooling zone 4 (kWh)
No-vent. roof	555	436
Vent. roof	506	415

Table 5 – Energy needs for ventilated roof (considering and not the effect of wind) divided by the two floors

Tabella 5 – Fabbisogni energetici per il tetto ventilato (con e senza effetto del vento) suddivisi tra i due piani

	Thermal zones 1+2		Thermal zones 3+4	
	Heating (kWh)	Cooling (kWh)	Heating (kWh)	Cooling (kWh)
Vent. roof wind on	4893	969	6400	921
Vent. roof wind off	4893	970	6399	960

becomes colder and colder due to the roof radiative heat exchange with the sky, so the flow is from the ridge to the eaves (this effect is more evident in summer).

It is interesting to analyze the thermal behavior of the two pitches comparing the performance of a ventilated and a no-ventilated roof, considering the wind. For the South-exposed pitch, the ventilation involves an increase of the heat exchange with external air during daytime (roof temperature is lower in ventilated roof); this an advantage in summer (Figure 6), but a penalization in winter (Figure 7).

A different behavior is observable during night-time, when the temperature of the upper surface of the thermal insulation layer in ventilated roof is greater than in no-ventilated roof: the effect is a decreasing in the heat losses, that is an advantage in winter, but a drawback in summer. It is worth to note that, for the North-exposed pitch, a different behavior is deduced by the simulation results: ventilated roof has a positive effect during all 24 hours (in daytime there is not substantially air flow in the cavity, during night-time air flow is from the ridge to the eaves). The results in terms of building energy needs for heating and cooling are reported in Table 3.

Ventilated roof allows an energy advantage in summer (cooling needs decrease by 76 kWh, that is 4%) while there is substantially no difference in winter. Table 4 highlights that the positive effect of ventilation is greater in the South-exposed pitch (zone 3) with a reduction of cooling needs by 9%.

In order to analyze the effect of the wind on the performance of ventilated roof, the model is run setting to zero wind velocity as well. Impact on season heating needs is substantially null, while there is a quite important saving on cooling needs (40 kWh of the total 76 kWh, see Table 5 and Table 3).

Influence of different variables

The influence of other parameters on building cooling energy needs is analyzed (the effects on the heating needs are quite negligible). Figure 8 depicts the effect of increasing the slope of the pitches and the thickness of the cavities. In both cases, the effect is positive because of the increase of the convective heat exchange coefficients. Conversely, the marginal improvement decreases (for example it is no more useful to increase thickness of the cavities besides 15 cm).

All the previous analyses are developed referring to a very insulated building (satisfying the Italian limits for the F zone, Table 1). Figure 9 depicts the effect of different U-values satisfying the limits for the E zone and even less stringent limits, as reported on Table 6, for the same climate of Milan, in order to simulate existing less insulated buildings. The energy saving on cooling needs increases as the thermal insulation decreases, as the thermal inertia of the building decreases.

Finally, the same building is placed in different climates, varying the thermal insulation according to the limits of the respective thermal zones (Figure 10). The energy savings in winter are negligible, while in summer they increase in milder climates with respect to Milan (even if they are always around 5% in relative terms) mainly due

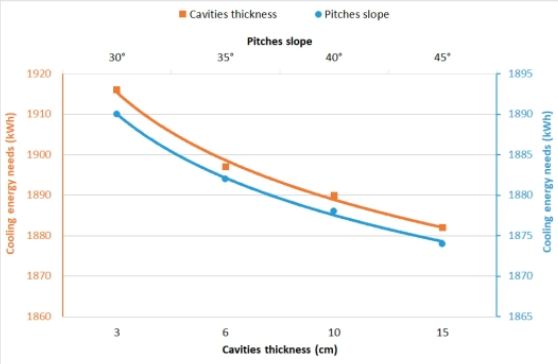

Figure 8 – **Cooling needs varying cavities thickness (bottom x-axis) and pitches slope (top x-axis)**

Figura 8 – Fabbisogni di raffrescamento al variare dello spessore della cavità (asse x inferiore) e della pendenza della falda (asse x superiore)

Table 6 – **U-values of the opaque surfaces for the different cases analyzed**

Tabella 6 – Valori di trasmittanza termica delle superfici opache per i diversi casi analizzati

	U-value (W m⁻² K⁻¹)			Insulation thickness (cm)		
	Wall	Floor	Roof	Wall	Floor	Roof
Base	0.254	0.288	0.228	10	10	12
F	0.33	0.32	0.29	7	8.9	8.9
E	0.34	0.33	0.3	6.7	8.5	8.5
E+	0.36	0.36	0.32	6	7.5	7.6
E++	0.4	0.4	0.36	5.3	6.6	6.6
E+++	0.43	0.43	0.4	4.9	6.2	6.2

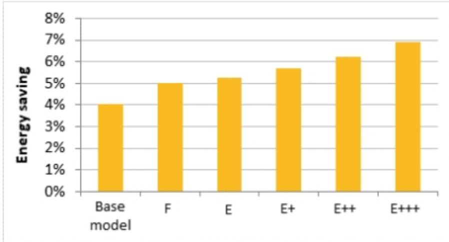

Figure 9 – **Energy saving on cooling energy with the ventilated roof varying the thermal insulation of the building**

Figura 9 – Risparmi nel fabbisogno di raffrescamento con il tetto ventilato al variare dell'isolamento termico dell'edificio

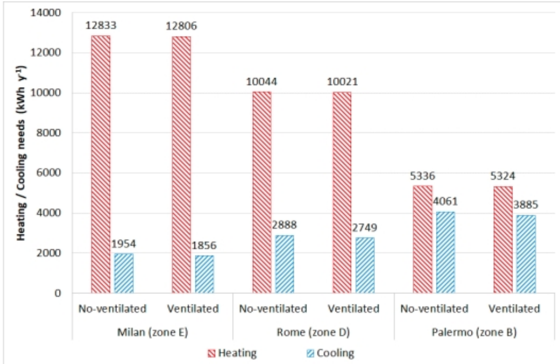

Figure 10 – **Energy needs comparison between ventilated and no-ventilated roof for three different climates**

Figura 10 – Fabbisogni di raffrescamento a confronto tra tetto ventilato e tetto non ventilato per tre climi diversi

to the greater solar radiation and the lower building thermal insulation in Southern resorts.

Other variables could have an impact on cooling energy needs mainly of the thermal zones 3 and 4 (the attic): for example, varying the orientation of the building as the pitches facing the East and the West decreases the cooling energy in the same order of magnitude of decreasing the thermal insulation.

Conclusions

This study is focused on the comparison of the energy performance of a ventilated vs a no-ventilated roof in a reference building, made by a ground floor and an attic. The results show that ventilation has substantially no effect in winter: during daytime the upward flow of air slightly increases heat losses, whereas during night-time the air flow is descending because of the radiative heat exchange between the sky and the roof. During cold winters, it could be advisable to close the air duct using suitable dampers from an energy savings standpoint. These dampers would favor only a very small ventilation to drain off any possible condensate in the duct.

Concerning the summer, a 10 cm thickness cavity in Milan allows to reduce cooling energy need of the attic by 8-12% (this percentage is halved with respect to the whole building). The performances of the ventilated roof depend mainly on three variables: cavity thickness, pitches slope and thermal insulation of the building. Concerning the first two, increasing thickness cavity besides 6-10 cm and roof slope besides 35°-40° is not useful as marginal advantages decrease. The main impacting factor is thermal insulation. Concerning the climate, the milder the resort, the more advantageous the ventilated roof.

The results here reported seem to not justify the investment cost of a ventilated roof in existing buildings. Anyway, considering new constructions, this kind of solution could be useful also in order to increase lifetime of layers constituting the roof as it limits temperature and humidity range inside the layers and reduces operating temperature of the insulation layer.

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