Improving summer energy performance of highly insulated buildings through the application of a thermal analysis by numerical simulation

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Abstract

The work presented in this paper is aimed at deepening the optimisation of the energy performance of highly insulated buildings in summer conditions through the application of an original methodology of thermal analysis.

The methodology, already presented in a previous work (Ballarini *et al.*, 2011), allows us to investigate the building energy balance and identify the most important parameters affecting the energy performance under certain conditions. The analysis is developed through the application of a dynamic simulation tool (*EnergyPlus*). The methodology consists of analysing the different contributions to the convective energy balance on internal air and their interrelations with different boundary conditions. Each contribution is split according to the dynamic driving forces of outdoor and indoor environment, i.e. external air temperature, solar radiation, internal air temperature and internal heat sources, and it is referred separately to the specific groups of components that exchange heat with internal air.

This work focuses on the application of the above thermal analysis to a highly insulated single-family house in summer conditions, in two different Italian climatic zones. The methodology provides the mean values and the standard deviations of the contributions to the convective energy balance on internal air, and allows both to identify the main causes of low energy performance and to quantify the effects of possible retrofit or operational measures.

As an exemplification, the effect of increasing the air change rate by natural ventilation during the night is investigated. The results show how the energy performance could be improved also in highly insulated buildings located in warm climates.

1. Introduction

Since the Seventies, the principles of energy efficiency and environmental sustainability have been progressively applied to buildings in Europe. Some experimental demonstrations and codes of practice were carried out, like *Passivhaus* (Germany), *Maison autonome en énergie* (France), *Green Building* (England). These examples show some common design strategies and building technologies, but they differ regarding the socio-economic, cultural and climate contexts and the habits of construction (Filippi *et al.*, 2011).

The concept of *Passivhaus*, proposed in 1988, was the first systematised concept in order of time. The typical *Passivhaus* is a residential building built according to a precise standard (*Passivhaus Standard*), obtaining a drastic reduction of the energy consumption mostly by means of a high level of thermal insulation. Since 2007, when the *Passivhaus Standard* was extended to southern European countries, the design solutions commonly implemented in the Central European passive houses have been adopted: high thermal insulation, avoiding thermal bridges, mechanical ventilation with thermal recovery from the exhaust air. In addition, further strategies of the passive cooling were introduced (Pagliano *et al.*, 2007).

Recently, a further boost towards nearly zero energy consumption has been given by the European Directive 2010/31/EU (*EPBD recast*), which requires the Member States to draw up national plans to guarantee that all the new buildings will be *Nearly Zero Energy Building* from January 2021.

More severe requirements of energy performance imply an optimisation of the building and its services, through the use of new strategies that enable high energy efficiency and exploit renewable energy sources, taking into account the geographical and social context specificities.

The improvement of the energy performance also involves the optimisation of the traditional technologies, such as the traditional building envelope components. For instance, the application of thermal insulation material in the building envelope is generally considered the most effective way of increasing the thermal resistance of a building component, even under a dynamic driving force (Al-Turki *et al*., 1991). However, some studies show that the building thermal insulation is a complex issue when analysed on an annual basis, because of different feedback on thermal load components when the insulation degree is increased. A higher insulation level does not always lead to lower yearly energy consumption. Some of the thermal load components show a significant dependence on user profiles and on site dependent and locally dependent climatic conditions. This dependence induces an inversion on the thermal load component sign, changing a loss into a gain and vice versa, making it impossible to have generalised conclusions only related to the insulation degree (Mazzarella *et al.*, 2011).

A detailed analysis of the thermal flows through the building envelope can show how the building energy performance in summer can worsen due to a different response of the various heat load components for the increase of the insulation degree, (Mazzarella, 2011). It was demonstrated that the energy need for the cooling of offices and commercial buildings is generally more affected by the internal gains than by the heat transfer through the building envelope, while the transparent envelope affects the energy performance in summer more than the opaque envelope in residential buildings (Ballarini *et al.*, 2012).

Taking into account these premises, the present work is aimed at identifying and quantifying strategies for the optimisation of the energy performance of highly insulated buildings in summer conditions. The analysis is carried out applying a methodology of thermal analysis presented in a previous work (Ballarini *et al.*, 2011). The analysis is developed by means of a dynamic simulation tool (*EnergyPlus*) which allows us to find out the most important parameters affecting the energy performance of buildings under certain conditions, through the investigation of different contributions to the convective energy balance on internal air and their interrelations with different boundary conditions and driving forces.

The thermal analysis methodology is applied to a highly insulated single-family house, built according to the standards of a *passive house*. The case study is supposed to be located in two different Italian climatic zones.

The causes of low energy performance in summer are identified and some strategies for improving the energy performance are proposed. The effects of the application of a higher air change rate by natural ventilation during the night is also quantified, using the same investigation method.

2. Analysis of a case study

2.1 Methodology of thermal analysis

The proposed methodology of thermal analysis is based on the classification of the convective heat balance terms as functions of the different dynamic driving forces of indoor and outdoor environments, in order to find out the elements that mainly affect the building energy performance under certain conditions. Each contribution to the heat balance equation (the effect) is split according to the driving forces (the causes), among which the external temperature, the solar radiation and the internal heat sources are mentioned (Table 1).

Each contribution can also be referred separately to specific groups of building components exchanging heat with internal air (e.g. opaque envelope components, transparent envelope components, internal partitions of the building), as shown in Fig. .

The thermal analysis of the building is carried out by means of the numerical simulation code *EnergyPlus*. The principle of superposition of the effects is applied in order to identify each contribution to the convective heat balance to be attributed to each driving force. Five simulations are sequentially run on the same model and in the

Acronym	Driving force	Phenomenon
T tr,op	External temperature	Heat transfer by thermal transmission through the opaque envelope
T tr,w	External temperature	Heat transfer by thermal transmission through the transparent envelope
T ve	External temperature	Heat transfer by ventilation
Int	Internal sources	Internal heat gains
Sol op	Solar radiation	Solar radiation incident on the opaque envelope, partially absorbed and transmitted indoor
Sol w	Solar radiation	Solar radiation entering indoor through the transparent envelope

Table 1 – Driving forces and associated phenomena

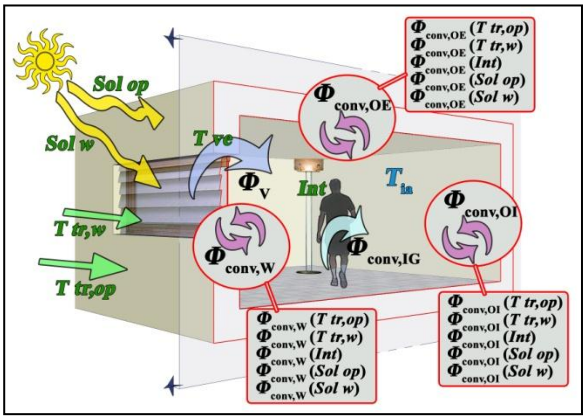

Fig. 1 – Driving forces and convective heat flows

same conditions, but adding a different driving force each time.

In simulations no. 1 and no. 2, the solar radiation and the internal heat sources are removed, so the only driving force considered is the outdoor air temperature. Moreover, in simulation no. 1 the windows are considered adiabatic by introducing null values of thermal conductivity and thermal emissivity of glass and frame. In this way, only the effect of the outdoor air temperature (*T tr,op*) on the convective heat balance of the internal air, considering only the thermal transmission through the opaque envelope components, is obtained. This effect is referred separately to the convective heat exchange of the internal surfaces of the opaque envelope, $\Phi_{conv,OE}$(*T tr,op*), of the transparent envelope $\Phi_{conv,W}$(*T tr,op*) and of the surfaces of the internal partitions $\Phi_{conv,OI}$(*T tr,op*).

In simulation no. 2, the effect of the outdoor air temperature is fully considered including also the heat transmission through the transparent envelope components (*T tr,w*), by re-establishing the correct values of the thermal/solar parameters of glass and frame. In this way, it is possible to obtain the contribution of the outdoor air temperature on the convective heat balance of the internal air in relation to the heat transfer through the transparent building envelope, by difference from simulation no. 1. Also this contribution is separately referred to the internal surfaces of the opaque envelope $\Phi_{conv,OE}$(*T tr,w*), of the transparent envelope $\Phi_{conv,W}$(*T tr,w*) and to the surfaces of the internal partitions $\Phi_{conv,OI}$(*T tr,w*).

In the first two simulations, also the effect of the outdoor air temperature (*T ve*) on the heat flow by ventilation (Φ_V) is directly obtained.

In simulation no. 3, the internal heat sources (*Int*) are added. The effect of the internal heat sources on the convective heat balance of the internal air is shown by a difference from simulation no. 2. This effect is both the convective part of the internal heat sources $\Phi_{conv,IG}$(*Int*), and the convective heat flow exchanged between the internal air and the internal surfaces of the opaque envelope $\Phi_{conv,OE}$(*Int*), of the transparent envelope $\Phi_{conv,W}$(*Int*) and of the internal partitions $\Phi_{conv,OI}$(*Int*), resulting from subsequent heat transfer by thermal radiation from the internal heat sources to the room surfaces.

In simulation no. 4, the contribution of the solar radiation incident on the opaque building envelope is added (*Sop op*), by considering completely reflective glazing. In such a way the effect of the solar radiation incident on the opaque envelope on the convective heat balance is obtained by a difference from simulation no. 3. This effect is split with reference to the internal surfaces of the opaque envelope $\Phi_{conv,OE}(Sol\ op)$, to the internal surfaces of the transparent envelope $\Phi_{conv,W}(Sol\ op)$ and to the surfaces of the internal partitions $\Phi_{conv,OI}(Sol\ op)$.

In simulation no. 5, the solar radiation through the windows is also considered (*Sol w*). The effect of this driving force on the convective heat balance is obtained by a difference from simulation no. 4. Also this effect is split with reference to the internal surfaces of the opaque envelope $\Phi_{conv,OE}(Sol\ w)$, of the transparent envelope $\Phi_{conv,W}(Sol\ w)$ and to the surfaces of the internal partitions $\Phi_{conv,OI}(Sol\ w)$.

The same hourly profile of the indoor air temperature is applied in all the simulations, in order to assure the consistency of the results. This temperature profile is obtained by running a simulation no. 0, in which all the driving forces are considered and a dead-band thermostat with a lower limit equal to the heating set-point temperature (20 °C) and un upper limit equal to the cooling set-point temperature (26 °C) is applied.

2.2 Description of the building

The simulated building is a two-storey detached single-family house: the first floor includes the kitchen, the dining room, the living room and some service rooms. Two bedrooms and two bathrooms are located on the second floor. Part of the first floor, coincident with the living room, has a double height. The vertical section of the building is shown in Fig. 2. The main geometrical data of the building are listed in Table .

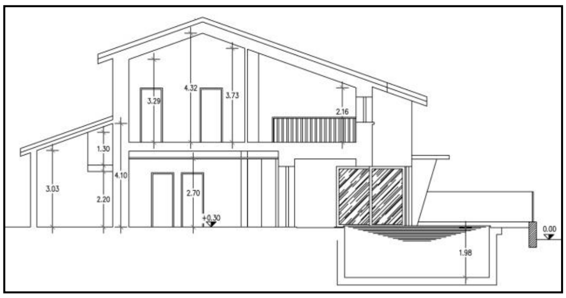

Fig. 2 – Vertical section of the building

Paramater	Value
A_f	192.4 m^2
V_n	758 m^3
V_g	1191 m^3
A_{env}	710 m^2
A_w	37.3 m^2
A_{env}/V_g	0.6 m^{-1}
A_w/A_{env}	0.05
A_w/A_f	0.19
A_{env}/A_f	3.69

Table 1 – Main geometrical data of the case study

The building was designed applying solutions commonly implemented in a *passive house*, in order to obtain a high energy performance both in winter and summer seasons. The main data of the building referred to the construction features are listed in Table 2.

Upper horizontal enclosure	U	[W·m^{-2}·K^{-1}]	0.084
	s_{tot}	[m]	0.50
	s_{ins}	[m]	0.40
	λ_{ins}	[W·m^{-1}·K^{-1}]	0.035
Lower horizontal enclosure (on ground)	U	[W·m^{-2}·K^{-1}]	0.083
	s_{tot}	[m]	0.98
	s_{ins}	[m]	0.25
	λ_{ins}	[W·m^{-1}·K^{-1}]	0.027
Opaque vertical enclosure	U	[W·m^{-2}·K^{-1}]	0.091
	s_{tot}	[m]	0.66
	s_{ins}	[m]	0.24
	λ_{ins}	[W·m^{-1}·K^{-1}]	0.036
Transparent vertical enclosure	U_w	[W·m^{-2}·K^{-1}]	0.69
	$g_{gl,n}$	[-]	0.60

Table 2 – Main construction data of the case study

2.3 Energy performance of the building in summer

The methodology of thermal analysis was applied to the analysed building to determine the net energy need for cooling and the contributions to the heat balance on internal air split by the different driving forces. In this way, it is possible to identify the terms that have the greatest influence on the summer energy performance of the building and the causes of a low energy performance. The analysis does not embrace the calculation of the delivered energy.

The building is located in northern Italy, near Bologna. The numerical simulations were carried out for the month of July considering the climatic data of Bologna, as the nearest city with available hourly climatic data ("G. De Giorgio" weather file). A conventional occupancy was considered in the simulations. Both the mean monthly value of the internal heat gains and the use profile (hourly values) were determined according to technical Standard EN ISO 13790, considering a conventional use. The internal heat gains of the building have a mean value of 2.4 W/m^2 and a maximum value of 8.2 W/m^2.

The ventilation of the indoor environment was set according to indoor air quality requirements. It was established that the indoor air quality was always guaranteed through hybrid ventilation. The minimum air flow rate was calculated applying technical Standard EN 15251, differentiating the occupied time from the unoccupied hours. In this way, it ensued a mean value of 0.34 h^{-1} and a maximum value of 0.54 h^{-1} of the air change rate.

The results of the application of the thermal analysis applied to the case study are shown in Fig. 3, concerning the monthly mean values of the contributions to the convective heat balance equation on the internal air, expressed in terms of mean heat flow rate normalised on the conditioned net floor area. The contributions to the energy balance are split according to the driving forces of the internal and external environment. These terms are identifiable in the graph of Fig. 3 with the same colour.

The sums of the terms characterized respectively by positive values and negative values are represented in the box at the top right of the graph (see Fig. 3). In the same box is the value of the mean monthly net cooling load (corresponding to an energy need of 2.94 kWh/m^2) and the number of hours in July in which cooling is required (724 hours on a total amount of 744 hours).

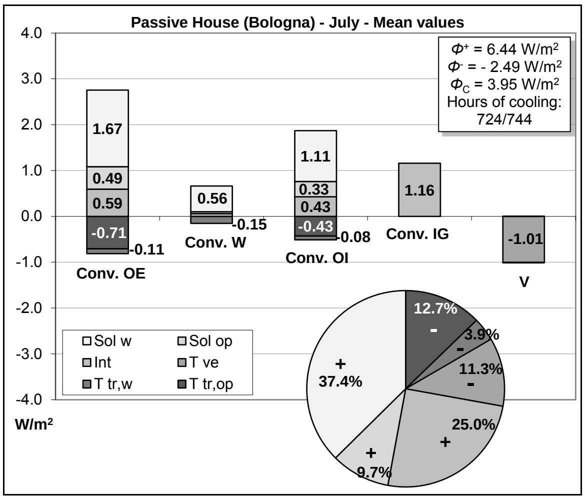

Fig. 3 – Mean monthly values of the convective heat balance contributions split by driving force and corresponding percentage weight of each driving force (July - Bologna)

From the analysis of Fig. 3, it can be pointed out that the main convective contributions to the cooling need are due to the solar radiation entering through the transparent envelope and the internal heat sources.

On the other hand, the outdoor air temperature gives a limited contribution. It induces a heat loss both by thermal transmission and by ventilation, because the outdoor temperature is lower than the indoor temperature on monthly average. For this reason, the effect of the outdoor temperature is characterised by a negative value, as shown in the pie chart of Fig. 3, in which the contributions to the heat balance are aggregated by driving force distinctly.

The standard deviations of the different contributions to the convective heat balance equation on the internal air are shown in Fig. 4. The standard deviation of the building's cooling load depends both on the internal heat capacity of the building structure and on the variability of the thermal driving forces. So this graph is a useful tool to identify critical situations and to adopt coherent solutions in order to improve the thermal performance of buildings under dynamic conditions. In particular, this representation allows to verify the effectiveness of a retrofit strategy finalized to reduce the variability of the thermal load and limit the load peaks through the increment of thermal inertia.

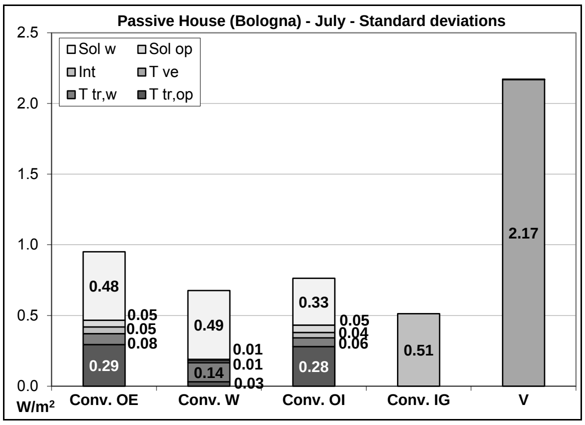

Fig. 4 – Mean standard deviation of the convective heat balance contributions split by driving force (July - Bologna)

Analysing the results of Fig. 4, the contributions characterised by the greatest deviation from the mean value refer to the internal heat sources and to ventilation. Another contribution with high standard deviation is the solar radiation entering through the transparent envelope. In order to reduce this last term, a design measure might consider the position of the window shading devices. The venetian blinds should be positioned outside and not in the cavity of the glass, as occurs in the case study.

The extremely limited deviation of the contribution of the heat transmission through the opaque envelope can be explained by the high heat capacity of the opaque building components together with their high insulation level.

2.4 Analysis under a different climatic context

In this section, the methodology of thermal analysis is applied to the same case study, but considering its collocation in the climatic context of Palermo, in southern Italy. The hourly weather file IWEC (*International Weather for Energy Calculations*) was applied in the numerical simulations.

The results are shown in Fig. 5, regarding the monthly mean values of the contributions to the convective heat balance equation on the internal air, and in Fig. 6, with regard to the mean standard deviations of the same contributions.

Comparing Fig. 3 and Fig. 5, the same building in Palermo shows higher mean monthly cooling loads than in Bologna (more than 27%). This is mainly due to the reduction of the heat transfer through the building envelope and of the heat flow by ventilation (around 53%).

The negative value of the effect of the outdoor air temperature (see Fig. 5) depends on the fact that in both locations the mean monthly outdoor air temperature is lower than the indoor air temperature and that both the thermal transmission through the building envelope and the ventilation cause a reduction of the energy need. For this reason the high insulation level of the building components contributes to reduce the heat transfer by thermal transmission through the opaque envelope and to increase the cooling energy need.

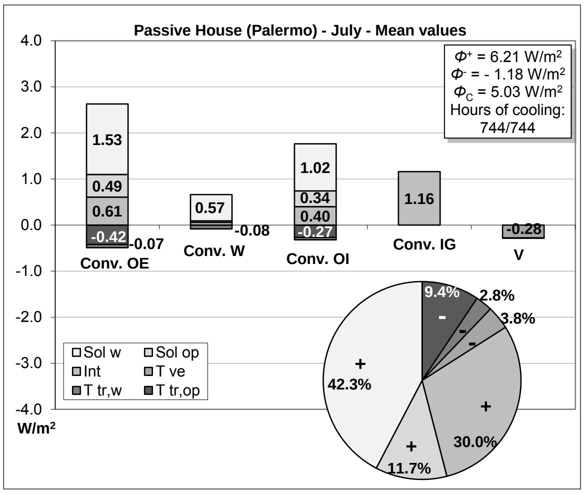

Fig. 5 – Mean monthly values of the convective heat balance contributions split by driving force and corresponding percentage weight of each driving force (July - Palermo)

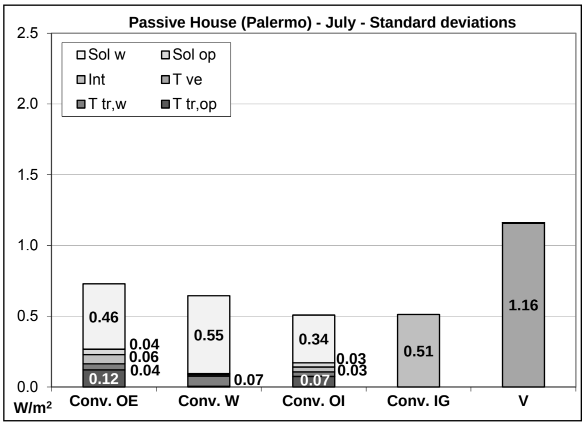

Fig. 6 – Mean standard deviation of the convective heat balance contributions split by driving force (July - Palermo)

Also the mean standard deviation of the ventilation contribution decreases for the building in Palermo compared to the same building in

Bologna, as shown in Fig. 6. This mainly depends on the limited variation of the external temperature in July in Palermo.

3. Strategies for improving energy performance

The results of the thermal analysis applied to the passive house show a satisfactory energy performance in summer. However, it is possible to identify some measures to further reduce the energy need for cooling, especially considering the location of the building in warmer climates (e.g. Palermo).

The choice of the best strategies should take into account the results of the thermal analysis and considering the contributions that mostly affect the energy need of the building in summer. However, it is chosen neither to modify the internal heat sources because they are fixed according to the building use, nor the technology of the building envelope, which is established by design choices.

As an exemplification, it is proposed to increment the air change rate fixed previously in the analysis to a value of 2 h^{-1} in the hours of July in which the outdoor air temperature is lower than the indoor air temperature (*free cooling*). This condition occurs in nearly all the days of July from about 10 p.m. to 9 a.m., in both locations. It is assumed that the fixed air change rate is always guaranteed, if necessary by means of fans. As the analysis only takes into account the net energy need for cooling, the electrical energy consumption of the fans is not considered in the study.

The thermal analysis is applied to the passive house both in Bologna and in Palermo, in order to evaluate the effects of the strategy. The results for Bologna are shown in Fig. 7 and in Fig. 8; for Palermo in Fig. 9 and in Fig. 10.

Compared to the original condition, the mean monthly thermal load of the building in Bologna decreases nearly 74% and the hours of cooling became 225, i.e. 30% of the total hours of July. The activation of the natural ventilation at night determines a decrement of the thermal load due to the increase of the negative contributions to the heat balance (Φ^-). The heat transfer by ventilation increases, while the heat transfer by thermal transmission though the building envelope decreases slightly, as a result of the reduction of the indoor air temperature for the *free cooling* effect. The greatest deviation of the loads from the mean value occurs firstly in the ventilation contribution, and secondly in the heat flow transferred through the opaque envelope. The latter aspect is ascribable to the variability of the indoor-outdoor temperature difference linked to the high variability of the indoor temperature due to the increase of the natural ventilation.

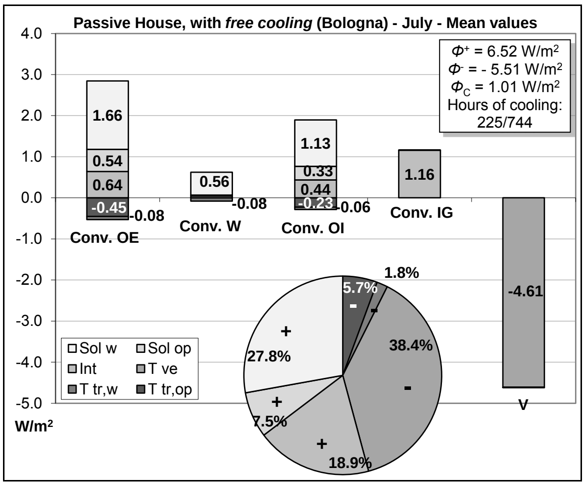

Fig. 7 – Mean monthly values of the convective heat balance contributions split by driving force and corresponding percentage weight of each driving force (case with free cooling, July – Bologna)

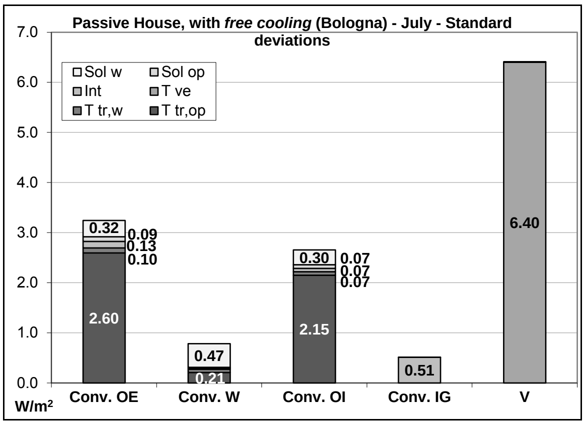

Fig. 8 – Mean standard deviation of the convective heat balance contributions split by driving force (case with free cooling, July - Bologna)

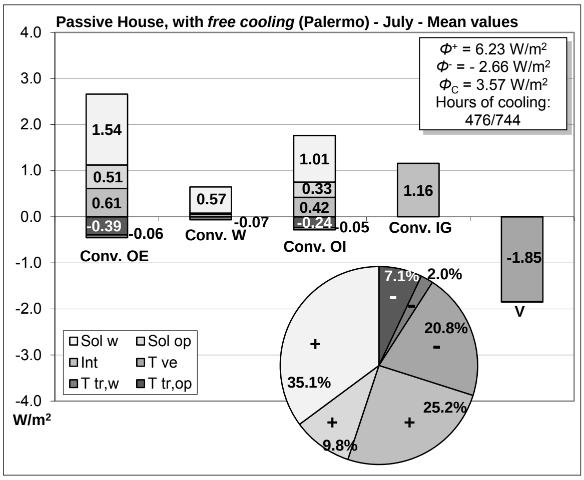

Fig. 9 – Mean monthly values of the convective heat balance contributions split by driving force and corresponding percentage weight of each driving force (case with free cooling, July – Palermo)

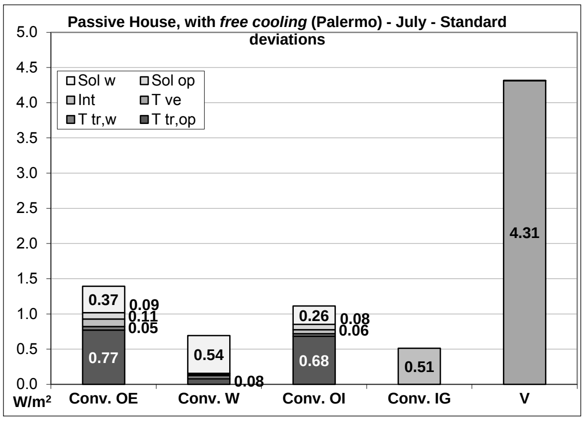

Fig. 10 – Mean standard deviation of the convective heat balance contributions split by driving force (case with free cooling, July - Palermo)

The increment of the air change rate causes an improvement of the summer energy performance of the case study in Palermo as well. However, the effect is less significant because the hourly values of the external temperature in Palermo are higher than in Bologna. In addition, they are characterized by a reduced variability (limited thermal excursion).

The building energy need for cooling in July decreases by 29% approximately, compared to the case without *free cooling*. The hours of cooling activation decrease by 36%, due to the increase of the convective heat flow by ventilation (561%), which is also characterised by the greatest standard deviation, compared to all the terms of the convective heat balance on internal air.

Considering thermal comfort implications, the mean monthly values of the indoor air temperature and their standard deviations are, respectively, 24.3 °C and 1.5 °C for the building in Bologna, and 25.7 °C and 0.5 °C for the same building in Palermo.

The relation between the cooling need reduction due to *free cooling* and the positive cumulative indoor- outdoor hourly temperature difference in July is shown in Fig. 11.

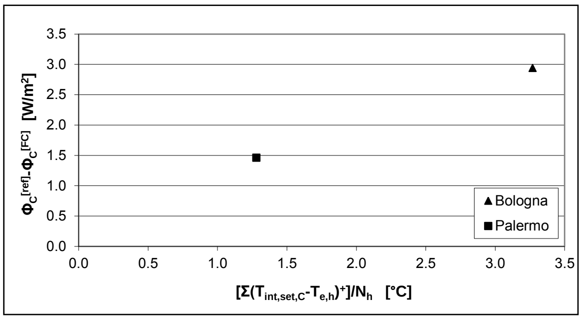

Fig. 11 – Cooling need reduction due to free cooling vs. positive cumulative indoor-outdoor hourly temperature difference (July)

4. Conclusion

The analysis presented in the paper is aimed at identifying and quantifying strategies for the optimisation of the energy performance of highly insulated buildings in summer conditions. A methodology of thermal analysis presented in a previous work (Ballarini *et al.*, 2011) has been applied to a *passive house* supposed to be located in two different Italian climatic zones (Bologna and Palermo).

The analysis was developed by means of a dynamic simulation tool (*EnergyPlus*) and the most important parameters affecting the energy performance of the case study in July were identified.

In order to reduce the mean monthly thermal load of the building, the effects of the application of a higher air change rate by natural ventilation were investigated through the same methodology.

The reduction of the net energy need for cooling (74% for the building in Bologna, 29% for the same building in Palermo) is linked to the increase of the convective heat flow by ventilation, as clearly shown in the graphical representation of the methodology of analysis. However, it is necessary

to point out that the effectiveness of the night ventilation is strongly linked to the specificity of the climate. For an effective *free cooling* strategy, the outside air temperature should be lower than the indoor air temperature, guaranteeing however a correct dimensioning of the air flow and avoiding draft risk.
The effectiveness of the use of *free cooling* was correlated to the thermal excursion of the outside air temperature in summer.

5. Nomenclature

Symbols

A	area (m^2)
g	total solar energy transmittance (-)
s	thickness (m)
T	temperature (°C)
U	thermal transmittance ($W \cdot m^{-2} \cdot K^{-1}$)
V	volume (m^3)
λ	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
Φ	heat flow (W)

Subscripts/Superscripts

ia	internal air
C	cooling
conv	convection
e	external
env	envelope
f	floor
g	gross
gl	glass
h	hour
ins	insulation
int	internal
IG	internal gains
n	net, normal
OE	opaque external
OI	opaque internal
set	set-point (temperature)
tot	total
W,w	windows
V	ventilation

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