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The Role of Natural Ventilative Cooling in NZE Temporary and Emergency Shelters Design: a Mediterranean Case Study

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Abstract

The paper presents a case-study of a pre-fabricated housing module built in Messina (Sicily, Italy) and the assessment of its energy performances under the net zero energy perspective. The potential of ventilative natural cooling application in the case-study is also investigated. Some particular features of the building - the modularity, the prefabrication, the rapidity of assembly, the possibility of being built on disconnected soils and the absence of maintenance - identify an effective use as a temporary housing solution for e.g. workers in proximity of an isolated working place or in emergency situations such as earthquakes and natural disasters. Monitoring studies were performed during some weeks in summer, the building was simulated in energy plus environment, validated obtaining small and acceptable differences between monitored and simulated data. Results identify the building as a plus zero energy building, with generation nearly doubling the overall electricity consumption. Natural ventilation in the hot Sicilian climate would prove efficient to reduce electricity consumption for cooling by 20% in a year mainly during mid-seasons but the design needs to be improved by including a more bioclimatic-oriented approach.

Keywords - Temporary housing, building simulation, ventilative cooling, Net Zero Energy Buildings

1. Introduction

Due to several causes, ranging from natural disasters to temporary working needs, the need for lightweight, prefabricated, and more in general temporary housing solutions is widespread around the world. The most frequently used temporary housing typology is tents [1], because of their low cost and maneuverability; however, due to the low thermal resistance and small thermal inertia, the indoor thermal comfort is usually poor. The lightweight prefabricated building units are another solution. Based on pre-built houses that only need to be transported to the site where they will be placed, the prefabricated houses require more construction time, but they provide higher safety and comfort standards but not yet comparable to standard housing. For this reason further research is needed to ensure higher comfort standards while limiting the use of energy for heating and cooling [2]. In a context where the reduction of energy requirement and the mitigation of environmental impacts in the traditional building sector have become key targets of energy policies in different countries, it is of paramount importance to orient research towards new designs of temporary housing solutions, to be both energy efficient and environmentally friendly [3] and to meet the requirements defined by the EU Directive on Energy Performance of Buildings (EPBD) on the ‘nearly zero energy buildings’ [4].

The objective of the study is the assessment of the energy performances of a prefabricated temporary housing solution built in Italy in order to perform future refinements of the design of the test units to be built in the following years. The building has been modelled with the Energy Plus software [5] and the model has been calibrated on the monitored data available for summer days. The calibrated model has been used to perform parametric analyses to explore the performances of the building. In particular, being a light building with highly insulated walls and large glazed windows, the unit is characterized by relevant cooling needs: the potential role of natural ventilative [6, 7] cooling in improving passively the building performances is examined in the following paragraphs.

2. The building

The case study is a prefabricated module, built in Messina (Italy) at the National Research Council, in the context of the research project: “CNR per il Mezzogiorno – Tecnologie avanzate per l’efficienza energetica e la mobilità ad impatto zero”. The entire structure of the living module is realized from pultruded fiber reinforced material (FRP).

The building has an area of 45 m^2, it has two main façades almost fully glazed (Fig.1), while on the other sides there are no windows. For the south-est façade, a glazed surface covers the whole surface (15 m^2) and it is openable by 20% of the total glazed area. The rear facade reaches around 65% of window to wall ratio. The windows are made of double low-emissivity insulated glazing with 0.005 m external glass, 0.016 m gap filled with argon and 0.004 m internal glass; the average global window U-value is 1.19 W/(m^2 K), solar heat gain coefficient (SHGC) is equal to 0.3 while the visible transmittance (VT) is 0.4.

Fig. 1 Aerial view of the prefabricated module immediately after the construction stage

The vertical and horizontal surfaces (Fig.2) U value is equal to 0.3 W/(m^2 K) for all surfaces.

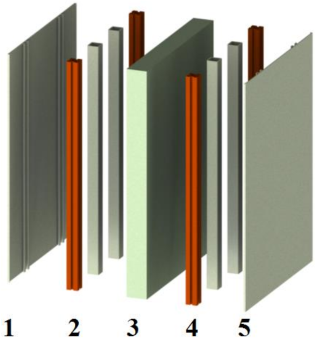

Fig. 2 Section of the wall (1and 5: FRP panels, 2 and 4: FRP profiles, 5: Thermal insulation)

The module will be equipped with a photovoltaic system for the production of electrical energy and a thermal system composed primarily of a geothermal heat pump. The building will be connected to electrical network, thus it will have the dual role of producer and consumer of energy.

The photovoltaic (PV) system will have a peak power of 3.5 kWp, made up of 12 modules of 290 Wp. Each PV module has an area of 2.2 m^2, for a total area of about 26 m^2.

3. Modeling and validation

The building has been modelled in Energy Plus environment [5]. The occupancy use modeled is “emergency shelter” thus for simplicity’s sake it includes two occupants being inside the building for half hours of the morning and of the afternoon and during the whole night. Only moderate electrical loads are included (5 W/m^2), lighting installed power is 6.7 W/m^2, controlled by an illuminance dimmering with a setpoint of 300 lux until 24:00, then they are always switched off until 6 in the morning.

Heating and cooling are provided through a heat pump with an EER around 4. Geometrical modelling is performed through the Google SketchUp Open Studio plugin.

Natural ventilation is modelled through the separate contributions of wind and stack to the airflow through the Wind and stack empiric formulation [8]: wind induced ventilation is obtainable through equation (1), equation (2) is used for calculating the ventilation rate due to stack effect:

$$Q_w = C_o \cdot A \cdot F \cdot W_s \tag{1}$$

$$Q_s = C_D A_{opening} F_s \sqrt{2g\Delta H_{NPL}(|T_z - T_o|/T_z)} \tag{2}$$

Where Co is the opening effectiveness, A is the opening area [m^2], F is the opening area fraction, Ws is the wind speed, C_D is the Discharge coefficient for opening, ΔH is the height from midpoint of lower opening to the neutral pressure level [m], Tz and To are respectively the temperature of the zone and the outdoor one [°C].

Windows are open when external air temperature is in the range of $18 < Te < 26$ °C, internal temperature is below 23°C and wind speed is lower than 2 m/s.

Monitoring was performed for around 20 days during May - June 2015, including indoor air temperature at different heights, surfaces temperatures (center of all the surfaces of the building), external temperature, horizontal solar radiation, wind direction and speed.

Validation was performed by comparing monitored and simulated data obtaining limited differences. As an example, Fig.3 reports the differences between indoor simulated (Ts) and monitored temperature (Tm) with a 10 minutes time-step.

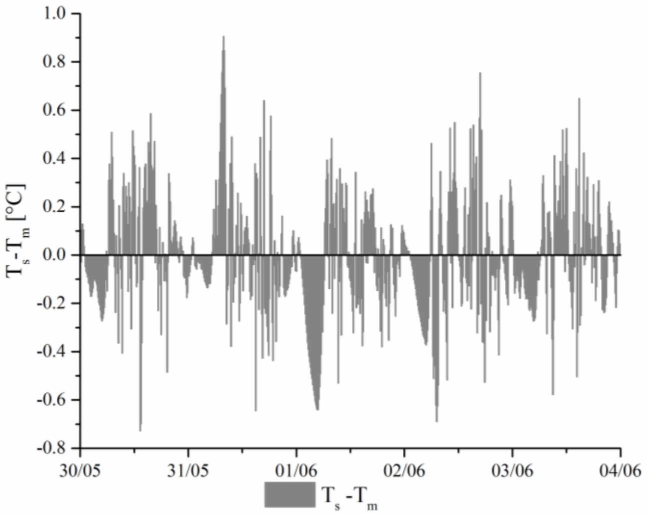

Fig. 3 Calibration results

In all cases the differences are below 0.9°C. In 90% of the data, the absolute error is below 0.41°C, for 75% it is below 0.27°C, while for 50% of the calibration data it is below 0.15°C.

4. Results

The base case results for the case study are reported in Fig.4 in a scenario that does not include any ventilation strategies. All year simulation use an Energy Plus weather file for Messina, Italy. PV generation and overall estimated electricity consumption are included in the Figure. Since overall PV generation (4,590 kWh_e) in a year largely surpasses the electricity consumption (2,448 kWh_e), the building achieves the target of Net zero energy building (NZEB) [9 – 11], however it is worth highlighting that, since the use of the building is considered in this paper as emergency shelter, appliances electricity uses are low than most other applications.

The building is operated as mixed –mode, comfort levels are quantified for the hours in which occupants are inside, when natural ventilation is performed (and therefore the building is free-floating) and in accordance to the temperature limits of applicability of the EN 15251 metrics.

As specified in the regulation [11], running mean temperatures (Θ_{rm}) are calculated as function of recurring average temperature values ($\Theta_{ed\text{-}i}$) calculated during previous week while the comfort temperature is calculated through Eq.3.

$$\Theta_c = 0.33\Theta_{rm} + 18.8^{o}C \tag{3}$$

The comfort temperature range (Category II) adopted for the study is reported in Eq.4.

$$\Theta_c - 3 < \Theta_{indoor} < \Theta_c + 3 \ \ {}^oC \tag{4}$$

Where Θ_{indoor} is the indoor air temperature. The 96.77% of the considered hours is included in the comfort temperature range.

Cooling and heating account for around 12.10% and 35.65 % of the total electricity consumptions respectively, the rest of the share being caused by lighting (30%) and appliances (22.25%). A mild climate, moderate insulation and large glazed facades allow for heating to be low in comparison to cooling, that is the main challenge the building must face. Although having low availability of thermal mass to be charged and discharged, the building is located in a windy site that may contribute to reduce cooling loads through natural ventilation.

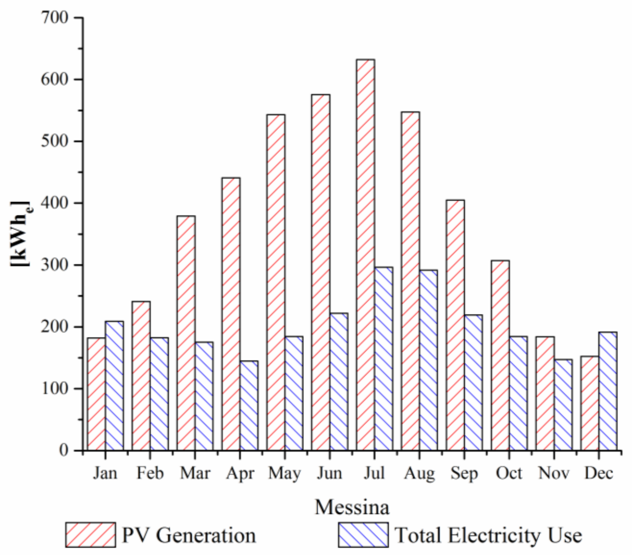

Fig. 4 Electricity generation and use

For this reason, other natural ventilation scenarios are added to the previous one to quantify the beneficial potential of natural ventilative cooling on the building performances:

- Night ventilation (18:00 – 08:00),

- All day ventilation.

Results for monthly cooling electricity uses are reported in Fig.5.

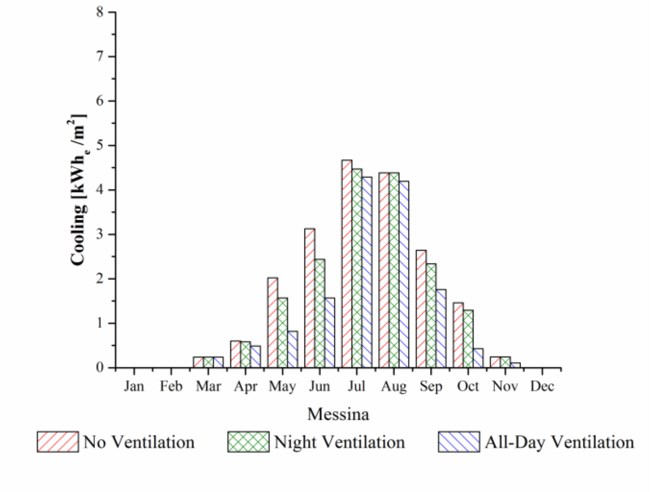

Fig. 5 Ventilative Cooling scenarios

Overall, total cooling ranges from 19.4 kWhe/m^2 (No ventilation) to 17.4 (night ventilation) and 13.8 kWhe/m^2 (All day ventilation).

The most significant reductions are available in mid-seasons, in particular in May (-59.5% for the all day ventilation scenario) and in October (-70.6%). More limited benefits in terms of energy use are available in summer (- 4.3% in August, -8% in July) due to high temperatures during daytime and only limited day-night temperature variations. As shown in Fig.6 including the differences between indoor temperature in the no-ventilation and in the all-day ventilation scenario for the case of Messina during May, temperature reductions of up to 13°C can be achieved in the building during peak loads hours. The monthly average temperature reduction is 1.78°C.

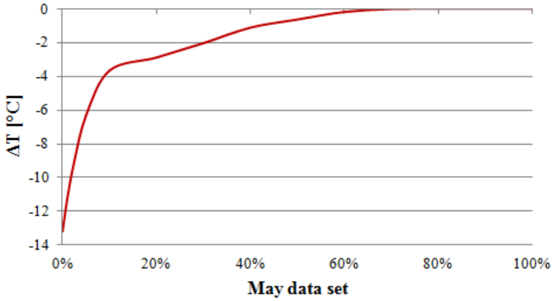

Fig. 6 Percentile analysis of indoor temperature reductions for the month of May

5. Sensitivity analysis

Since the analysis aims at the assessment of the energy performance of the existing module targeted at the optimization of the design of the next test unit to be built, a sensitivity analysis has been performed on the main parameters of the design, to explore the effectiveness of the solution sets used in current design and plan different solution for the future ones.

The design of the building identifies a particular design solution set in which a major role is played by glazed surfaces. In particular the sensitivity of some of the most impacting parameters on the final results will be analyzed: the effect of using a low-e glazed surface and the limitation on the 20% opening area on the south oriented opening.

Fig.7 shows the cooling required in the case of a clear double glazed window (U=2.55 W/(m^2 K), SHGC =0.66, VT = 0.75), opposed to the low-e one, used in the building.

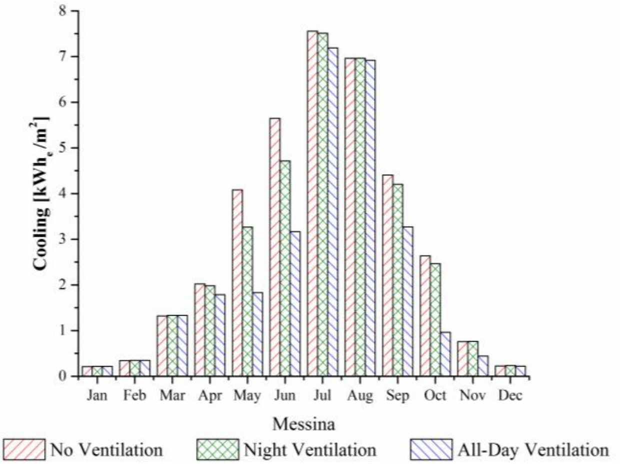

Fig. 7 Cooling scenarios, standard window

Results differ largely to those analyzed in Fig.7. Although natural ventilation Scenarios are for sure effective in reducing cooling loads, in the case described in Fig.7, the whole dataset has now cooling energy use higher by around 50% in comparison to the low-e case in Fig.5.

Table 1 shows instead the results comparison of the base scenario (discussed in Figure 5) in the hypothesis of using a larger operable area (50% of the total glazed area). Results do not vary largely since to a more than double windowed area is associated a reduction in cooling requirements of 0.26 kWh$_e$/m^2 in the case of the night ventilation scenario and 0.59 kWh$_e$/m^2 in the whole day ventilation scenario.

Table 1. Sensitivity analysis on cooling scenarios, different openable area

Month	**No Vent. [kWh$_e$/m^2]**	**20 % Openable Area**		**50 % Openable Area**	
		All-Day Vent. [kWh$_e$/m^2]	**Night Vent. [kWh$_e$/m^2]**	**All-Day Vent. [kWh$_e$/m^2]**	**Night Vent. [kWh$_e$/m^2]**
Mar	0.24	0.24	0.24	0.24	0.24
Apr	0.60	0.49	0.58	0.48	0.58
May	2.02	0.82	1.57	0.76	1.53
Jun	3.13	1.57	2.44	1.45	2.35
Jul	4.67	4.29	4.47	4.16	4.40
Aug	4.38	4.19	4.26	4.17	4.25
Sep	2.64	1.76	2.34	1.65	2.31
Oct	1.46	0.43	1.29	0.38	1.28
Nov	0.24	0.11	0.24	0.10	0.24
Yearly	**19.39**	**13.89**	**17.44**	**13.40**	**17.18**

6. Conclusions

The study has presented the results of the energy performance assessment of a temporary housing unit built in Messina, Sicily and the potential role of applications of ventilative cooling to improve its performances.

The building is able to achieve the Net Zero Energy Building target by a large extent, with a generation higher by 87% than the consumption. It is also worth mentioning that although it would be possible to achieve such a high generation, due to the use of the unit as temporary housing solution, it would be better to tailor the peak power of the PV system in order to reach the Net zero level.

The analysis on the housing unit has shown mixed results: although ventilative cooling could allow for around 20% of cooling electricity use reduction, such savings are mostly concentrated during May, June, September and October due to the features of the climate and to the very light and glazed structure of the building.

The two solutions examined in the sensitivity analysis proved effective: the existing window is well performing in comparison to a standard window, and the openings are large enough to guarantee the ventilative cooling effect in the building. The problem that needs to be faced in future versions of the design is the reduction of the solar gains through shadings on the glazed surfaces.

It would be more appropriate to reduce the glazed surfaces since they do not give significant large contributions to the ventilative cooling potential and they increase cooling needs and to shade them appropriately to better fit the local climate bioclimatic requirements. The application of phase change materials to increase the inertial-like behavior of the next prototypes is also under examination.

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