Natural ventilation and passive cooling for energy efficiency of residential buildings in Mediterranean climate

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Abstract

The upcoming new energy requirements for European buildings impose Nearly Zero Energy standards within few years. In order to achieve such a result, new buildings will need to combine high performance envelopes, energy-efficient active energy systems, on site renewable energy production and passive systems. The latter seem the most difficult to be widely implemented in the conventional buildings, despite their proven effectiveness. Particularly, natural and hybrid ventilation systems in Mediterranean climate have a huge potential in terms of energy savings and indoor comfort improvement. The main obstacles for a wider use of such systems lie probably in difficulties and uncertainties inherent in the design and in the predictability of actual performance. The article describes a methodology to overcome these problems and presents two case studies that illustrate the process and give an example of the possible results.

The design process is articulated through the use of analysis and simulation tools, progressively more detailed. So the general strategies are adapted to the climate and the main building features; site and general building design depend on the microclimate specific characteristics; detailed design and systems calibration are defined on the basis of internal CFD and sub hourly energy simulations. Likewise, other aspects of passive design, such as solar systems, are determined through a similar process of progressive deepening by means of specific simulation tools.

The case studies, two public housing buildings in Tuscany (Italy), are designed on a high energy standard, with passive solar systems, natural and hybrid ventilation strategies, high-efficiency systems, integrated photovoltaic modules and, in one instance, a solar cooling system. The design process and the estimated performance are illustrated with particular regard to ventilation and cooling systems. The buildings are expected to have very low energy consumption and a high quality standard for the indoor comfort, showing a good potential for these strategies in Mediterranean climate. Namely, the cooling needs are reduced by a quantity between 74 to 100%, meaning that an effective ventilation systems (combined with other strategies, can get to completely eliminate the need of mechanical cooling.

Introduction

With the global temperature rising, the progressively higher frequency of heat waves and the higher standard of environmental indoor comfort in residential and working environments, Europe countries saw a dramatic increase in the number of air conditioning systems and of the related energy consumption (Santamouris, 2007) (Kwon, 2013). In the perspective of Nearly Zero Energy Building, a major importance is assumed by the summer energy performances control by means of low energy technology, particularly those using natural ventilation.

Technologies and control systems are now available to significantly reduce the Energy demand, still maintaining excellent indoor comfort conditions. In Mediterranean climate, controlled natural or hybrid ventilation is particularly effective in the reduction of energy consumption and in the improvement of Indoor Air Quality, even in winter and in intermediate seasons (Tucci, 2012). IAQ represents a major problem, especially in new buildings with highly airtight envelopes. Also for energy efficiency purposes, beyond a certain limit, is not possible, neither convenient, to reduce consumption improving the envelope and it is necessary to use fluid dynamics (Grosso, 2011).

The obstacles to a more extensive use of natural and hybrid ventilation are posed mainly by the extreme variability of conditions, determined by climate, biophysical site characteristics and building features. For an effective design of the devices, the general building configuration and the control systems, an innovative approach is needed (Allard, 1998) (Mahdavi, 2005), one that studies in deep the building system through simulation and evaluation methods (Morbitzer, 2003) (Chen, 2009). This contribution describes the design methodology adopted to face these problems and illustrates a few case studies, built or in the construction phase.

This approach includes a series of progressive steps that move from the site and building analysis for the definition of a general strategy, up to a detailed verification of airflow in the indoor environment. In different steps, the most updated simulation instruments are used in order to obtain reliable information on both energy consumptions and environmental comfort. Case studies pertain to residential building in central Italy, featuring buried earth pipes, underground slab (or air labyrinth) ventilation towers and control systems for wind driven cross ventilation.

All the devices are part of a more comprehensive design strategy, which includes several passive solar systems and a tight integration with HVAC systems. Several physical models were used, such as computational fluid dynamics for external ventilation and detailed analysis of main internal spaces, dynamic simulations and air node networks for internal-external and inter-zonal ventilation, overall energy performance and indoor environmental comfort on a yearly base.

Research and literature review on earth-to-air heat exchangers (that include both buried earth pipes and underground slab), can be found in (Tucci, 2012), (Grosso, 2011), (Cimillo, 2013), (Peretti, 2013). (Hughes, 2011) and (Khan, 2008) contain a general review on passive cooling and wind driven ventilation techniques. Energy saving potential of natural and hybrid ventilation, modelling and simulations reliability are addressed by (Zhai, 2011), (Schulze, 2012) and (Freire, 2013).

Methodology

Given the conditions stated above, the project of natural ventilation is approached through a process that involves several progressive steps of analysis and design, as described by the following table. The table includes existing and new buildings and not all the steps are applicable for both. Furthermore the analysis-design steps define an iterative process rather than a simple sequence, so normally each stage can be repeated more than once.

Data gathered in the first step allows to define the climate type and the overall design strategy, with particular attention to the daily thermal range that above certain thresholds (14 °C in the case studies) allows an excellent application of natural ventilation strategies based on thermal inertia (Givoni, 1998). From these input data, in the second step, solar analysis is performed by means of simulations to study the optimal placement of passive and active systems and to maximize the solar protection of passive systems glazing in summertime. The study proceeds by analysing the urban microclimate. Airflows between buildings and plant masses, thermal exchanges of heat and vapour between the soil and building facades, vegetation hygrothermal and energy exchanges and the mean radiant temperatures, are simulated and analysed through a CFD (Computational Fluid Dynamics) software providing important information for the correct positioning of envelope openings to get the most out of cross ventilation strategy. In the third step, once defined the building general structure, the building energy performance is analysed through multi-zonal network simulations that allows to tune with a greater level of detail all the passive and active systems (including for example the window to wall ratio or the real efficiency of natural ventilation). Finally, air flows within the individual apartments are simulated via CFD software to optimize the internal distribution of partitions, to improve the flow arising from cross ventilation. Other CFD simulations have been successively performed run in order to correctly position the inlets and outlets of ventilation systems and to study their interaction with natural ventilation.

Table 1 – Methodology.

Step	Analysis	Design	Tools
1	General climatic data (temperatures, wind, humidity and solar radiation) General building features (functions, occupancy, internal loads)	Selection of natural ventilation strategy and period of usability	Statistical data analysis, simple manual calculations
2	Microclimate features (air speed and pressure and solar radiation on the building envelope and around it) Building geometry, envelope, plants and thermal mass	Site design (trees and obstructions) Building position and orientation, layout and massing	Solar simulations External CFD simulation
3	Air change needs, Thermodynamics, cooling loads, energy demand and potential for natural ventilation	Building envelope (glazing, opening position and dimension)	Nodes network simulations and Thermal simulations (including effects of natural ventilation)
4	Airflow features Internal comfort	Detailed design of openings and internal air paths	Internal CFD simulations

The final adjustments are made to reduce turbulence and related discomfort areas, in favour of an optimal air washing of the room and to improve the energy performance of natural ventilation.

Case studies

The aforementioned methodology described above has been applied in the projects of two apartments buildings in Florence. Both are multi-storey public housing that will be built with wooden structures and envelopes. Both are designed on a high energy standard and aim to achieve an A+ class, the highest in the Italian Energy certification system. This objective will be pursued through the integration of several energy saving measures: a super insulated envelope, the use of passive solar systems, natural and hybrid ventilation strategies, high-efficiency heating and cooling plants.
In both cases, passive cooling strategies are based on natural/hybrid ventilation (in addition to solar control, used as a prevention system). Other cooling techniques, such as evaporative or radiant systems, indeed perform at their best in dry climates and are less effective where the atmosphere is more humid. In Florence, where both buildings are located, relative humidity range from 65% to 69% during summer months.

ied earthpipes that mitigates the temperatures of external air ventilation both during the winter and the summer. The apartments are then heated by a radiant ceiling powered by an air-to-air heat pump. Besides, the plan is conceived to allow for natural cross ventilation during the intermediate seasons in all apartments. During the summer, the common sunspace, in connection with staircases, can be passively cooled, operating openings on opposite facades for cross ventilation. At the same time, the private sunspaces can turn into open loggias, as their glazing are completely operable.
Passive cooling strategies have been planned on the basis of local climate, with regular (natural) ventilation for the deactivation of solar systems and for intermediate condition in the apartments and with buried earth pipes that allow to achieve a passive cooling even in the hottest periods. In fact monthly maximum temperatures in Florence are above 26°C from June to September, and untreated outdoor air is not sufficient to ensure acceptable indoor conditions.
The overall energy performance and the buried earthpipes have been simulated through a dynamic thermal model, using EnergyPlus, while natural ventilation design has been assisted by CFD simulations for both exterior (using mainly Envi-Met software) and interior environment (with software selected on the basis of the geometry and of the conditions of each simulation). The figures 2 to 5 show the progressive

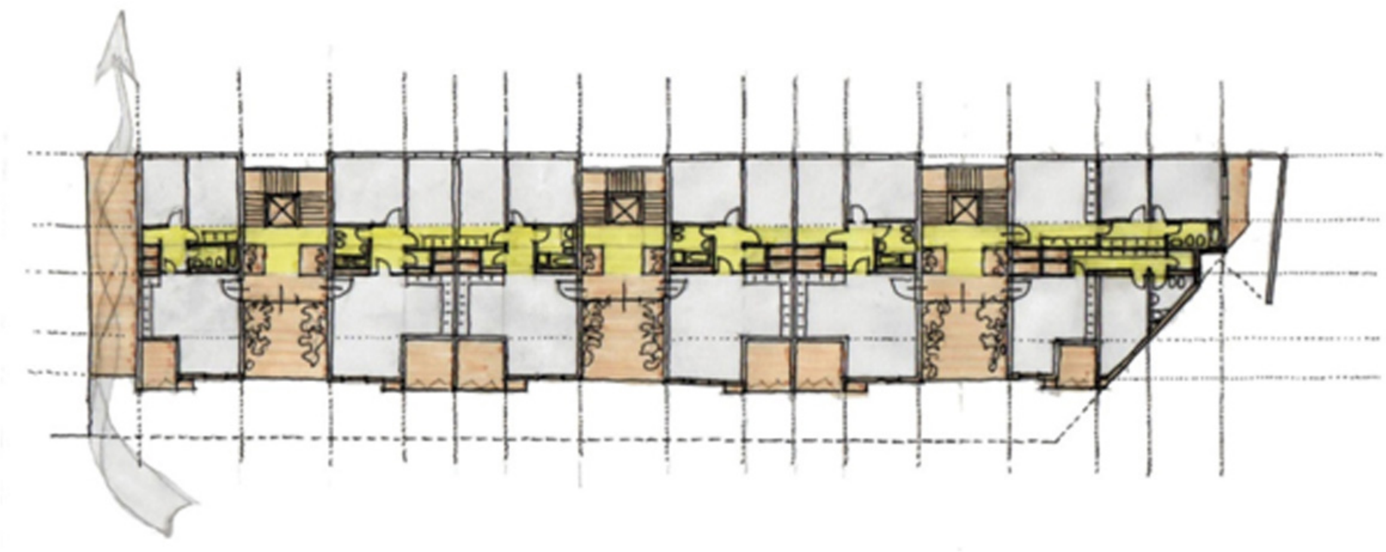

Figure 1 – Pegna ex Benelli public housing, plan with apartments in grey, distribution in yellow and bioclimatic spaces in orange.

1. Residential building in *Pegna ex Benelli* area, Florence: the project is located near the airport of Peretola and will provide non residential functions on the ground floor and 21 apartments on the other three levels (Figure 1). Each of the three staircases is coupled with a three-level sunspace and each apartment is provided with its own private sunspace and a Trombe-Michel wall, that contributes to the sunspace heating. The fresh air is provided through a system of buried earthpipes that mitigates the temperatures of external air ventilation both during the winter and the summer.

deepening of simulation scope. These studies made possible to calibrate the sizes of atrium and apartments opening, to detail interior spaces configuration and to assess indoor comfort conditions.

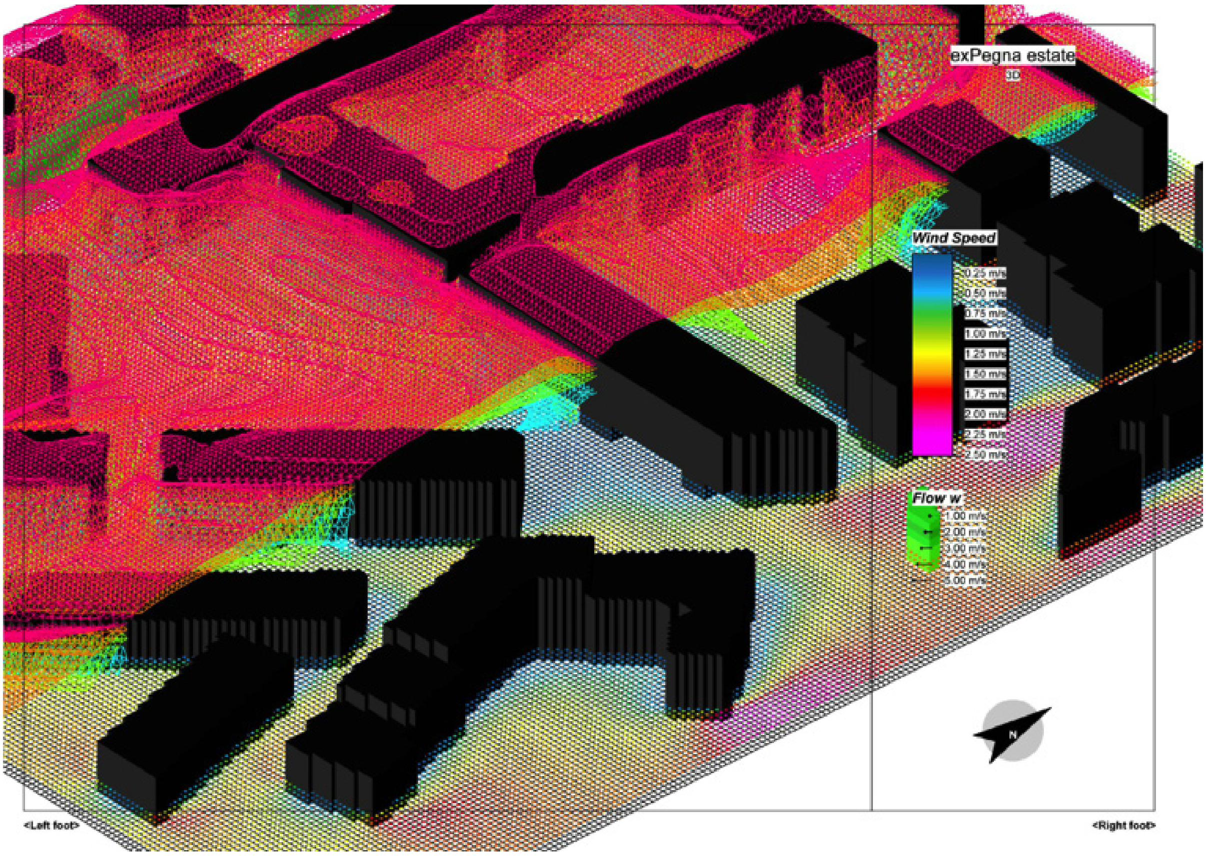

Figure 2 – External CFD simulation in typical summer conditions.

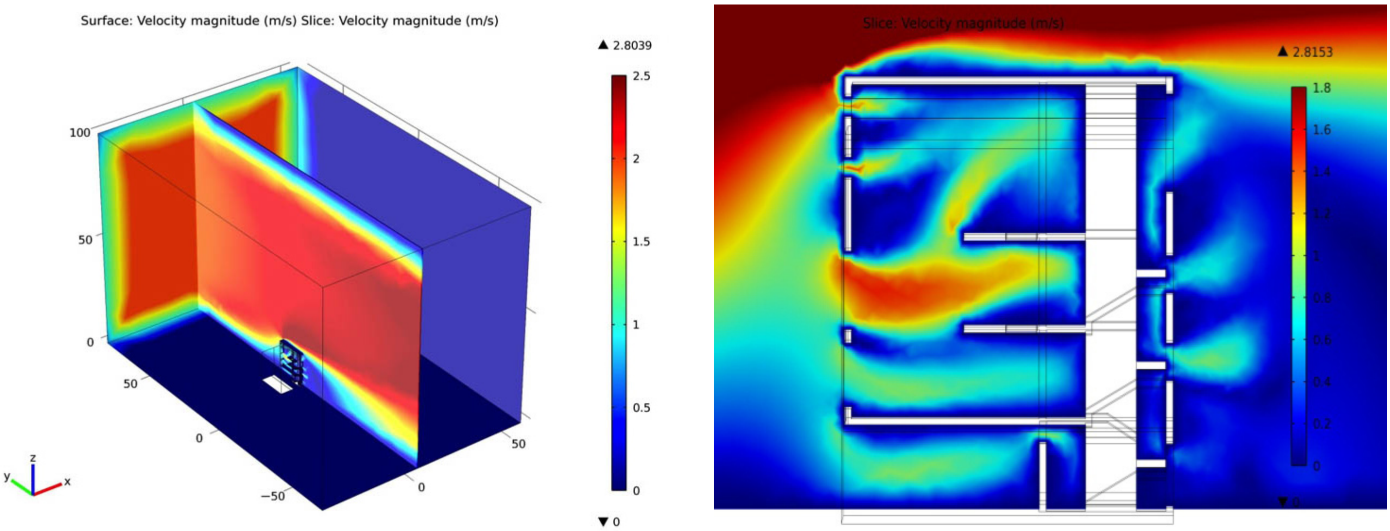

Figure 3 – CFD simulation of cross ventilation in one of the atria. External and internal environment are both included in the same model.

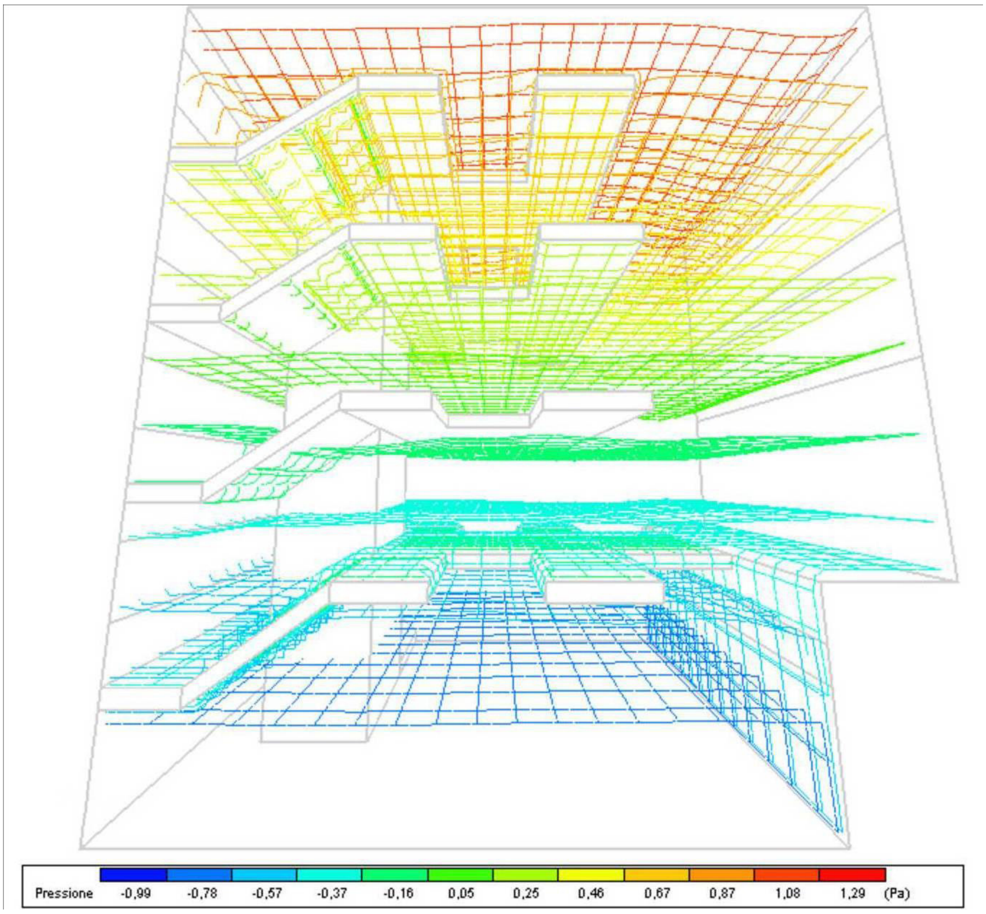

Figure 4 – Internal CFD simulation in the atrium for buoyancy effects, without wind, in summer conditions. The isosurfaces show the pressure variations due to the stratification of air layers with different temperatures.

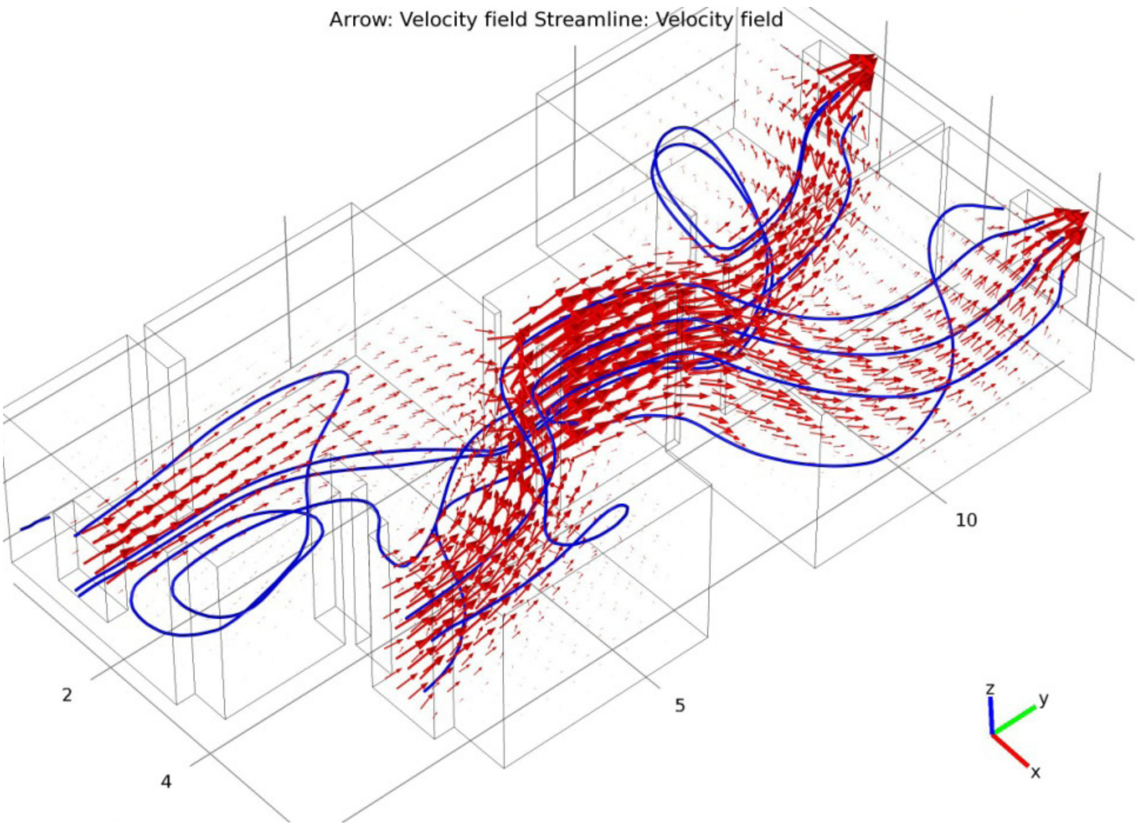

Figure 5 – CFD simulation of cross ventilation in one of the apartments. Lines and vectors show the airflow path and velocity.

Furthermore the investigations provided more reliable data for the overall energy simulation, whose main results are presented in Figures 6 to 9. More in detail the buried earth pipes, with an average length of 30 m, provide air with temperatures one to six degree lower than the exterior air, with the best performance during the hottest hours, by lowering the cooling demand by 83%. The pipes will be installed at a depth of 2 metres, and will have a net internal diameter of 35 cm. The resulting energy demand for cooling is limited to 1,5 kWh/m². With the additional contribution of the shading devices and the cross ventilation, the building can do without air conditioning, with few discomfort hours throughout the year. According to simulated PMV values, hours within the optimal range (-0,5 to 0,5) account for 61,96% of total time, hours within the 0,5 to 1 range and hours above 1 account respectively for 12,53% and 1,2% of total time (figure 9). Moreover, the simulated indoor comfort with passive systems in summertime is better than that of the building controlled by traditional air conditioning, due to the good performance during the hottest hours (figure 9). The influence of passive systems on indoor operative temperature in the free running (without plants) building is illustrated in figure 8.

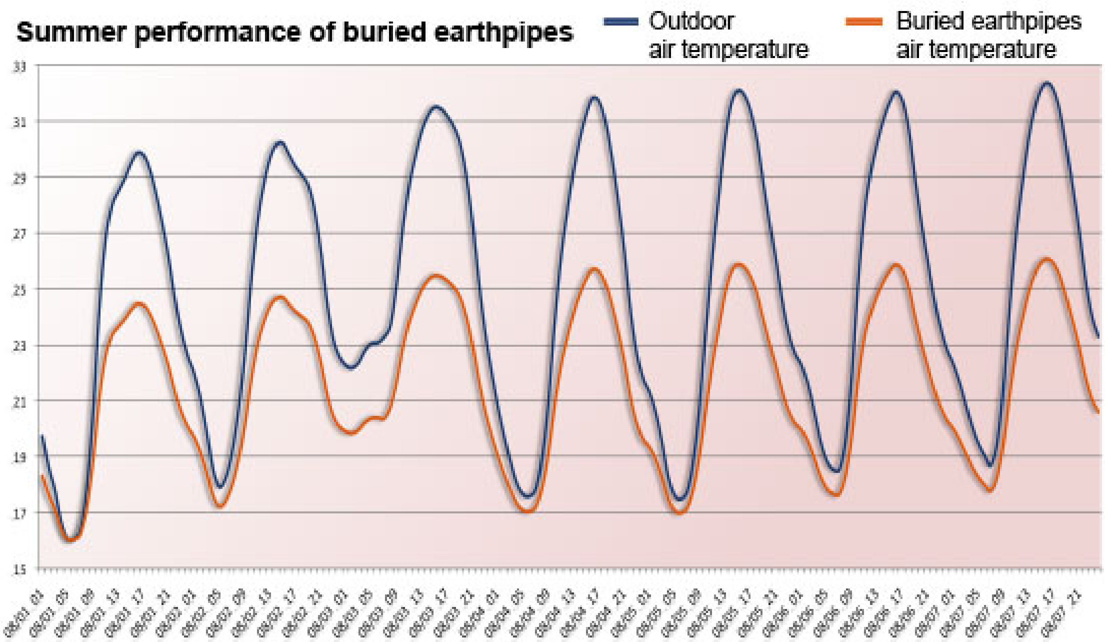

Figure 6 – Simulated temperatures of buried earth pipes compared with external air temperatures (in blue) in summer conditions.

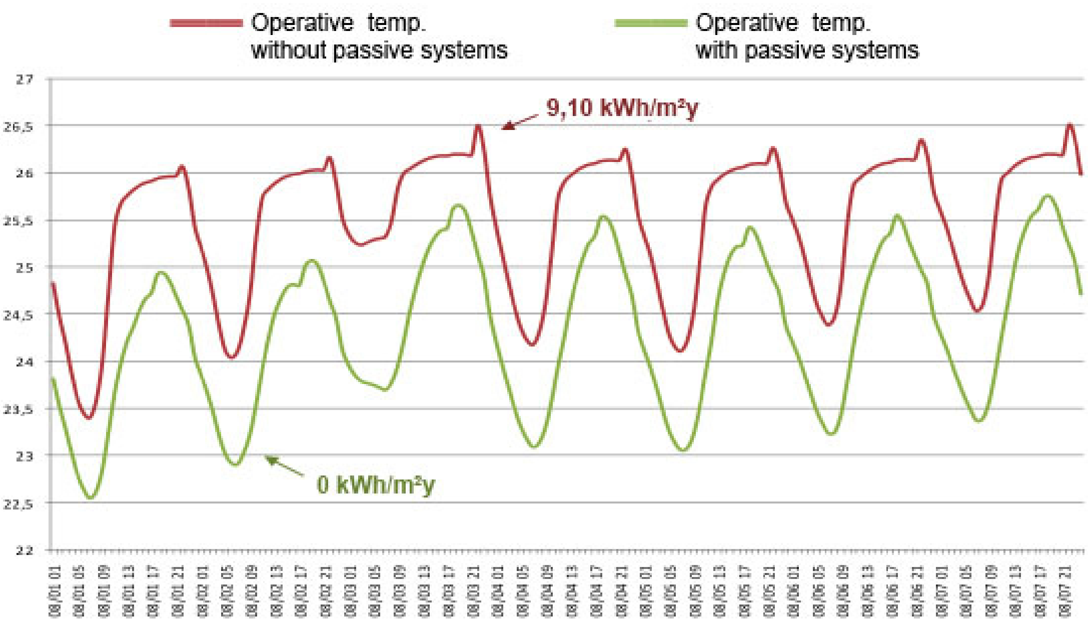

Figure 7 – Simulated indoor temperatures with buried earth pipes (and no cooling energy demand) and without them (and a cooling energy need of 9,10 kWh/m2).

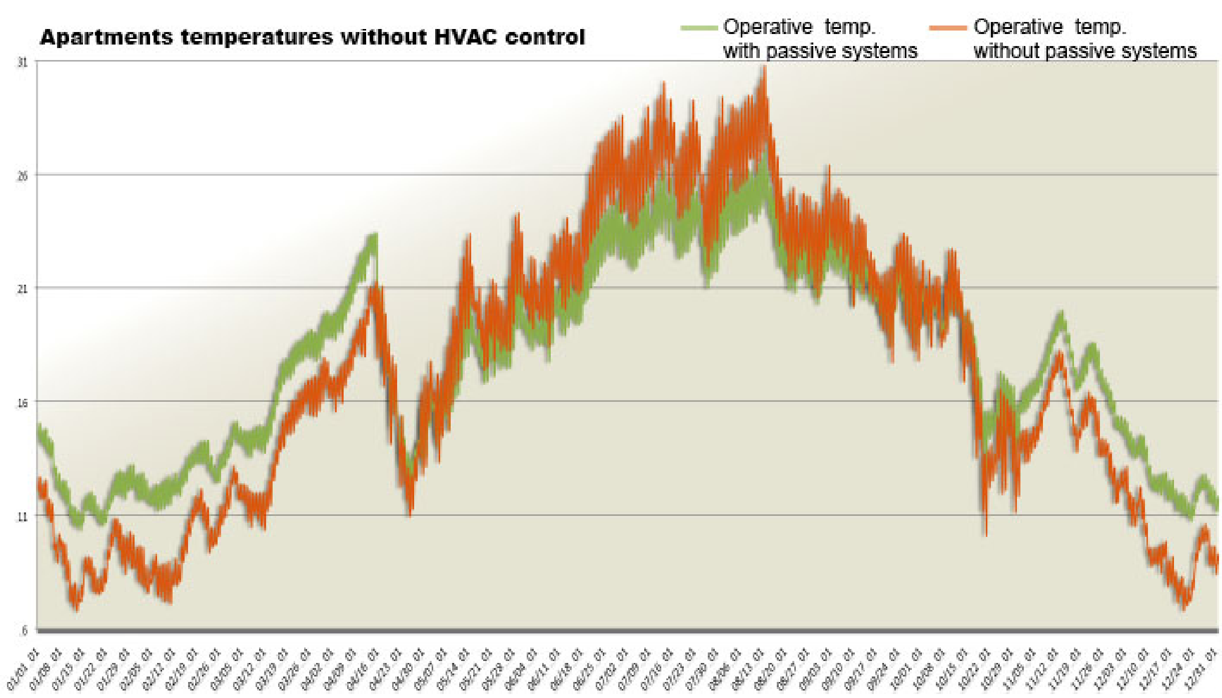

Figure 8 – Simulated hourly operative temperatures with (in green) and without (in orange) passive systems for the building without HVAC control.

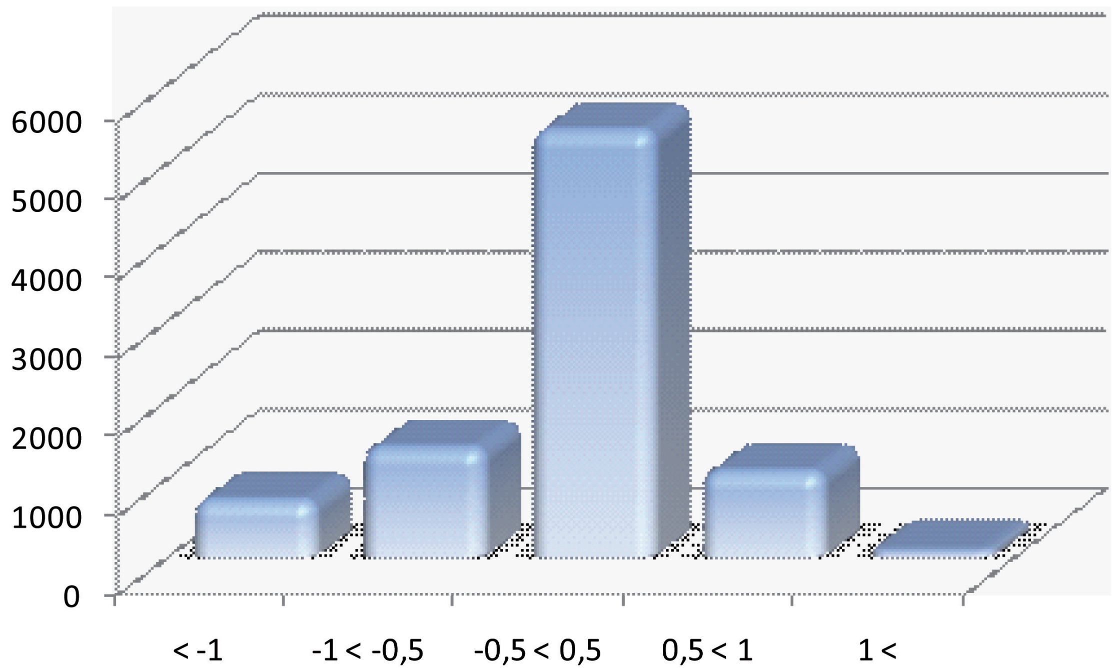

Figure 9 – Simulated hourly PMV values throughout the year.

2. Residential buildings in *Torre degli Agli* area, Florence: the project was planned to replace three obsolete public housing buildings in Florence, and will provide 84 apartments in two six-floor buildings with a common underground parking on two levels. The buildings incorporate passive systems and high-efficiency plants similarly to the Pegna Project (Figure 10). Common, large sunspaces will be built adjacent to the staircases, in order to provide pre-heated fresh air for apartments. The air will be further treaty by a heat recovery unit and then conveyed to each apartment through a distribution system that extends to all floors. In addition, each apartment has a private sunspace that completely encloses it on the south side. Furthermore, an experimental solar cooling plant will be installed on the roof. Also this project was completed

through a simulation based design process. The overall energy performance has been studied using several simulation models and natural ventilation has been designed with the support of computational fluid dynamics. Figure 3 shows one of the simulations, that include both indoor and outdoors environment in the same three-dimensional CFD model.

tion in vertical is inverted.

Compared to earthpipes (Figure 12), the performance of this system is more stable in the 24 hours, even though air temperatures tend more toward the daily average, cooing the air during the day and warming it during the night both in summertime and in wintertime. For this reason, the system will

Figure 10 – Building plan with passive solar systems: in yellow the common six-floor sunspaces that provide preheated air for apartments in winter; in orange the private single-floor sunspaces for heach apartment; in orange the Trombe-Michel walls that support the private sunspaces; in blue the ventilation tower that distribute air from sunspaces and from the underground slab.

Conversely, compared to the previous case-study, n replacement of buried earthpipes, a hollow space integrated in the underground slab under the parking will be used to cool the air during the summer. The hollow space is divided into separate portions for each distribution tower, proportionally with the volume served by each of them; each portion is configured as a maze, in order to involve in the thermal exchange

be used only during the summer, when the air is constantly under the comfort threshold in the apartments.

The complex of passive cooling measure (cross ventilation, underground slab and shading systems) is expected to reduce energy demand for cooling by 74% from 17,3 to 4,1 kWh/m^2.

During the winter, the fresh air for the apartments will be

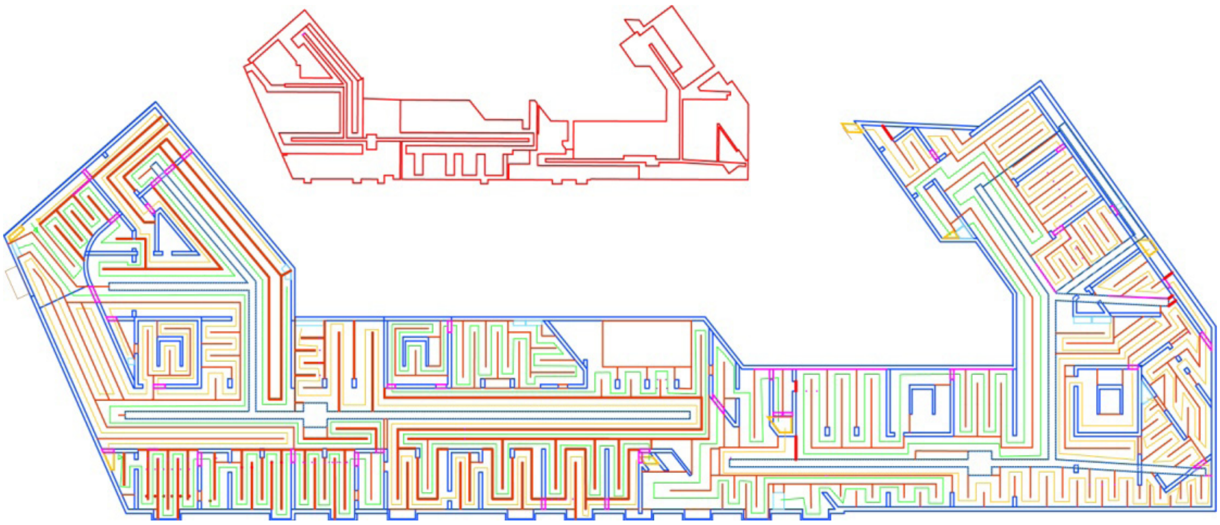

Figure 11 – Plan at the hollow space level in the underground slab.

all the available surface (figure 11). The air is taken from outside by vents integrated in the facades of the building and driven through the distribution tower by fans installed under each of them. The distribution system is the same used during winter for the air taken from sunspace, but the flow direc-

provided through the common sunspaces. In these periods, as a precautionary measure to maintain better hygiene, the hollow space in the underground slab will be used to provide fresh air to the (not conditioned) parking and storage in the underground floors.

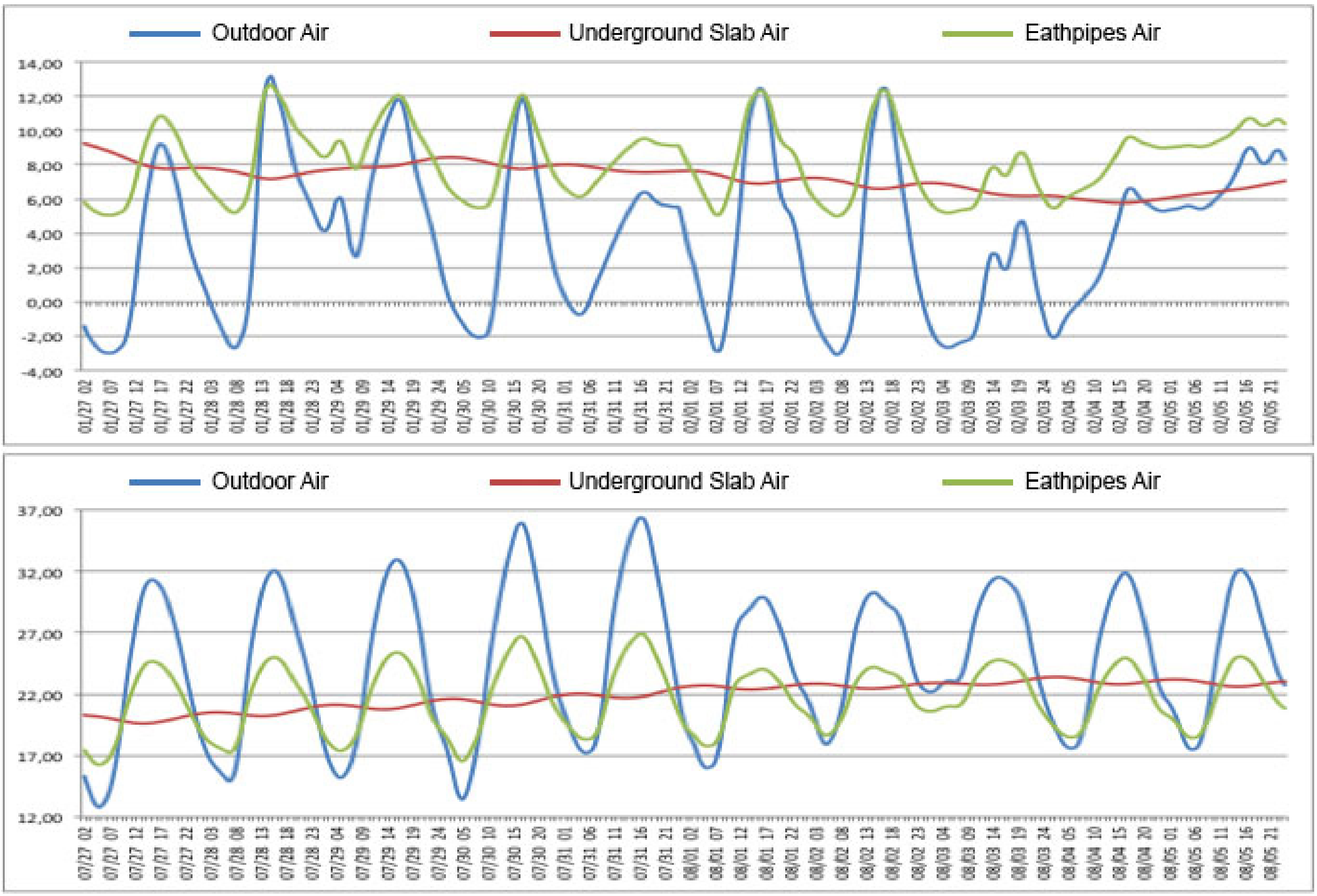

Figure 12 – Air temperatures from underground slab during the winter (above) and during the summer (below).

Conclusions

The paper deals with passive cooling and natural ventilation systems in Mediterranean climate, and describes how it is possible to design an effective natural ventilation system by integrating different analysis methods and tools for each stage of the design process. Moreover the examples treated illustrates how effective these systems can be in providing high quality internal comfort conditions while reducing energy demand in Mediterranean climate. The simulation of internal comfort conditions demonstrates that in many cases would be possible to completely eliminate the need for mechanical cooling plants, provided that occupants are willing to accept a slightly less controlled and stable condition inside the building and to tolerate few discomfort hours per year during particularly heavy climatic conditions.

In the examples analysed in the article, (i.e., two residential buildings in Florence), the estimated energy savings range from 74% to 100%. These savings have been quantified by comparing the consumption of the actual buildings to those of correspondent reference buildings. The latter were modelled identical to the actual buildings, but without natural ventilation.

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