Passive cooling strategies in the refurbishment of Mediterranean buildings: simulation analysis of thermal mass and natural ventilation combination

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Abstract

This paper aims to analyse in existing building refurbishments the complex relation between natural ventilation systems (single sided and cross ventilation, thermal chimney, evaporative cooling tower and earth pipes) and thermal inertia (medium-light and heavy) in the Mediterrean climate represented by three locations, Rome, Naples and Messina. Results show that, assuming equal comfort, the energy reduction potential is 67.7% with single-sided ventilation, 76.5% with cross ventilation, 30.2 with a thermal chimney, 20.1% with a cooling tower and 95.5% with earth pipes (where the consumption is due to the fan). In combination with the above-mentioned cooling strategies, the 30 cm thick wall maintains its role of thermal flywheel, while the 18 cm thick wall shows an excessive reactivity to climatic stresses, resulting in an average of 2.8% greater energy consumption. The scenario in Rome reaches the highest average energy consumption reduction for all the analysed systems (88.0%). Naples follows (83.1%) because of poor performance of the cool tower system (-23.4%), while the scenario in Messina is last (71.4%) because of the low thermal range that limits the efficiency of all the systems without the pre-treatment of the outside air (-37.4%).

1. Introduction

The existing building stock in Europe accounts for over 40% of the global demand of primary energy: buildings in Europe consume approximately 40 % of the economy’s incoming materials and are responsible for over 45% of the total amount of greenhouse gases produced (Ardente et al., 2011). With the increased air tightness of buildings, Mechanical Ventilation (MV) has been responsible for the largest increase in energy consumption of the building sector in recent years (Kwon et al., 2013; Heiselberg, 2002). Considering that in Europe new constructions account for 1.5% of the building stock, there is great potential for reducing global energy consumption and mitigating the environmental impact through interventions on existing buildings (Economidou et al., 2011; Baek et al., 2012). Energy refurbishment consists of applying the most appropriate technology to achieve improved energy performance while maintaining satisfactory levels of service and indoor thermal comfort, under a operational constraints (Ma et al., 2012). For retrofits that exploit thermal inertia and natural ventilation, it is essential to analyse the complex relationship between the two bioclimatic control strategies and environmental, technological and design-specific factors (Braun, 2003).

2. Research framework

2.1 The Mediterranean Area and building regulations issue

The Mediterranean area defined in this study follows Köppen-Pinna climatic classification (Fig. 1). The definition refers to those territories directly facing the Mediterranean basin, because of their climatic specificity. The following subtypes are defined: subtropical (Csa prone to Bs), a humid tropical climate with very hot summers prone to arid climate with average temperature above 18°C, low and irregular rainfall; mild temperate (Csa), a

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humid tropical climate with very hot and dry summers with average temperature of the hottest month above 22°C; sub-coastal (Csb prone to Cfb), a humid temperate climate with hot summers and average temperature of the hottest month below 22°C.

Fig. 1 - Reference areas of the Mediterranean basin

The Köppen-Pinna Mediterranean classification for Italy is compared with the national legal classification (only valid for winter conditions) that is largely employed as a reference in architectural practice and energy certification (Fig. 2).

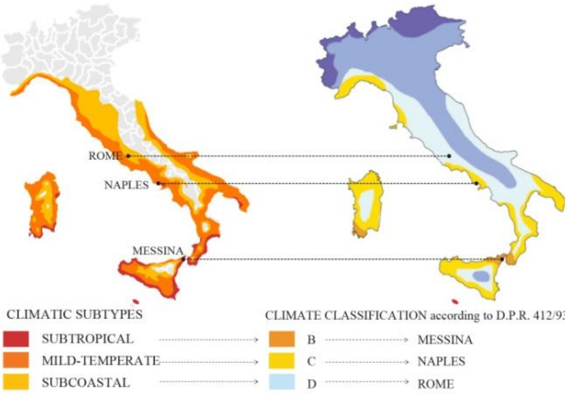

Fig. 2 - Reference location matching to the climatic subtype compared with climatic classification according to D.P.R. 412/93

The regulatory asymmetry between winter and summer conditions, with the emphasis on envelope insulation is already inside Directive 2002/91/EC and has produced with its implementation in southern Europe a number of side effects such as the reduction of the thermal mass of the buildings, a standardization of materials and technologies in stark contrast to the Mediterranean building tradition, with an overall reduction of the effectiveness of traditional passive cooling systems, based on thermal mass, air permeability and natural ventilation (D'Orazio et al., 2010; Tronchin et al., 2008). The analysis of microclimatic thermal stresses influencing thermal mass and natural ventilation represents an important step for the passive building refurbishment, as the thermal mass is most effective when interacting with intermittent heat sources (both internal and external), operating in swinging temperature conditions. Several studies show that in certain climatic circumstances, such as the Mediterranean area, an acceptable Thermal Range (TR), of about 15°C is able to maintain the temperature of a confined environment within the limits of comfort (Givoni, 1998). The thermal range amplitude (a key element for the future legislation for the summer conditions) represents a prerequisite to the optimal operation of both thermal inertia and natural ventilation strategies, especially under summer conditions when it is necessary to facilitate the dispersion of the high heat load gained during the day (Szokolay, 1985; Balaras, 1996). To choose the test cities to be used in this study, a map of thermal range is used (Cecchini 2014). Three climatic subtypes, according to Köppen-Pinna classification of the Mediterranean climate in Italy, are selected: the subtropical subtype represented by Messina with a TR of 6°C, below the threshold of efficient application of the strategies examined (Givoni, 1998; Szokolay, 1985), the mild-temperate subtype represented by Naples and the sub-coastal subtype, represented by Rome (both with TR above 14°C).

2.2 Thermal Inertia

The thermal mass of the building acts as one of the most important ways to achieve occupant comfort by controlling the internal environment through passive strategies (unlike a low thermal transmittance value that limits heat losses and therefore the optimization of the building dynamic behaviour): it allows the building to maintain the internal temperature within a certain range, theoretically close to the range of comfort, giving the building thermal stability (Kossecka et al., 2002). The choice of two representative measures of thermal mass is useful to show the effect on reducing the cooling load of the building and to analyse how the thermal mass cooperates with the natural ventilation in convective heat dissipation.

The two thermal mass measurements chosen are: a medium-light one, and a heavy one, representative of a massive wall with high heat absorption and capable of modulating the external thermal oscillations.

2.3 Existing building stock

In Europe, residential buildings cover approximately 75% of the total building stock and are the main energy consumer, because they were mainly built before laws on energy saving (Economidou et al., 2011). In Italy the most common and most energy-consuming buildings were built between 1961 and 1981 (Corrado et al. 2012; Decanini et al. 2010; Sorrentino et al. 2011) as shown in Fig. 3. Typically, these buildings have massive concrete structures with medium-light or heavy massive envelope (Pasca, 2012).

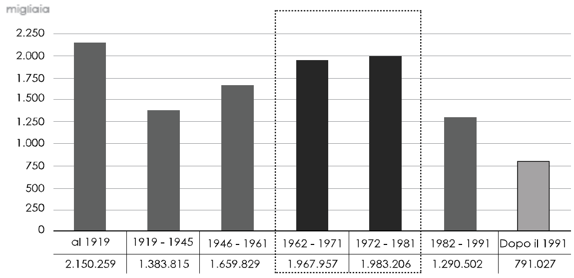

Fig. 3 - Data relating to the 2001 ISTAT census of Italian building (Corrado et al. 2012)

2.4 Natural Ventilation Systems

In the process of ventilation inside a building, air exchange occurs within the confined environment. Ventilation performs two main functions: it regulates the concentration of air pollutants and affects the igrothermal condition of the environment (Tucci, 2012). Ventilation that uses simple physical principles such as driving force is called natural (NV). Natural Ventilation principles, techniques, heat exchange type and element classification are described in Grosso (1997), Siew (2011), Calcerano et al. (2014). In this paper five different natural room ventilation systems (characterised by igrothermal comfort limits for the occupants) with automatic control (with the exception of the thermal chimney) are simulated: single sided (SSV) and cross ventilation (CV) that occur through envelope openings, thermal chimney (TC), evaporative cool tower (CT) and earth pipes (EP) that occur through spaces specifically designed.

2.5 The Simulation Contribution

The impact of strategic decisions on energy and environmental characteristics of bioclimatic design is higher when these decisions are close to the early stages of the process (Lechner, 1991). In order to maximize comfort and reduce energy consumption the design of a naturally ventilated massive building has to adapt to site-specific microclimatic conditions on a daily basis. A simulation analysis can be a useful starting point for solving the problem (Stephan et al., 2007). A numerical simulation allows to analyse the "behavioural" model of a building (reduced to a certain level of abstraction) and is therefore a key tool to improving the energetic retrofit of the building stock, because it treats the building as a system of interrelated elements that can be optimised, rather than a sum of a number of elements designed and optimised separately for subsystems (Augenbroe, 2002; Hensen, 2004). The simulations in this paper address two specific questions: in the Mediterranean climate thermal mass and natural ventilation together interact with each other to play a dominant role in the energy behaviour of a building. What is the impact in terms of comfort and energy savings of their interaction and which are the sensitive variables (Attia et al., 2013) for maximizing the benefit of this effect? Among various simulation sub-categories (Calcerano et al. 2014) multi-zonal software was chosen to tackle our questions. This approach represents a good compromise between computation time and the degree of knowledge acquired on the simulated building, thus allowing immediate results on the igrothermal state of the simulated environments, air flow, comfort, and energy consumption. (Morbitzer, 2003; Clarke, 2001; Chen, 2009; Hensen, 2003; Foucquier et al., 2013; Ramponi et al., 2012).

2.6 Performance Indicators

During the last two decades, the time spent by people in confined environments has increased (it is currently around 90% of a person’s life).

European and national legislation have gradually tightened quality standards on living spaces (Lopardo, 2011), placing indoor environmental comfort (including igrothermal comfort and indoor air quality, IAQ) as the ultimate goal, and as the main condition for the success of adopted refurbishment strategies. According to an approach that places the comfort as an "objective" and the energy consumption as a "cost" aimed at achieving comfort, the passive behaviour of the building is assessed through a comparison of the energy performance index and the environmental comfort achieved (both in the hot season). Since this study focuses on the passive thermal mass and natural ventilation simulated control in Mediterranean area, it will be possible to proceed according to the adaptive comfort model defined by EN 15251:2008 which identifies three categories in relation to the ideal operating temperature trend To, among which the paper chooses the second with To = 0.33 Te (external temperature) +18.8 ± 3 (with an 80% of acceptability). The above-mentioned indicator is associated with the ideal energy consumption value for cooling (shown in kWh/m^2y), in order to relate the modelling to professional practice. The considered range for the ideal building plant's setting refers to the adaptive comfort temperature range, larger than that of Fanger - in order to better evaluate the contribution of a passive strategy to the reduction in energy consumption without the overestimation of the impact of technology (Corgnati, et al., 2008). A third synthetic indicator, air changes per hour (ach), is used to monitor and control that natural ventilation systems ensure the minimum air changes per hour required for IAQ (0.7 ach according to EN 15251:2008) inside a building with low infiltration (average 0.23 ach with Class 3 EN 12207/1999 windows); that simulation results show the difference between systems that use a larger crack (such as the openings on the building envelope of 3.45 m^2) and can generate many air changes per hour with relatively low internal air speed, and systems that use smaller ducts (0.09 or 0.07 m^2) and linear paths to avoid air flow losses and therefore have lower air changes per hour to prevent internal air speed becoming annoying for the occupants, with the advantage of eliminating problems of safety related to intrusion (Allard, 1998).

3. Simulation

The simplified model, representative of the most diffuse and energy-consuming building typology in both European and national area (Corrado et al. 2012), is a south and north-facing apartment (7 m width x 8 m depth and a height of 3 m with two opposite low-emissivity air tight glass windows of 3.45 m^2 according to the hygiene regulations in force in Italy), located inside a multi-storey building and characterized by two thicknesses of the external concrete massive envelope: heavy (A, 30 cm) and medium-light (B, 18 cm). All the remaining surfaces are considered adiabatic. Internal gains (lights, people and electric equipment) are set according to a hypothetical residential occupancy pattern. A set of numerical multi-zonal simulations is then run using single sided and cross ventilation that occur through envelope openings, thermal chimney, evaporative cool tower and earth pipes that, with automatic control in their interactions with two different thermal masses, referring to the hot season (from the 1st June to the 30th September) for three different cities (Rome, Naples and Messina).

Table 1 - Model envelope thermo physical properties (*adiabatic)

Constr. Type	**U** **[W/(m²K)]**	**Y_{ie}** **[W/(m²K)]**	**Φ** **[h]**	**F_d** **-**
Upper floor*	1.34	0.46	8.37	0.34
Lower floor*	1.49	0.64	7.82	0.43
30 CLS wall	2.01	0.48	9.14	0.24
18 CLS wall	2.41	1.13	6.00	0.47
Window	1.00	SHGC = 0.3		

The software adopted for the simulations is EnergyPlus (Henninger and Witte 2011). For each combination between natural ventilation system (NV Syst.), locations and envelope type (e.g.

SSV_R_A), two Benchmark Simulations (BS), set with a minimum of 0.23 ach from infiltration, paired with two natural ventilation simulation, are run to carry out a correlational analysis. The first simulation, called Discomfort Benchmark Simulation (DBS) that serves as a reference case for subsequent analysis, calculates the model as it is and shows the total hours of discomfort during the simulation running period (expressed in hours/yearly in reference to the heat excess discomfort in the summer period). The DBS relative simulation with Natural Ventilation systems (DNVS) allows obtaining an estimate of the Discomfort hours Reduction Potential (DRP) expressed as a percentage, of the passive systems in examination. The other benchmark simulation, called Energy Benchmark simulation (EBS), has a thermostat that activates (on adaptive comfort range) a theoretical plant whenever the igrothermal condition of the building goes beyond a normalized temperature threshold for comfort (EN 15251), taking into account the subsequent primary energy consumption (expressed in kWh/m^2y for cooling purpose). The EBS relative simulation with Natural Ventilation (ENVS) along with thermostat and theoretical plants shows the Energy Consumption Reduction Potential (ERP). The relationship between these two reductions and the effectiveness of natural ventilation and thermal mass are then investigated. In order to simulate single sided and cross ventilation, the Airflow Network model of EnergyPlus that allows for calculation of multi-zone airflows due to wind and surface leakage, is adopted (NREL, 2013) implementing a ventilation control mode based on the temperature differential between inside and outside temperature (if the room temperature T_{room} > outdoor temperature T_{out}, T_{room} > summer threshold temperature (21 °C), windows are opened with an opening factor set to 0.5, with a T_{room} and T_{out} difference lower and upper limit set to 2 °C and 10 °C. The Thermal chimney (designed in the model with a 18 m high tower with low emissivity glass on the south facade and a cross section of 0.09 m^2), evaporative cool tower (18 m height with a cross section of 0.09 m^2 and a water pump of 0.016 l/m) and earth pipes (25 m concrete duct 0.004 thick with a cross section of 0.07 m^2) are simulated through in built Zone Airflow model of EnergyPlus (NREL, 2013).

4. Analysis and discussion of the results

Results are shown in table 2. The absolute values of discomfort hours and energy consumption of the simulations confirm the results of previous research (Cesaratto et al., 2010; Sibilio et al. 2009) around 18.3 kWh/m^2y and 2300 discomfort hours per year in Rome and Naples with a sharp rise in Messina (on average 1.2 times the hours of discomfort, 2 times the energy consumption).

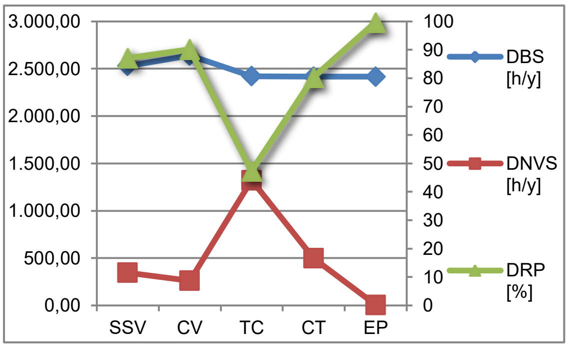

Fig. 4 - Discomfort hour analysis

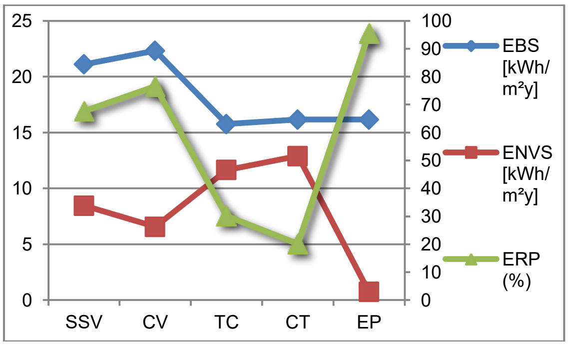

Fig. 5 - Energy consumption analysis

DRP of natural ventilation simulations is 88.0% in Rome, 83.2% in Naples because of poor performance of the cool tower system: -25% compared to Rome although not dependent on the average temperature and relative humidity (RH), but probably by the dynamic behaviour of Naples during the season. The RH standard deviation is 18% compared to 14% of Rome, which results in greater fluctuations of the value, the days of extreme heat are double in comparison to Rome, precipitation one and a half, heavily reducing the effectiveness of the system in the most critical hours). DRP is 71.4% in Messina because of the low thermal range that limits the efficiency of all the systems without pre-treatment of the outside air (-19.6% compared to Rome and Naples). In absolute terms the energy saved and the largest decrease of discomfort hours take place in Messina (average reduction of 9.9 kWh/m^{2}y against 7.8). Concerning ventilation systems earth pipes reach highest average discomfort hours reduction in every location with a DRP of 99.7 % (optimized design flow are assumed constant with a small fan), single sided and cross ventilation follows (88.6 %) while the thermal chimney is last due to small air changes per hour without air pre-treatment (47.3%). Assuming equal comfort, the energy reduction potential is 67.7% with single-sided ventilation, 76.5% with cross ventilation, 30.2% with thermal chimney, 20.1% with cool tower and 95.5% with earth pipes (where the energy consumption is due to the fan). In combination with the above-mentioned cooling strategies, the 30 cm thick wall maintains its role of thermal flywheel (with the exception of the CV), while the 18 cm thick one shows an excessive reactivity to climatic stresses, resulting an average of 2.8 % greater energy consumption.

Table 2 – Simulation results (NV Syst: Natural Ventilation System: SSV, CV, TC, CT, EP, TM: Thermal Mass - DBS: Discomfort Benchmark Simulation - DNVS: Discomfort Naturally Ventilated Simulation - DNVS syst: infiltration due to natural ventilation system in DNVS - DRP: Discomfort hours Reduction Potential - EBS: Energy Benchmark simulation - ENVS: Energy Naturally Ventilated Simulation - ENVS Syst.: infiltration due to natural ventilation system in ENVS - ERP: Energy Consumption Reduction Potential – *average)

NV syst._ City_ TM	DBS [h/y]	DBS [ach]*	DNVS [h/y]	DNVS inf. [ach]*	DNVS syst. [ach]*	DRP [%]	[EBS] [kWh/m^{2}y]	EBS [ach]*	ENVS [kWh/m^{2}y]	ENVS [ach] *	ENVS syst. [ach]*	ERP [%]
SSV_R_A	2359	0.23	144	/	2.14	93.90	14.59	0.22	1.69	/	2.07	88.41
SSV_R_B	2212	0.23	150	/	2.17	93.22	15.09	0.22	2.70	/	2.07	82.10
SSV_N_A	2540	0.17	46	/	2.05	98.19	17.11	0.15	2.42	/	1.98	85.85
SSV_N_B	2449	0.17	88	/	2.09	96.43	17.73	0.15	3.56	/	1.98	79.91
SSV_M_A	2816	0.21	775	/	2.54	72.48	29.83	0.18	18.95	/	1.69	36.48
SSV_M_B	2797	0.21	879	/	2.57	68.56	32.20	0.18	21.43	/	1.70	33.44
CV_R_A	2444	0.23	210	/	3.95	91.40	15.83	0.20	1.74	/	3.65	89.02
CV_R_B	2355	0.23	279	/	2.62	88.15	16.30	0.20	0.68	/	2.97	95.80
CV_N_A	2638	0.19	59	/	3.06	97.76	18.21	0.15	3.13	/	2.80	82.82
CV_N_B	2575	0.19	313	/	2.42	87.85	18.79	0.15	1.65	/	2.33	91.25
CV_M_A	2926	0.21	564	/	4.44	80.74	31.29	0.16	16.54	/	3.55	47.12
CV_M_B	2899	0.21	146	/	4.34	94.97	33.52	0.16	15.65	/	3.52	53.32
TC_R_A	2241	0.23	935	0.92	0.69	58.28	11.15	0.23	6.60	0.99	0.76	40.84
TC_R_B	2012	0.23	775	0.93	0.70	61.50	11.25	0.23	6.97	0.99	0.76	37.98
TC_N_A	2420	0.23	1078	0.90	0.67	55.46	11.97	0.23	7.39	0.98	0.75	38.28
TC_N_B	2127	0.23	957	0.91	0.68	55.03	12.05	0.23	7.80	0.99	0.76	35.25
TC_M_A	2885	0.23	2129	0.99	0.76	26.20	23.52	0.23	19.95	1.21	0.98	15.17
TC_M_B	2836	0.23	2060	0.99	0.77	27.37	24.60	0.23	21.19	1.21	0.98	13.86
CT_R_A	2246	0.23	32	0.23	1.81	98.56	11.39	0.23	7.59	0.23	1.81	33.38
CT_R_B	2020	0.23	87	0.23	1.81	95.69	11.56	0.23	8.15	0.23	1.81	29.48
CT_N_A	2423	0.23	628	0.23	1.81	74.07	12.22	0.23	11.07	0.23	1.81	9.42
CT_N_B	2132	0.23	642	0.23	1.81	69.89	12.40	0.23	11.59	0.23	1.81	6.54
CT_M_A	2859	0.23	758	0.23	1.81	73.48	24.09	0.23	18.83	0.23	1.81	21.85
CT_M_B	2816	0.23	840	0.23	1.81	70.18	25.31	0.23	20.16	0.23	1.81	20.34
EP_R_A	2246	0.23	0	0.23	0.77	100.00	11.39	0.23	0.45	0.23	0.77	96.07
EP_R_B	2020	0.23	1	0.23	0.97	99.96	11.56	0.23	0.56	0.23	0.97	95.12
EP_N_A	2423	0.23	0	0.23	0.82	100.00	12.22	0.23	0.48	0.23	0.82	96.10
EP_N_B	2132	0.23	27	0.23	1.01	98.76	12.40	0.23	0.59	0.23	1.00	95.26
EP_M_A	2859	0.23	5	0.23	1.66	99.82	24.09	0.23	0.97	0.23	1.67	95.99
EP_M_B	2816	0.23	6	0.23	2.26	99.80	25.31	0.23	1.31	0.23	2.26	94.81

5. Conclusions

Reported results highlight:

1. the effectiveness of minimally invasive refurbishment actions for energy retrofits of existing buildings, such as implementing automatic control on already existing openings on the building envelope because single sided and cross ventilation produce the greatest benefits in relation to their cost;
2. an effectiveness reduction of systems without air pre-treatment due to a lower daily thermal range, and an effectiveness reduction of the evaporative cool tower due to a higher average humidity ratio;
3. the variation of some parameters for the optimization of automatic control systems in different climates: in Rome to avoid discomfort hours from cold in the simulated period, the activation threshold of the systems is 22°C with the difference between outside and inside air temperature between 2 and 5°C, in Naples and Messina the activation threshold drops to 21°C and the difference increases from 2 to 7°C in Naples, from 2 to 12°C in Messina;
4. the increased efficacy demonstrated by the earth pipes should be related to the higher invasiveness and difficulty of implementation that make this type of intervention only recommended when working on large refurbishments;
5. when retrofitting a single apartment of a multi-storey building, the small solar gains make it less significant the effect of the thermal mass compared to an intervention on a building where all surfaces are exposed (cf. Calcerano et al. 2014).

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