Doctoral School on Engineering Sciences
Università Politecnica delle Marche

Extended summary

Experimental and numerical study on solar walls for energy savings, thermal comfort and sustainability of residential buildings

Curriculum: Architettura, Costruzioni e Strutture

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Date: 30-01-2013

Abstract. This thesis presents a study on the behaviour of solar walls in a residential building under a Mediterranean climate, in terms of energy performance, thermal comfort and sustainability. The use of solar walls in temperate climates is problematic due to undesired heat gains and overheating phenomena in summer, especially in super-insulated buildings in keeping with current energy standards. Few studies in literature focus on the behaviour of the system in temperate climates and on their life cycle.

The objectives of this study are: the experimental analysis of thermal parameters of solar walls in different conditions; the estimation of solar wall influence on energy needs and indoor thermal comfort of dwellings with different insulation levels; the minimization of energy needs and environmental loads throughout the life cycle.

The methodology included several phases: a series of monitoring campaigns on a case study in different seasons and conditions; simulations in dynamic state on a model calibrated with experimental data to generalise energy and thermal comfort results; development of an integrated approach for the optimization of energy and environmental performances that combines life cycle assessment, energy simulation and optimization with level factorial plan.

The results demonstrated that solar wall is an efficient system in providing energy savings and suitable indoor thermal comfort in Mediterranean climates. The combined use of overhangs, roller shutters and cross ventilation can significantly reduce cooling loads and assure a satisfactory thermal comfort level in summer. Results of the optimization analysis demonstrated that it is possible to reduce environmental burdens and energy demand of solar walls throughout their life cycle up to -55% using aerated concrete, double glazing and wooden framing instead of a traditional design. This methodology might be generally applied to sustainability analysis, design and optimization of efficient façade systems.

Keywords. Passive solar walls, Sustainable architecture, Energy savings, Thermal comfort, Life Cycle Assessment.

1 Problem statement and objectives

The urgent need of reducing energy consumption and greenhouse gases emission of buildings determines the importance of an accurate design of the building envelope able to assure energy savings, sustainability and indoor comfort. The increasing interest in passive solar systems is motivated by their capability of providing high energy and thermal comfort performance for buildings and their use is encouraged by European Directives [1,2] and national regulations of the Member States. However there are still open problems regarding the design of passive solar systems as well as many uncertainties about their real performance and environmental impacts, in particular for solar walls.

Solar wall is a passive solar system generally made up of a south-facing concrete wall painted black on the external surface, an air layer and glazing on the exterior side. Shading devices such as overhangs or movable shutters provide solar radiation control. Solar walls catch solar radiation by means of the greenhouse effect created in the glazed cavity, absorb and store thermal energy using the massive wall and finally exchange it with the indoor environment by transmission through the wall. *Trombe wall* is a particular type of solar wall equipped with vents at the top and the bottom for the air thermo-circulation between the air gap and the indoor environment; external dampers provide external ventilation to the air layer. In a Trombe wall system heat exchange with the indoor space is both by transmission and by ventilation through the vents.

Most of the research work about solar walls focuses on the optimization of winter energy performance, as this system was originally conceived for passive heating of buildings. Few studies focus on summer behavior, indoor thermal comfort conditions and life cycle.

In winter, drawbacks of the systems concern [3,4] low thermal resistance, uncertainty of ventilation exchanges and inverse thermo-siphon phenomena that can determine high heat dispersion. Actions suggested to enhance winter performance include: wall insulation and double glazing [5], using a more complex design such as composite Trombe wall [6,7], deactivation of ventilation and proper management [8].

In summer overheating phenomena can occur due to high heat gains of Trombe walls [9-12]. Overheating problems can be solved or reduced by several actions: insulation of Trombe wall [5]; use of solar shading [12,13]; ventilation of Trombe walls [5,10]. However, most of the studies about summer behaviour of the system only give recommendations and rarely quantify benefits of the different solutions.

Despite the number of studies about solar walls, only few researches regard their life cycle [12]. Life cycle assessment (LCA) is a technique used to assess potential environmental impacts of products throughout their life cycle and has been widely applied to building components and entire buildings [14-21]. Analysis of the life cycle of solar walls is needed as they are often made up of materials and components characterized by relatively high environmental impacts in the production phase. Furthermore an optimization process based on several aspects related to building envelope systems is needed.

This study focuses on the behaviour of solar walls in a Mediterranean climate and their contribution to indoor thermal comfort, energy and environmental performance of residential buildings. The configuration of the system assumed is a classic Trombe wall used as non-ventilated solar wall in winter while in summer the use of cross ventilation and different shading devices are considered. The methodology combines experimental analyses on a case study and numerical simulation on a calibrated model.

The objective of this study is to demonstrate that satisfactory energy performance, thermal comfort level and environmental performance can be achieved using solar walls for residential buildings in a Mediterranean climate, supposed to assume the proper wall configuration and operative management. The study encompasses the development of a new methodology generally applied for the optimization of energy and environmental performance of complex façade systems and tested on the case of solar walls.

2 Research planning and activities

The methodology included several activities: monitoring campaigns on a case study to collect real data on the thermal parameters of solar wall systems; simulations on a virtual model in dynamic state calibrated with experimental data to generalise and extend energy and thermal comfort results; development of an integrated approach for the optimization of energy and environmental performances of complex building envelopes that combines life cycle assessment, energy simulation and optimization analysis with factorial plan technique.

2.1 Experimental analysis

Experimental analyses consisted of a series of monitoring campaigns on a solar house provided with Trombe walls and located in Ancona - central Italy. Monitoring campaigns were carried out for several years in different seasons to collect data regarding thermal behaviour of solar walls and thermal comfort parameters. A detailed monitoring was carried out to investigate the effect of shading, ventilation and room occupation on the behaviour of the system in summer conditions.

The monitoring set-up consisted of an external climatic station to collect weather data, an internal station for the survey of indoor microclimatic condition and a set of probes for thermal parameters of the wall, including surface temperature, air temperature, air velocity, heat fluxes probes.

2.2 Numerical analysis

Numerical simulations were performed in dynamic state in EnergyPlus on a model calibrated with experimental data. Calculations were run to extend the experimental results to the whole year and to compare solar walls with conventional masonry walls characterized by different insulation levels. Comparisons were made both on the system performance (wall heat gains and losses) and energy performance of the dwelling (heating and cooling energy needs) varying the building envelope insulation level according to several standards (as built, conventional in keeping with national regulation and passive house). Indoor thermal comfort conditions were calculated for the different cases considered using appropriate methods (PMV and adaptive method).

An environmental analysis of solar walls system was carried out to estimate environmental impacts. The environmental performance of solar walls was calculated in terms of CO_2 emissions and energy demand during the life cycle and optimized using a new integrated approach combining LCA, energy simulation in dynamic state and factorial plan technique. The methodology, tested on the case study, is generally applicable to optimize energy and environmental performances of building envelope systems considering their life cycle.

3 Analysis and discussion of main results

3.1 Thermal behavior and energy performance study

3.1.1 Experimental results

Thermal monitoring of Trombe wall provided information about the thermal behavior of the system in several seasons and conditions.

In intermediate seasons and winter the system unscreened and unventilated presents relatively high internal surface and can provide significant daily heat gains in sunny conditions: 0.95 MJ/m^2 in October and 0.45 MJ/m^2 in December. The time lag in heat transmission proper of the system delays the heat gains from daytime to nighttime and ensures indoor stable temperature condition.

In summer the effect of schading devices and ventilation of the system on its thermal behaviour was studied in detail. It was found that roller shutters have a beneficial influence in reducing surface temperatures of Trombe wall of -1.4 °C and daily heat gains toward the room of about 0.5 MJ/m^2. Air velocity in the cavity is influenced by both wind conditions and temperatures in the air gap and it was found relatively low, especially in the case of Trombe wall screened by roller shutters. Thermo-graphic survey was useful to prove that Trombe wall external surface temperature distribution is rather uniform when screened from direct solar radiation. The analysis of Trombe walls in real use conditions showed that the presence of occupants in the house determines an increase in room air temperature, but also higher ventilation rates due to window opening. In such conditions, heat fluxes from the wall to the room are reduced while air velocity in the gap are higher.

3.1.2 Numerical results

Numerical simulations showed that during the heating season the energy performance of solar walls is higher than conventional walls in terms of total energy contribution due to the high solar gains, in particular using exterior double glazing. Solar walls assure low heating energy needs in the dwelling at the changing of the building envelope insulation level.

Results confirmed that in summer solar walls generally determine increased heat gains and cooling energy needs. The use of shading devices such as overhangs and roller shutters is more effective than cross ventilation in saving energy for the cooling of a dwelling with Trombe walls; increasing the insulation level of the building envelope determines decreased efficiency for solar shading and increased efficiency for ventilation of Trombe wall; regardless of the insulation level of the building envelope, the best energy performance was obtained combining overhangs, roller shutters and cross ventilation, with a reduction in cooling energy need up to -72.9 % compared to the case of an unventilated Trombe wall without solar protections.

The overall energy performance in terms of primary energy for heating and cooling of a dwelling representative of the current construction practice is up to -9.3 % lower using solar walls with single glazing on the South-façade instead of conventional masonry walls. The operation mode of solar walls assumed to obtain this result is unscreened and unventilated during the heating season, screened and ventilated in summer.

3.2 Thermal comfort study

Analysis of indoor thermal comfort performed based on experimental data collected on the case study showed that a satisfactory thermal comfort level can be assured in many periods of the year. Thermal comfort analysis for a selected period characterized by severe summer conditions confirmed that comfort level was complying with comfort standards.
Numerical analysis were performed to extend results to the whole year and to compare the thermal comfort level at the changing of south-facing wall (conventional or solar wall) and insulation level of the envelope. In winter the comfort level is similar in both cases of solar walls and conventional walls on the south façade. In summer, overheating drawbacks are more severe using solar walls instead of conventional walls and especially in the case of more insulated building envelopes. However, the application of further strategies, such as cross ventilation, improves summer behaviour of solar walls and leads to an adequate level. The use of solar walls not screened by shutters determines the highest number of hours over the thermal comfort limit and it should be avoided.

3.3 Environmental study and optimization

Results showed that the solar walls in the as built case have high environmental impact both in the pre-use and use phases. In the production process, environmental burdens are mainly caused by aluminium and concrete while, in the operational stage, high CO_2 emissions and energy requirements are due to the energy use for summer cooling.

The optimization process with level factorial plan demonstrated that it is possible to reduce the CO_2 emissions and energy demand of solar walls for both the production and use phases up to -55 % from a traditional set-up (concrete layer 40 cm thick, aluminium frame and single glazing) to an optimized set-up (aerated concrete blocks layer 20 cm thick, wood frame and double glazing). However, the final choice can be based on different objectives or conditions set on the design process, for instance limiting summer energy needs adopting a configuration with single glazing instead of double. Using single glazing instead of double glazing, the façade system has lower energy needs for cooling and minimum GWP for the pre-use phase.

4 Conclusions

An experimental and numerical study on the performance of solar walls in a residential building under Mediterranean climate conditions was carried out. The study confirmed that solar wall can be an efficient system from the point of view of energy savings, indoor thermal comfort and sustainability assumed the proper configuration and management.

Thermal behaviour and energy performance were investigated through thermal monitoring of the system, essential to test solar walls in real conditions, and simulation in dynamic state allowing the generalization of the results to a whole year and to different types of building envelope. It was shown that solar walls assure suitable thermal behaviour and energy savings for heating compared with a conventional solution, but also increased energy need for cooling due to solar gains. However, the combined use of overhangs, roller shutters and cross ventilation can assure a substantial reduction of cooling energy needs. The total primary energy for heating and cooling of a dwelling representative of the current construction practice is -9.3 % lower using solar walls with single glazing on the South-façade instead of conventional masonry walls.

Thermal comfort conditions produced by the system are suitable in winter and intermediate seasons, while in summer overheating drawbacks might occur during the hottest months. The combined use of overhangs, roller shutters and cross ventilation can assure a satisfactory thermal comfort level in summer, while the use of solar walls without screening is to be avoided.

The application of a methodology based on LCA has shown its effectiveness for the design of complex building envelopes and the optimization of energy and environmental performance. The strength of LCA is the capability of recognizing the implications of a design choice given a certain context and to choose consciously the optimum solutions taking control of every stage of their life cycle. Level factorial plan is able to assess the effect of single variations and interaction between parameters thus showing the direction for further optimization steps. The study provided relevant results for the conscious design of solar walls in the specific context considered and demonstrated that it is possible to reduce the CO2 emissions and cumulative energy demand of solar walls significantly with a proper design. Furthermore, the methodology developed may be generally applied to the sustainability analysis, design and optimization of efficient façade systems.

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