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The Solar Wall in the Italian Climates

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***Abstract*—**Passive systems were born with the purpose of the greatest exploitation of solar energy in cold climates and high altitudes. They spread themselves until the 80's all over the world without any attention to the specific climate and the summer behavior; this caused the deactivation of the systems due to a series of problems connected to the summer overheating, the complex management and the rising of the dust.

Until today the European regulation limits only the winter consumptions without any attention to the summer behavior but, the recent European EN 15251 underlines the relevance of the indoor comfort, and the necessity of the analytic studies validation by monitoring case studies.

In the porpose paper we demonstrate that the solar wall is an efficient system both from thermal comfort and energy saving point of view and it is the most suitable for our temperate climates because it can be used as a passive cooling sistem too. In particular the paper present an experimental and numerical analisys carried out on a case study with nine different solar passive systems in Ancona, Italy.

We carried out a detailed study of the lodging provided by the solar wall by the monitoring and the evaluation of the indoor conditions.

Analyzing the monitored data, on the base of recognized models of comfort (ISO, ASHRAE, Givoni's BBCC), is emerged that the solar wall has an optimal behavior in the middle seasons. In winter phase this passive system gives more advantages in terms of energy consumptions than the other systems, because it gives greater heat gain and therefore smaller consumptions. In summer, when outside air temperature return in the mean seasonal value, the indoor comfort is optimal thanks to an efficient transversal ventilation activated from the same wall.

***Keywords*—**Building envelope, energy saving, passive solar wall, thermal comfort.

I. INTRODUCTION

UNTIL today the European regulations limit only the winter consumptions without any attention to the summer behavior but, the recent European EN 15251 underlines the relevance of the indoor comfort, and the necessity of the analytic studies validation by monitoring case studies.

The same regulations wish the introduction of passive systems also in temperate climates, only with the function of passive heating. Also a big part of the international literature is directed only to the study in winter phase (Arumi 1977, Fang 1999, Zalewsky 2002). Recent studies (Gan 1998 and Khedari 1999) perform the analisys and the optimization of some systems (trombe wall, solar chimney) for the passive summer cooling.

But are left open problems:

-on the summer phase is not defined the optimal management of the system;

-most past studies make considerations on the system energy performance without assess the comfort by objective models;

-for the parametric analysis the siad studies do not use validated models from real monitored buildings, emphasizing an absence of correlation between experimental studies and analytic, and indicating a problem of models reliability.

-there are very few studies on the thermo – phisic behavior of the solar wall in a temperate climate.

The present paper's objective is to solve these problems studying the winter and summer behavior, of a lodging provided by a solar wall in temperate climate, on the base of recognized models of comfort (ISO, ASHRAE, Givoni's BBCC) and consumptions, using a method with a deep relationship between analitical and experimental phase.

II. METHOD

The work is characterized by a method settled in four phases: (i) monitoring; (ii) software simulation, in static and dynamic state, of the as-built state; (iii) validation of model using experimental monitored data; (iv) parametric analysis to extend the study to many climatic conditions and envelope typologies.

The parametric analysis allow us to quantify how every constructive choice affect the solar wall behavior, and choose the better solution.

III. THE CASE STUDY

The house has a compact shape and is oriented along the E-W axis in order to maximize solar supply. Sun exposure only affects the vertical southern wall that ensures the greatest sun supply at our latitudes. The other walls are of conservative kind – equipped with a 4-cm outside coat and designed in such a way as to minimise the glass surface and ensuing heat dispersal. It includes nine flats (6 duplex and 3 simplex) with the same internal surfaces and distribution. The south-facing wall of each flat includes a particular solar system, i.e. 9

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passive solar systems, which make the prototype a very interesting laboratory still today. One flat was built in a traditional way for the sake of a comparison in order to test the efficiency of passive solar systems.

The passive solar systems tested can be classified as follows:

TABLE I
PASSIVE SYSTEM TESTED

Diffused accumulation	Direct gain storage Solar wells	
Southern vertical accumulation	“hot” greenhouse - with outside glass screening	
	“cold” greenhouse – with inside wall screening	
	Trombe-wall	simple
		lightened
		with greenhouse
Floor accumulation	Separate flat collector (blade interceptor and floor accumulator)	
	Slate collector	

In particular we analyzed the performance of the lodging provided by solar wall that, from our precedents studies [1,2], is resulted the most suitable system in our climates.

This system is made up of a rammed concrete wall 40cm thick painted black on the outside and equipped with manually adjustable vents (2 at the bottom + 2 at the top). At a distance of 10cm on the outside wall an openable glass surface brings about the greenhouse effect. The vents allow the activation of air flow that in summer agrees a transversal ventilation of the environments, while in winter produces the indoor heating across convective movements. The solar radiation control is carried out from balcony and shutters.

Fig. 1 Outside and inside view of solar wall

IV. PROCEDURAL METHOD

A. Lodging with Solar Wall Behavior: Comfort Point of View

The environmental conditions were measured by using two mobile monitoring stations; these instruments allow to record the values of:

- air temperature and humidity ratio (psychrometer);
- mean radiant temperature (black-globe thermometer),
- relative air speed (anemometer).

in three different indoor environments (position 2, 3, 4 in Fig. 2).

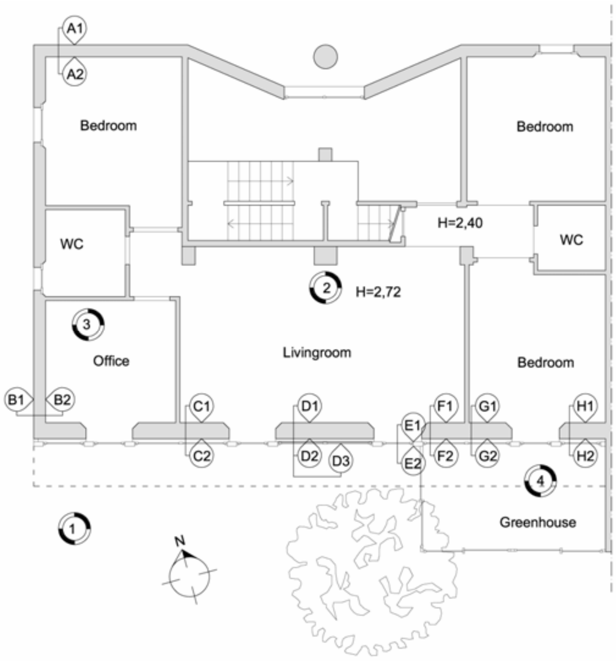

Fig. 2 Position of probes and monitoring station

B. Monitoring Solar Wall: As Built Yield

The monitoring activities were carried out in two phases:

- the first time to compare superficial temperatures of the varied portions of wall in different use conditions (screened, whitout screen, with greenhouse) employing three data taker (positions A, B, C, D, E, F, G, H in Fig. 2)

- the second one, performed from October the 12 to November the 20, consisted in survey the environmental parameters insides and outside the solar wall, the surface temperature and thermal fluxes across the wall with the purpose to determine the thermo – physic behavior of system in the intermediate and winter season, particularly the thermal mechanisms of exchange between wall and inside environment, and between wall and outside environment.

To carry out the monitoring of solar wall we employed three data taker. The first one was employed for the survey of the climatic conditions near the solar system by using the following sensors:

- thermohygrometer (outdoor air temperature and relative humidity) [probe 1 in Fig. 3];

- anemometer (speed and wind direction) [probe A in Fig. 3];

- radiometer (solar radiation accident on the wall) [probe B in Fig. 3].

The other two data taker were connected with probes for the measurement of temperatures and flows on the solar wall surfaces:

- contact temperature probe PT100 screened (glass outside surface temperature) [probe 2 in Fig. 3],

- contact temperature probe PT100 not screened (concrete outside surface temperature) [probe 3 in Fig. 3],
- contact temperature probe PT100 screened (concrete outside surface temperature) [probe 4 in Fig. 3],
- contact temperature probe PT100 screened (air gap temperature) [probe 5 in Fig. 3],
- contact temperature probe PT100 (concrete inside surface temperature) [probe 6 in Fig. 3],
- thermohygrometer (indoor air temperature and relative humidity) [probe 7 in Fig. 3],
- heat flux sensor (heat flux across inside surface) [probe C in Fig. 3],

The external probes were screened from the solar radiation to avoid value alteration.

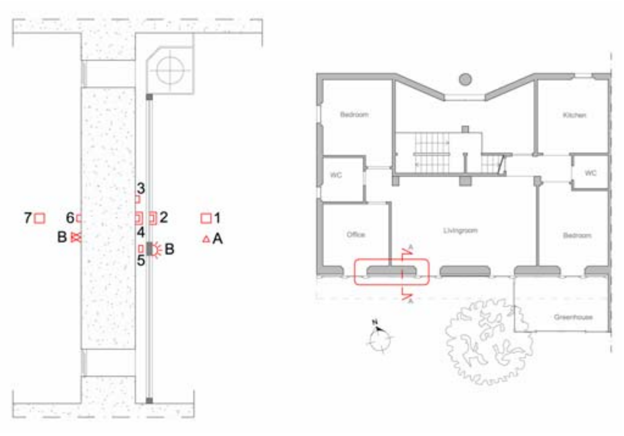

Fig. 3 Monitoring specific element

Fig. 4 Outdoor climatic station

Fig. 5 Heat flux sensor and contact temperature probe

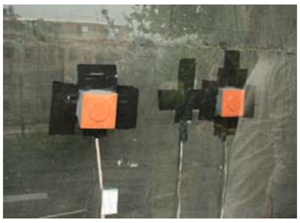

Fig. 6 External probes

C. *Carring out and validating simulation model*

The simulation model was realized using dynamic-state software (energy plus). We simulated the solar wall behavior thanks to a specific algorithm present in this software, by realizing a zone with dimensions of the gap, and assigning to it, in energy plus' text editor, the feature *TrombeWall*. The model validation is fundamental if we want to obtain reliable result from the simulation; in fact, our previous study [3], on software tuning up, showed that simulation results, is strongly influenced by input values, like:

- really monitored climatic conditions;
- presence outside of screens;
- surface properties (emissivity, adsorptance);
- materials conductance;
- air infiltrations.

On the base of these consideration, we performed the model validation varying the envelope characteristic that affect the thermal exchange, to obtain a satisfactory approximation of the reality, showed as follows:

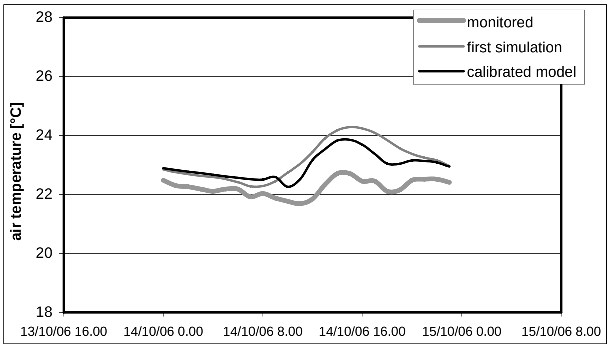

Fig. 7 Model calibration effects

The mean difference between monitored and simulated temperature is 0,7°C.

D. Comparison of Measured and Calculated Values

The monitored indoor conditions were assessed using specific comfort models for every season:

- In winter we considered ISO 7730 (PMV) method [11];
- In summer we adopted the Adaptive ASHRAE model [9];
- In fall and spring we used the Givoni's BBCC [5] and PMV

The solar wall thermo - physical study was performed considering a square meter of surface of wall, we carried out a daily system energy balance like sum of four components: incident solar radiation (W); stored heat by concrete (Q); exchangeed heat with inside ambient (Fi); exchangeed heat with outside environment (Fe). The directly measured values are the solar radiation (radiometer) and the exchanged heat with inside ambient (fluximeter); the stored heat by concrete was calculated knowing the concrete temperature time variation and using the well note relation:

$$Q = \rho V c \frac{\Delta T}{\Delta t} \tag{1}$$

where:

ρ is the concrete density (2200 kg/m3);
V is the concrete volume (0,4 m3);
c is the concrete specific heat (880 J/kg K);
Δt is the time between two misuration (10 minutes);
ΔT is the variation of concrete temperature;

The exchanged energy with outside environment was calculated by the wall daily heat balance showed below:

$$W + Q + Fi + Fe = 0 \tag{2}$$

Besides the daily energy values we calculed the system mean daily yield by the relation (3):

$$\eta = \frac{Fi}{W} \tag{3}$$

Finally we can extract two experimental relation that bind system yield and exchangeed heat with indoor ambient (Fi) to the outdoor environmental conditions (solar radiation and air temperature).

- $\eta = f(t_{ea})$
- $Fi = f(t_{ea})$

The climatic conditions were expressed by sol – air temperature (t_{ea}), calculated according to the method proposed from [8].

The effects on comfort producted from every parametric variation were assesed by calculating the mean difference between daily operative temperature and the optimal operative temperature of the environment; this difference was calculated using the following relation:

$$\overline{\delta} = \frac{\sum_{i=1}^{24} \left| Top_i - Topt_i \right|}{24} \tag{4}$$

Where:

- Topi is the indoor operative temperature at the i - hour of the day;
- $Topt_i$ is the indoor optimal operative temperature at the i - hour of the day.

V. REFLECTIONS ON THE SOLAR WALL MANAGEMENT

Thanks to the previous studies [1,2] we defined an optimized method of control that allows to solve the complex daytime seasonal management.

In summer, the outside upper and inside lower vents are always open. The air gap heating activates the chimney effect, and creates a comfortable trough ventilation with the openings facing to north.

The original winter management, prescribed that the inside upper and lower vents were open on day and closed on night, but that cuased problem of dust rising. Moreover, the lower vents must be closed to aviod the inversion of the thermal flow during the night.

Therefore we decided to deactivate the system holding all the vents closed; however the wall is able to produce heat gain during the day and to perform the function of thermal flywheel.

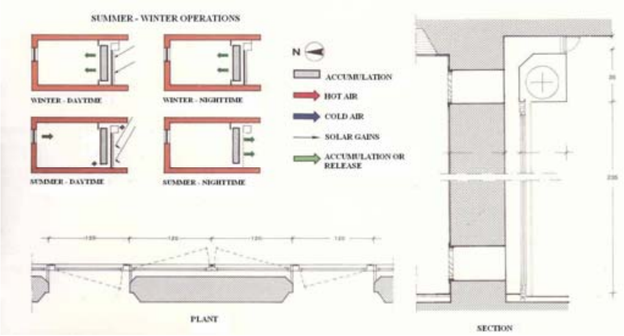

Fig. 8 Management of solar wall

VI. RESULTS: WINTER

A. Experimental Study: Indoor Comfort

The PMV value was calculated for a daily light activity level (1.2 met) and nocturnal activity level (0.8 met) with a heavy clothing (1 clo) and nocturnal cloting (1.8 clo). The comfort conditions are optimal (-0,5<PMV<0,5) for all the period due to the heating system maintains the indoor temperature around the 21°C. In this phase, the benefit produced from the wall, is not on the thermal comfort but on high heat gain and low consumptions. The Fig. 9 highlight that the comfort levels are directly connected with the heating system daily operation (grey zones).

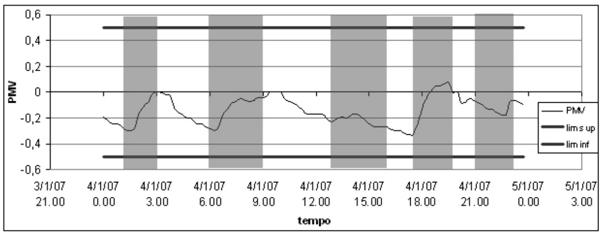

Fig. 9 Daily PMV and operation schedule

B. *Analytic Study: Outside Glass Optimization*

In winter the glass type takes an important role, because it affects the heat losses trough the wall.

The Fig. 10 show us that a double glass allow to have heat gain from the wall, because it reduce the heat loss without reduce the pick up capacity of solar radiation.

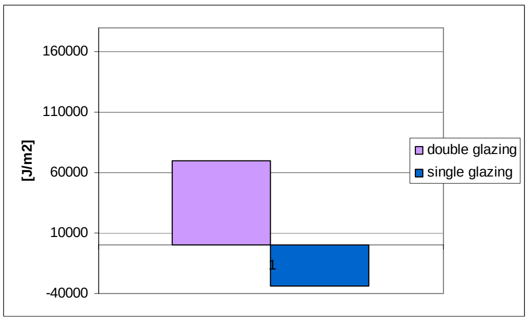

Fig. 10 Daily heat gain and loss trough the wall in January

VII. RESULTS: INTERMEDIATE SEASON

A. *Experimental Study: Indoor comfort*

From the monitored data is emerged that the solar wall has an optimal behavior in spring and fall, both in comfort and in heat gain, in fact, at our latitude the solar radiation on vertical surface reaches the greatest values in March-April and September-October producing the best system yield. In March with the increase of irradiation increase the positive effects on comfort produced from the wall allowing an early heating system turnig off.

From the Fig. 11 shows how the solar, from middle of March, wall begins to influences the conditions. In fact with the increase of solar radiation, improves the yield and the heat gain from the system. In the second half of month the solar wall is sufficient to guarantee the indoor comfort, without any heating system.

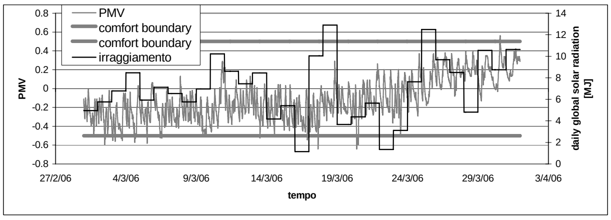

Fig. 11 PMV and global solar radiation in March

In autumn, the comfort is raised for all of the period with a temperatures fluctuation between 20°C and 25°C, with the heating system turned off. (Fig. 12)

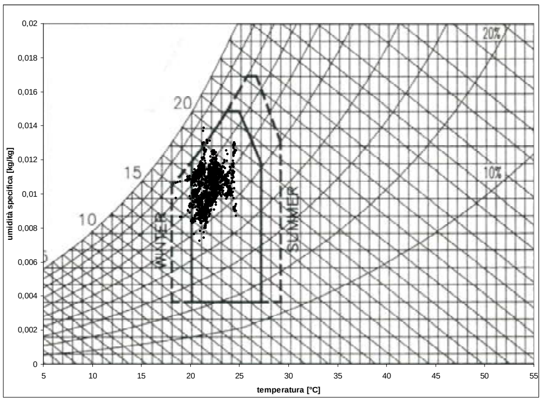

Fig. 12 Building Bio Climatic Chart of October

B. *Analytic Study: Optimization of Storage Wall*

Simulating the solar wall with all vents closed (Fig. 13), is emerged that the comfort level depends from the caracteristic of storage wall because the heat arrives to the indoor only by conduction trough the wall. The heat gain increase with the material conductance.

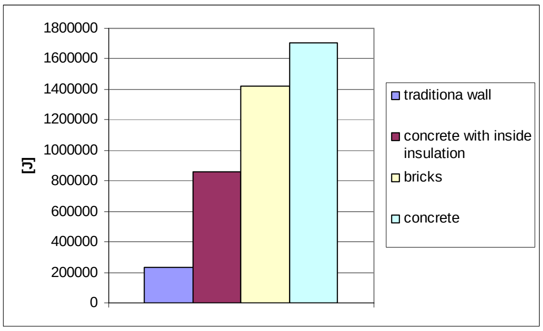

Fig. 13 Daily wall heat gain in October

For the effects on comfort (Fig. 14), we have that the wall concrete with inside insulation gives the worse results because the insulation limits the thermal exchange with indoor ambient. The traditional wall behaves better because, even if with small heat gain, it reduces the losses thanks to its low conductance.

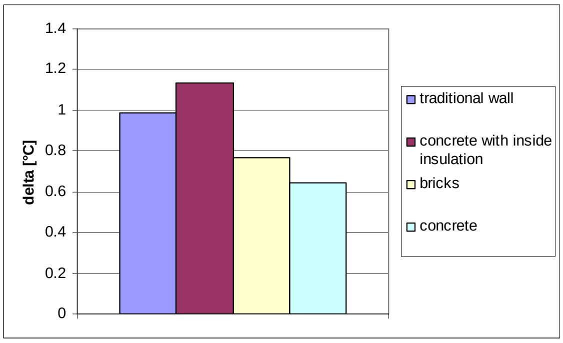

Fig. 14 Distance from optimal operative temperature

VIII. Results: Summer

A. Experimental Study: Comfort

The adaptive ASHRAE comfort model considers the indoor operative temperature, defining an optimal temperature range.

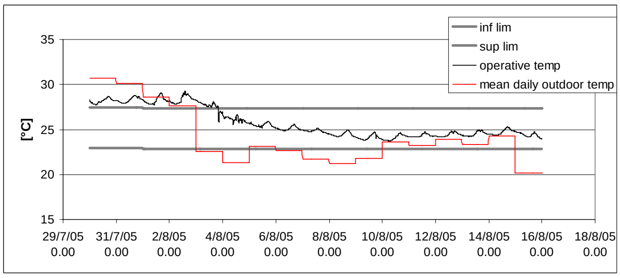

Fig. 15 Indoor ASHRAE comfort

The Fig. 16 shows the monitored operative temperature in summer period. From the graph emerges that: if the mean daily outside temperature doesn’t go over the 27°C, the comfort level is optimal. When the said temperature value is surpassed, the ventilation activated from the wall isn’t sufficient to guarantee the comfort: there is a problem of overheating caused by hot ventilation air coming from outdoor.

B. Analytic Study: Management Optimization

In summer season we examined the behavior of different configuration of shading and ventilation condition of the solar wall.

- With and without screening

Simulating the solar wall without screening, we see that respect to as build condition (screened), we have a light increase of indoor operative temperature. But the screen reduce the wall chimey effect in external gap producting a reduction of transversal ventilation.

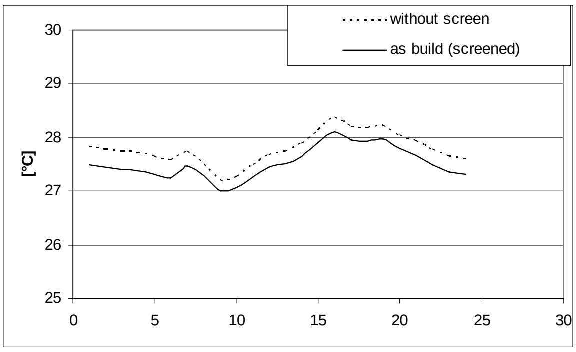

Fig. 16 Indoor operative temperature for a summer day

- Continous or night ventilation

From the simulations we see that the type of ventilation influences the comfort (Fig. 17, 18). If we perform a night ventilation, closing vents in central hours of the day (9:00 – 18:00), we will have a reasonable enhancement of indoor conditions obtaining a reduction of time not comfortable hours from 26% to 19% of the summer period (1/6 – 30/9).

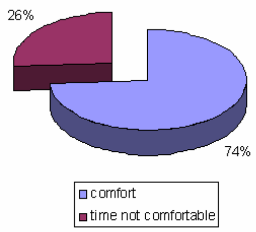

Fig. 17 Continous ventilation

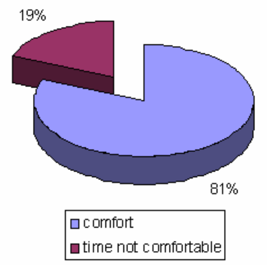

Fig. 18 Night ventilation

IX. Results: Themo – Physic Behavior of Solar Wall

A. As Built Yield

To understand the the system behavior, using the energy balance (W + Q + Fi + Fe = 0), we analyzed three consecutive days: the first sunny day and two cloudy successive one, distinguishing between daytime phase and nocturnal phase.

- Day 1 sunny (daytime):

The following figure (Fig. 19) shows the values of temperature, heat flow and irradiation monitored on October the 14 from that allow us to calculate the energy balance.

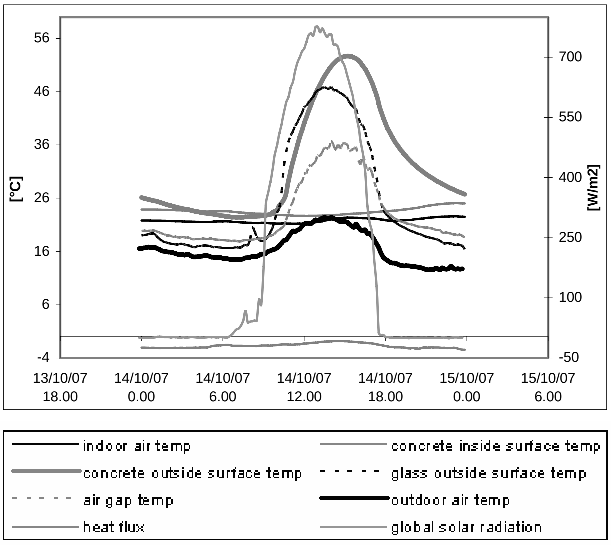

Fig. 19 Monitored value on October the 14, 2007

During daytime (Fig. 20), the 5% of solar radiation come inside (Fi = 0,606 MJ/m2), 58% is stored from the concrete (Q = 7,144 MJ/m2), and 37% is released to outdoor (Fe = 4,609 MJ/m2).

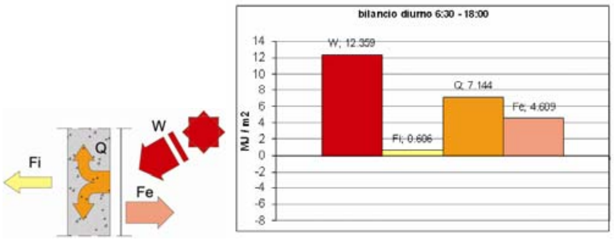

Fig. 20 Day 1 (daytime)

- day 1 sunny (nighttime):

During night (Fig. 21) the 83% of the stored heat is relaesed to outdoor (Fe = 5.812 MJ/m2), the remainig 17% come inside (Fi = 1.201 MJ/m2). We note that a big part of heat is spent to heat the concrete and that energy is released to outdoor.

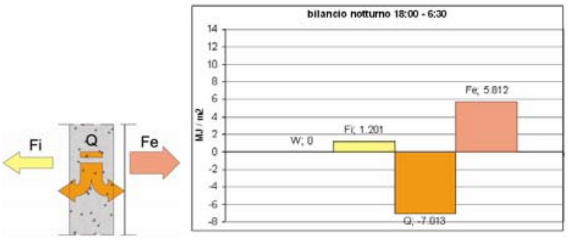

Fig. 21 Day 1 nighttime

From the comprehensive energy balance of 24 hours we see that the wall completely loads and unloads itself and the 85% of solar radiation, is released to outdoor, because the energy comes inside only for conduction trough the concrete.

The opening of the vents activates the air recirculation, allowing to recover some heat.

- day 2 cloudy (daytime):

When we have cloudy days successive to sunny (fig. 22), the concrete yields the heat accumulated in previous days (Fi = 0.777 MJ/m2); but the system can't recharge itself because the solar radiation in cloudy day isn't sufficient to heat in depth the concrete.

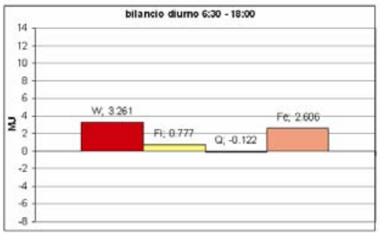

Fig. 22 Day 2 cloudy (daytime)

- day 2 cluody (nighttime):

During night (Fig. 23) the system continue to unload itself (Q = -2,563 MJ/m2) therefore the solar wall has a thermal autonomy of two days, after that; if there aren't sunny days it will behave like a normal wall.

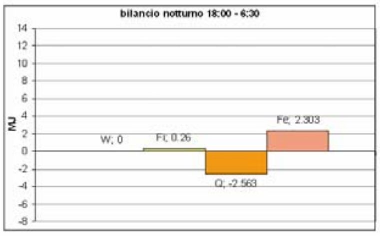

Fig. 23 Day 2 cluody (nighttime)

- day 3 cloudy:

When there are more than two cloudy days, the wall completely unloads itself and does not supply more heat gian to indoor environments, in fact, in this case the flow across the inside surface became negative (Fi = -0,123 MJ/ m2).

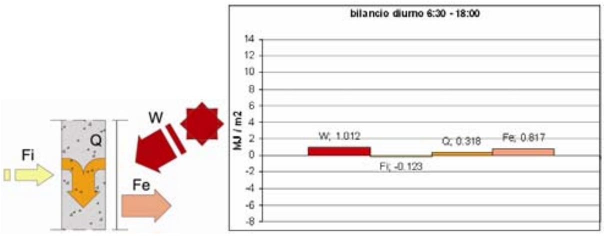

Fig. 24 Day 3 cloudy

B. Empirical Connections

Elaborating monitored data, we were able to find, in function of sol – air temperature, the variation law of mean daily flow trough the wall.

The following figure (Fig. 26) shows for each value of sol air temperature the correspondent values of flow after a time lag of twelve hours.

The empirical connection obtained is:

$$flux = 9.0236 \ln(t_{ea}) - 7.2387 \qquad (5)$$

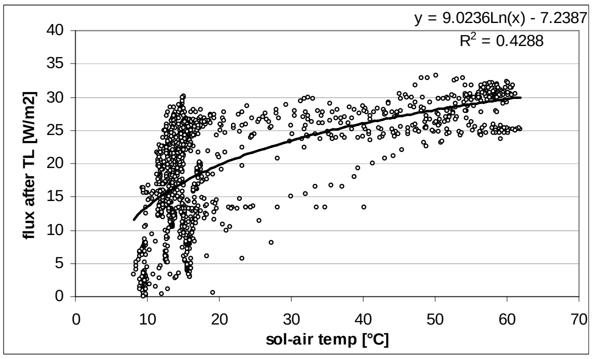

Fig. 25 Termal flux and sol – air temperature

The mean daily yield, calculated with (3), follows a logarithmic law:

$$\eta = 0.218 \ln(t_{ea}) - 0.5766 \qquad (6)$$

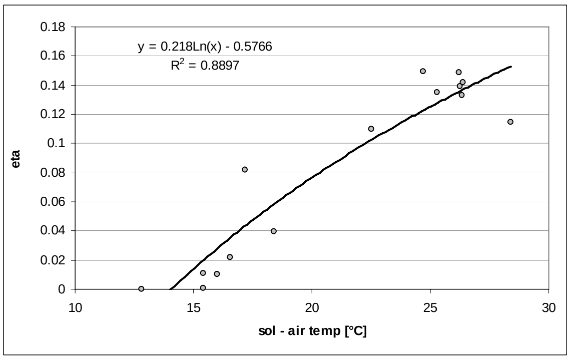

Fig. 26 Yield and sol – air temperature

C. Heat Gain Calculation

Calculating the daily solar heat gain according to UNI 832 we see that activating the recirculation we'll have a heat gain increase.

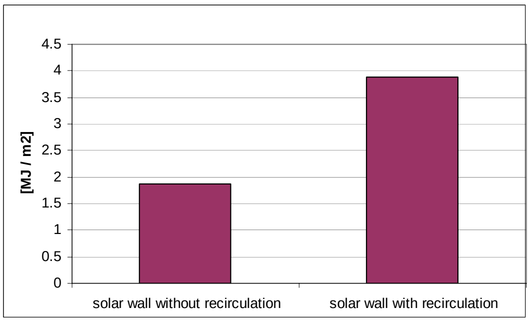

Fig. 27 Daily solar heat gain

X. CONCLUSION

Employing a case of study with nine different passive systems, we carried out an in-depth analytical and experimental of the lodging with the solar wall.

Particularly were appraised the comfort conditions in every season on the base of recognized comfort models (ISO, ASHRAE, Givoni's BBCC). We carried out a series of monitoring activities of the specific system and performed the simulation of the wall using dinamic-state software (energy plus) with a consequent model validation. Finally we've been able to perform a parametric analysis for the solar wall optimization. The results obtained from this analysis were confronted both in comfort and heat balance point of view.

From the monitored values is emerged that the solar wall has an optimal behavior in spring and fall. Besides we could demonstrate that the indoor comfort is linked to the tipe of storage wall. In winter the solar wall does not succeed to produce effects on comfort, but we obtain advantages on energy consumptions. Using a double external glass, in winter, allows to reduces the heat loos trough the wall. In summer, when the outside temperature is in the mean seasonal value, the comfort is optimal thanks to the ventilation activated from the solar wall. When the mean daily temperature go over 27°C we have overheating problems in central hours of the day. Simulating a night ventilation we obtained a considerable reduction of hour not comfortable.

Elaborating the data of the monitoring we were able to find, in function of sol – air temperature, the variation law of heat flow and mean daily yield.

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