Thorough Study of a Proposal to Improve the Thermal Behaviour of a Bioclimatic Building.

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ABSTRACT: The purpose of the ARFRISOL project is to reduce conventional energy consumption of office buildings by up to 80%. The construction of five Research and Demonstration Building Prototypes (RDBP) in different Spanish climatic zones is part of the project. One of these prototype buildings is to be built at the Plataforma Solar of Almeria (PSA), located in the Tabernas Desert.

The PSA building was designed taking into account the local climatology and making best possible use of Bioclimatic Architecture principles: massive walls to prevent extreme temperatures, a corridor with high windows to allow natural ventilation by convection and shading of the South façade to avoid direct radiation inside the offices. This first project has been evaluated and several changes have been proposed to improve the thermal behaviour of the building, including active and passive techniques, such as solar chimneys, cross ventilation with humidification filters, shading on the south side of the roof and different types of integrated solar collectors combined with radiant floor heating and cooling.

The size and orientation of shading devices have been optimised. The materials, shape and dimensions of the solar chimney along with the position of the humidifier filters have been designed for optimal cross ventilation. The influence of each proposal on the thermal behaviour of the building has been quantified using dynamic simulation programs such as TRNSYS, DOE-2 and EnergyPlus. The results of this study should be useful to the architect in the final building design.

Keywords: Bioclimatic architecture, solar chimneys, cross ventilation, radiant floor, radiative cooling

1. INTRODUCTION

The building sector is responsible for about 30% of total energy consumption and 25% of CO_2 emissions in Spain, and this has been rising steeply in recent years due to increased use of air conditioning. Energy consumption in Spanish buildings has thus increased by 5% since 2000, approaching the level of energy consumption in Northern European countries, in spite of its warmer climate.

A current Singular Strategic Research and Development Project promoted by the Spanish Ministry of Education and Science aims at reducing energy consumption in buildings, particularly conventional energy for heating and cooling, through the use of bioclimatic architecture. The project, called ARFRISOL (Bioclimatic Architecture and Solar Cooling, in Spanish), is intended to demonstrate that it is possible to save up to 80% of conventional energy by making good use of solar energy in five different office buildings, using passive heating and cooling techniques (natural ventilation), as well as active systems, such as solar thermal collectors, solar absorption pumps for cooling, PV panels, etc.

The CIEMAT Energy Efficiency in Buildings Research Group is coordinating the project and is responsible for advisory building prestudies and for evaluation of energy consumption after construction. Some of the most important companies in the Spanish building industry, as well as solar energy technology manufacturers and installers are involved in this project, working together with research groups from the universities of Almería and Oviedo. The construction companies participating, ACCIONA, DRAGADOS, FCC Construction and Obrascon Huarte Lain (OHL), will undertake the construction work. ISOFOTON, GAMESA, ATERSA UNISOLAR Group and ACCIONA, will work on the solar heating and cooling systems and photovoltaic power generation. The research groups at the Universities of Almería and Oviedo are involved in the study of the physical phenomena in the buildings (climate resources, theoretical study, cooling systems,…). There are nine different work packages in the PSE-ARFRISOL project.

The main goal of the ARFRISOL project is to demonstrate bioclimatic techniques in office buildings in different climates with very special requirements. In this project, the buildings are not only containers for research but also demonstrators, so they are called *Research and Demonstration Building Prototypes* (RDBP). The five RDBP included in the project are located in as many different climate zones in Spain (see Fig.1). The first building, called CIESOL, is in Almería, on the Mediterranean coast, in southeast Spain. The second RDBP is in Madrid at CIEMAT facilities, where the climate is continental. The third is located at the Plataforma Solar of Almeria (PSA) facilities in the Tabernas Desert, a semiarid region, also in Almería Province. Another is to be built in Asturias, in the North of Spain, where the climate is oceanic, and the last RDBP is a building to be rehabilitated in Soria at the CEDER facilities, where the climate is extreme continental.

This paper concentrates on the proposals made to the basic RDBP project for improving PSA building in Almería, where the summers are very hot and winters are cold,

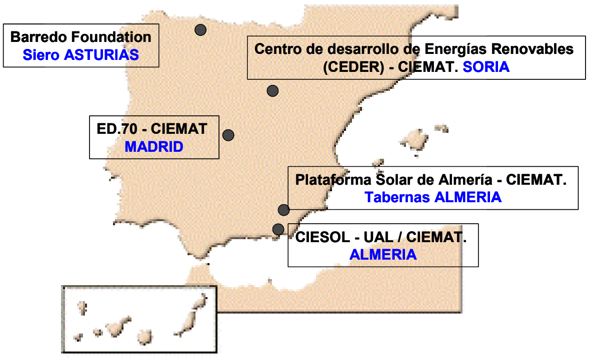

Figure 1: Location of the RDBPs in Spain.

2. BASIC BUILDING PROJECT

2.1 Climate survey

The Plataforma Solar de Almeria is in the Tabernas Desert (37º05'27.8"N by 2º21'19"W) in south-eastern Spain, a privileged location for solar concentrating technology research due to its over 1900 kWh/m^2 per year of direct annual insolation, and very dry microclimate with 57% average annual relative humidity. The relative humidity in summer varies between 15-30%. The average annual temperature is around 17ºC and average maximum and minimum are 32.9ºC and 2.8ºC, respectively. The daily variation in temperature is around 12ºC.

The PSA's location in a valley surrounded by mountains to the North, West and South makes winds from the southwest (from the Atlantic Ocean) and the East (the Mediterranean breeze), predominant as shown on the compass rose in Fig.2 below.

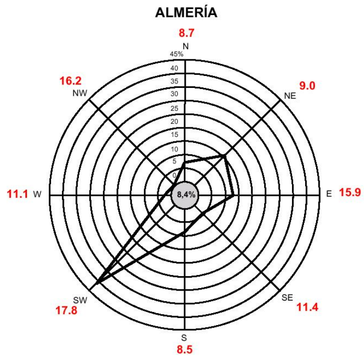

Figure 2: Tabernas wind compass rose.

2.2 Initial strategies

The RDBP in PSE-ARFRISOL Work Package 4 will be the new PSA technical-staff office building, a one-floor ground-level building, polarised around an east-west axis. The building has two main parts, a public zone comprised of the reception area, the meeting room and the conference room, at the east end of the building, and a more private work area at the other end. This zone includes staff offices on the south side, and service spaces (photocopying, installations and lounge) and student and guest offices on the north side.

According to the head architect, the building is conceived as an open element, blending in with its unique surroundings, in which the opaque walls are broken by windows and glass doors to bring the landscape inside the building. The PSA building was designed following Bioclimatic Architecture principles, taking into account local climatology, as well as typical regional construction (such as whitewashed one-floor buildings). The offices face south to collect the solar radiation in winter for natural warming. The south façade is protected by a 2-m projection (porch roof) to avoid beam radiation during the summer.

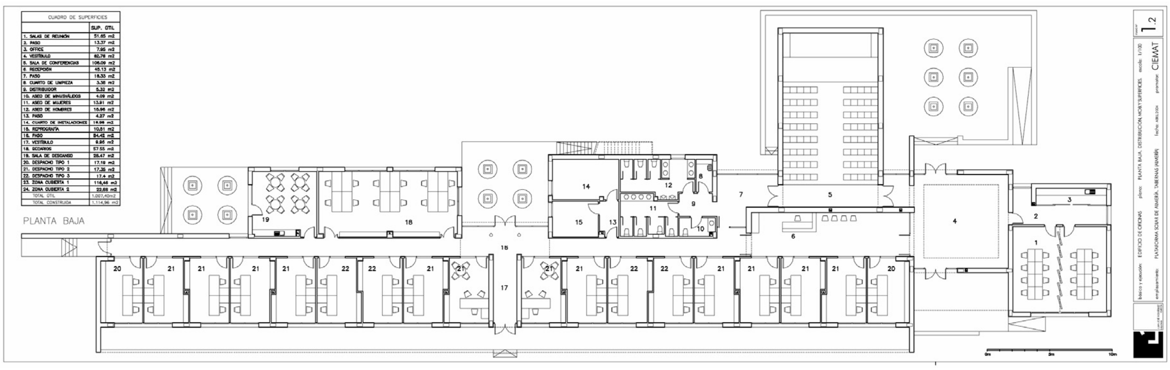

Figure 3: Floor plan of the new PSA technical building (PSE-ARFRISOL SP4).

The basic building design makes use of thick walls to prevent extreme indoor temperatures and reduce the effect of daily variation in outdoor temperatures. This thick wall is made of 14-cm hollow brick with a 6-cm air chamber, 4 cm of rigid polyurethane foam thermal insulation and another 7-cm layer of brick. This high-thermal-inertia wall assures good building insulation and mitigates the temperature wave amplitude in the interior.

Another strategy uses the east-west corridor between north rooms and south offices, which is higher than the rest of the building, to take advantage of the solar radiation coming in through high windows, providing natural lighting all year long and cross ventilation by convection (by opening the windows) in summer. In winter this corridor would minimise thermal losses.

In front of the windows and openings in the west façade, protection from deciduous trees will avoid excessive solar gain on hot summer afternoons, while allowing the solar radiation to get in during the winter.

The building configuration facilitates the use of modular HVAC systems for individual comfort in each zone.

2.3 Basic Design Simulation Results – Software Comparison.

The thermal behaviour of the new PSA building was simulated with three different programs: TRNSYS [1], DOE-2 [2] and EnergyPlus [3], using their respective graphical interfaces: TrnBuild, VisualDoe and DesignBuilder. For the TRNSYS and DOE-2 simulations, 16 different thermal zones were identified, with four different zones in the south offices to take into account the different behaviour at either end. Other zones of interest for energy demand are the students' office, the meeting room, conference room and lounge. DesignBuilder considered only 13 thermal zones, slightly different from those of the TRNSYS simulation, and grouped the hall, the entrance and the corridor in just one area.

The free-floating temperatures in each zone of the building were studied. According to the TRNSYS simulation, the indoor temperatures stay at around 5ºC on cold winter days, when the outdoor temperature is near 0ºC, while in summer, the temperatures in the offices are around 27ºC when ambient temperatures reach about 37ºC.

The energy demand for conditioning the building was analysed using the HVAC system criterion of keeping temperatures over 20ºC in winter and below 26ºC in summer. Although energy consumptions calculated by the programs used are different, they are all in the same range. The simulations show an average annual energy consumption of 20 kWh/m^2 for heating and 30 kWh/m^2 for cooling. Comparison to the conventional office building energy demand in Seville (25 kWh/m^2 for heating and 77.1 kWh/m^2 for cooling per year) [4], shows a significant reduction in energy for cooling.

3. ALTERNATIVE STRATEGIES PROPOSED FOR IMPROVEMENT

A double-wing collector structure, which we called *solar wings*, installed on the roof all along the building main axis, houses the main active and passive system strategies of the building.

The *solar wing* facing south is inclined at a fixed angle to provide shade during the summertime and let solar radiation reach the building during the wintertime. Two different types of solar collectors will be installed on this structure. On the north-facing wing, collectors without glass covers act as radiant coolers by night, while solar collectors on the south-facing wing supply hot water for the heating and cooling systems.

In keeping with the specific climate conditions of the Desert of Tabernas (high daily temperature oscillations and low relative humidity in summer), a combined strategy based on cross ventilation induced by a solar chimney and the use of humidifier filters has been proposed. The aim of this proposal is to cool down the building during the night, in order to retard high indoor temperatures during the day and improve thermal comfort.

Also integrated in this rooftop structure, are small solar chimneys between the wings, installed in the southern vertical wall of the corridor and connected to the offices on the south side of the building to induce cross ventilation.

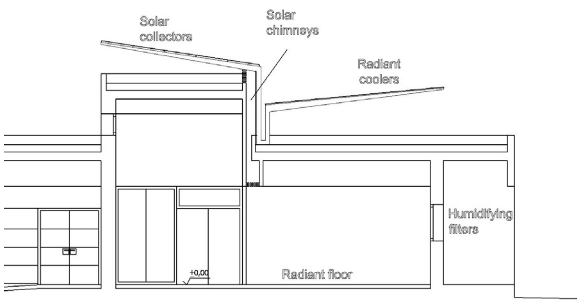

Figure 4: Multifunctional double wing, or *solar wings,* on the rooftop.

On summer days, the south shades prevent direct solar gains. In addition, the small solar chimneys will receive radiation inducing cross ventilation, which combined with humidifier filters, will reduce the indoor offices temperature by latent cooling. The sum of cross ventilation, evaporative cooling and thick, thermal-inertia walls, are expected to help reach comfort conditions. The offices are cooled longer by passive strategies during the summer.

On very hot days, when the high thermal inertia and cross ventilation are not enough to prevent high indoor temperatures, the active cooling solar system, consisting of an absorption heat pump fed by hot water from the collectors, cools down the offices

During the summer, night-time strategies are combined, and the solar energy stored during the day in the chimney's concrete walls is transferred to the air in the chimney flue at night, forcing cross ventilation in the offices.

In addition to cross ventilation, the radiative cooling system also works at night, as follows: On the north-facing wing, uncovered collectors operate as night sky radiative coolers. The cooling collector field connected to the circuit in the radiant floor removes the heat stored in the massive walls, reducing the average temperature of the building by several degrees. Night cooling and thermal inertia produce lower indoor temperatures in the morning and a delay in temperature rise, which is expected to improve building thermal comfort.

In winter, two passive heating strategies, the large south-facing openings that contribute to solar gains and the thick insulated walls preventing heat losses, are supplemented by the solar heating and radiant floor distribution system.

In the following lines, the passive strategies are discussed in further detail.

3.1 Analysis of Massive Wall Composition

The wall configuration proposed in the basic design consists of 7 cm of hollow brick on the inside, 4 cm of rigid polyurethane foam, a 6 cm air chamber and 14 cm of hollow brick on the outside.

Three different configurations were analyzed with TRNSYS:

1) 14 cm of hollow brick on the inside, 4 cm of rigid polyurethane foam, a 6-cm air chamber and 7 cm of hollow brick on the outside;

2) Replacement of the 14 cm of hollow brick on the inside with 7 cm of solid brick;

3) A ventilated façade to verify its heat evacuation capacity.

All the massive wall configurations studied yielded an increase in the heating energy demand of the building, so the order of the layers was left as originally designed.

3.2 Analysis of shading devices.

In order to reduce the heating demand during the winter, solar beam radiation should enter through the building openings.

The southern porch of the RDBP case study was conceived as a 2-m-wide passage, with a vertical parapet.

Direct solar gains can be increased either by narrowing the porch or by shortening the parapet. Both solutions were studied to quantify the reduction in energy consumed for heating compared to the base case. The final solution is a combination of narrowing the porch and shortening the parapet that reduces the heating demand by 10%, while the cooling demand is increased only by 1%.

Another shading device proposed is an overhang for the south openings of the meeting room. The optimal overhang dimensions calculated are 0.3 m from the top of the window to the overhang and 0.98 m horizontal overhang projection. This device reduces annual incoming solar radiation by 46%.

3.3 Solar Chimney Proposal

A small chimney placed in each of the south-facing offices induces cross ventilation during the day. This ventilation, combined with the humidifier filters, cools the rooms down by latent cooling. During the night, solar chimney performance combines with the radiative cooling strategy (see 3.4.).

Different solar chimney configurations were analysed using a dynamic physical model for a solar chimney with inertial mass [5]. The chimneys have a 20-cm-thick reinforced concrete wall, a flue and a front cover. Three different cover materials were proposed. The inside of the concrete wall is painted black to absorb solar radiation better. The simulation model considers the back of the chimney an outer wall. A real weather data series for two sunny days in July at the Plataforma Solar de Almeria, were used as input.

Three different chimney heights were selected based on the shape of the building and the location of the chimneys (1 m, 1.5 m and 1.8 m). For each of the chimney heights, the optimum flue depth was calculated using the Eckert and Jackson equation [6]. The following front cover materials were simulated for a glass cover, metal cover and a semitransparent photovoltaic (PV) cover with 5% radiation transmissivity.

The air mass flow rate curves for the three different front cover materials at 1.5 m are shown in the figure below.

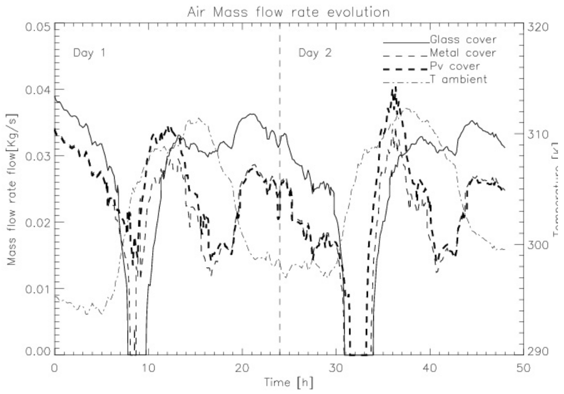

Figure 5: Simulated mass flow rate in solar chimneys

The results show that the thermal inertia of the thick wall produces ventilation during the night for all three cover materials. The glass cover shows the best results for induced night-time flow, with a very stable flow rate. On the other hand, the daytime response is slower. The daytime response is faster for metal covers due to heat transfer in the metal plate. Similarly, in the PV cover, heat is transferred to the air channel from the PV cells while they are working. Although night values are lower for PV, the flow rate is satisfactory for a night-time ventilation strategy.

3.4 Estimated potential of radiative cooling with a radiant floor circuit.

The potential for radiative cooling with a radiant floor in the Tabernas Desert was evaluated to find out the feasibility of this hybrid technique for night-time cooling of office buildings.

Simulations were based on real weather data from the PSA and TRNSYS software. The simulation included calculation of the sky temperature depression based on ambient temperature and relative humidity data.

The minimum threshold temperature attainable by the radiator at a certain temperature was calculated from the net heat flux in the radiator, where the convective heat transfer coefficient is a function of wind and the net radiative power of a black body [7,8].

The outlet temperature of the water circulating in the radiator was calculated as a function of the threshold temperature using the Duffie and Beckman equations for solar collectors [9]. The simulations were performed for a 100-m^2 field of uncovered flat-plate water coolers.

The outlet temperature of the radiator field was entered in the TYPE56 multi-zone building model, including the radiant floor system.

The results of the simulations show that radiative cooling combined with a radiant floor can provide a night-time cooling power rate of 10-20 W/m^2.

3.5 Estimation of Evaporative cooling.

It is easy to cool down the air temperature with humidifier filters because of the low relative humidity in the Tabernas Desert. The climate favours the use of evaporative cooling, as observed in the Givoni diagram below. In this climate, with temperatures of about 35ºC and relative humidity below 30%, the potential reduction in temperature is about 34%. This means the air temperature could drop to 23ºC, which would be cool enough to ventilate the offices.

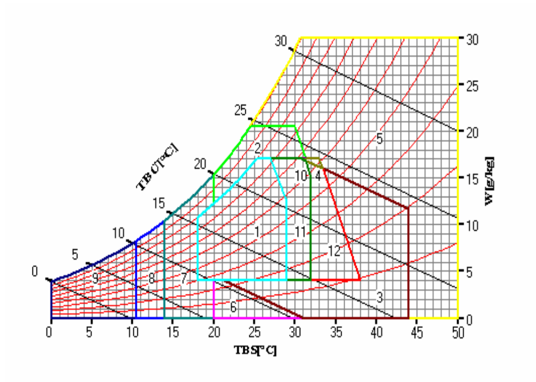

Figure 6: Givoni comfort diagram

4. MONITORING AND CONTROL OF THE RDBP

Once designed and built, the building's energy features will be evaluated under real conditions of use, in order to validate the simulations. This methodology is based on several test campaigns and analysis of the results. Variables such as temperature, heat flux, radiation, mass flow rate, humidity, etc. will be registered at the points of main scientific interest, the weather station, the solar chimneys, the active solar systems and the building itself.

A multifunctional control scheme is under development to optimise building energy behaviour by the combined active-passive conditioning system.

5. CONCLUSION

To optimise energy performance, passive solar strategies, such as building orientation, shadowing, natural ventilation with solar chimneys, radiative cooling, thermal mass walls, solar gains, etc. were analysed during design taking the specific climate conditions into consideration.

Analyses of each passive strategy alone show that they improve thermal comfort in the interior of the offices. Nevertheless, further simulations combining all of the strategies and later evaluation are still needed. Comparison with experimental data from monitoring would validate the theoretical results. However, this study already shows the high potential for reducing the energy demand by means of well-combined solar passive strategies.

By the end of the ARFRISOL project (2009), with the optimisation of the best suitable control for active and passive strategies, a reduction of up to 80% in conventional energy consumption is expected.

ACKNOWLEDGEMENT

This work was funded by the Spanish Ministry of Education and Science under PSE-ARFRISOL (PSE1-2005).

The authors wish to thank the architect, Juan José Rodríguez, and the SP4companies: ACCIONA, UNISOLAR and ATERSA, especially Amandine Gal and Joaquin García of Acciona Infraestructuras for their assistance.

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