Declaration of interest: None

Heat collection in an attached sunspace

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Abstract

The attached sunspaces are classic bioclimatic systems. Normally, they are used as solar passive techniques in buildings. However, it has been suggested that they could also be used as active systems in order to collect solar energy and harness it in the heating, ventilation and air conditioning (HVAC) equipment. This paper analyses the sunspace built during the ARFRISOL project, which has a validated simulation tool of its thermal behaviour, developed in a previous research. In this paper, this tool is applied to study the possibility of the energy collection. Although this energy is not enough to be used as direct heating system, it can pre-heat the air before entering the HVAC equipment. Two configurations have been studied: collecting the energy during the whole day or only at night to take advantage of the sunspace thermal inertia. Also, the results obtained with these configurations have been compared with the sunspace used in passive mode. For this analysis, several characteristic days with summer and winter climatic conditions have been considered. Finally, an economic evaluation of this innovative system –a solar active sunspace- is performed taking into account the results of the different configurations.

Keywords: Sunspace, CFD, Energy-efficient building, Solar passive design, Heat collection, Economical evaluation.

1. Introduction

In recent years, energy efficiency and passive solar design have become essential features in modern buildings (new or renovated) in order to reduce their high-energy consumption [1-3]. One of these passive solar solutions is the attached sunspace (or greenhouse). It can be considered as a –in façade– solar heating system with thermal inertia. The usual design of these systems is a room with an exterior wall wholly glazed and facing south (north in the southern hemisphere), and a partially glazed interior wall connecting the sunspace with the main building. The space between both walls is relatively wide because, in the bioclimatic architecture concept, it is designed to collect the solar radiation energy on the floor. Sometimes, in order to accumulate this thermal energy the floor has a thick layer of sand or gravel, acting as a thermal mass.

This paper describes and analyses the thermal characteristics of a sunspace built during the ARFRISOL (Bioclimatic Architecture and Solar Cooling) project, organized and promoted by the Spanish Education and Science Authority. This Strategic Singular Project has studied the energy behaviour of five demonstration-containers, located in different climatic conditions. The aim was to demonstrate that it is possible to reduce the conventional energy consumption and the consequent emissions in more than 80% by combining both passive (sunspace, ventilated façade, glass corridor, etc.) and active (solar collector, photovoltaic, geothermal, biomass) energy systems [4]. One of these demonstration-containers has been built in Asturias (northern of Spain) and it has, among other bioclimatic solutions, the sunspace studied in this paper (Fig. 1).

Fig. 1. Attached sunspace in demonstration-container located in the north of Spain viewed from the exterior.

In this case, the exterior of the sunspace is a glazed wall, with transparent simple glass in the central stripe and semi-transparent photovoltaic panels on both the upper and lower parts. The floor of the interior space is composed of sand and a partially glazed wall partition separates the sunspace from the hall and meeting room. On the top of this interior partition, there are some grilles in order to provide a possible connection with the air ducts and the heating, ventilation and air conditioning (HVAC) equipment (Fig. 2).

Fig. 2. Interior of the attached sunspace.

The passive thermal behaviour of this sunspace was analysed in a previous study [5], where a numerical model was developed and validated using experimental tests made during the ARFRISOL project. The study confirmed that the sand at the floor is a good inertia element, collecting the solar radiation as thermal energy, and releasing this stored energy to the interior air, not only during the daylight hours but also during the night. The analysis of the sand and air temperatures showed that there was a fair amount of heat transfer, mainly during the coldest seasons, although the highest temperature differences were found in spring and autumn, even more than in winter. The effect in summer is somewhat dampened due to the bigger shadowed area, as a consequence of the sun elevation.

In this paper, the numerical model has been used to analyse the sunspace as an active energy system. This is an innovative application of sunspaces (and even glazed spaces in general), that has been suggested [6,7], but has not been properly developed. The objective is both to evaluate the possibility of collecting the thermal energy stored and use this energy for the heating of the building during the winter season. Although the system has not been fully implemented, the sunspace has a grille in a lateral wall allowing the entry of outside air, and several grilles in the interior wall, which can be connected to the HVAC system. It has been found that the air temperature in the sunspace in winter does not rise enough to be used as a direct heating system, but it can be utilised, for example, to pre-heat the air employed for renovation by the HVAC equipment. This arrangement has been studied with two configurations: collecting the air during the whole day or only during the night. The second configuration should benefit from the thermal inertia, using the available energy when the outside air is colder.

Both configurations have been simulated with the numerical model, for different specific days, and the energy collected has been calculated. In addition, an economic evaluation has been performed to compare the energy savings with the construction costs.

The novelty of this article is mainly the solar active use of the sunspace, but also the energy calculations in the sunspace are meaningful because the quantitative analysis of glazed spaces available in the scientific literature have been made almost exclusively in smaller spaces, basically glazed galleries (or balconies). The studies of full scale installations are scarce as well, and even more those containing elements of inertia. Furthermore, it is distinctive the precise evaluation of the investment recovery.

2. Literature review

The solar passive heating systems (Trombe walls, glazed spaces, sunspaces…) help to reduce the conventional energy used to heat the buildings [2,8,9]. The most used are the glazed spaces, ranging from a narrow corridor to a wide hall, with or without thermal mass. They have been widely studied and their thermal performance has been analysed using numerical or thermal simulations and experimental data. Some authors only point out the energy efficiency of these solutions, giving some recommendations on the use of these elements to reduce the loads of the buildings [1,10]. In other papers, the energy savings are explicitly calculated. These values vary in function of the climatic conditions among other variables. For example, Suárez et al., [11] study a glazed gallery located in the northern Spain (Asturias), which can obtain between 15% and 32% of the energy required to heat the adjacent local. Monge-Barrio and Sánchez-Ostiz [2] analyse different balconies in several locations of Spain and they find that the general thermal conditioning demand can be reduced 50% as an average (up to 67% in zones with cold winters). Hilliaho et al., [7] study the impact of different types of glazed balconies on the energy consumption of a building located in Finland, where the energy saving potential is typically about 9% (although the maximum value can be 30%).

Regarding the sunspaces, there are several general studies that analyse the thermal performance of these solutions. They usually employ analytical or numerical methods (such as TRNSYS) to show that the sunspaces can be very effective mainly in winter [12,13]. Some of these analysis include comparisons with experimental data as Chen and Liu [14], who use a laboratory scale model or Mottard and Fisore [15] with a full-scale prototype.

There are studies where energy savings are calculated, usually for specific locations. Bakos [16] studies a sunspace located in northern Greece and states that the annual electricity savings can be around 80%. Bataineh and Fayez [17] study numerically the thermal performance of a sunspace located in Jordan and they find that, combining the sunspace and passive cooling techniques, the annual heating and cooling loads can be reduced around 42%. Ignjatovic et al., [6] show that for the climate characteristics of Belgrade, a big impact on energy consumption (about 1.9 MWh annual reduction) is achieved with a sunspace with average glazing solar coefficient and part of the sunspace envelope opened for ventilation.

Papers about sunspaces with an enhanced inertia element are scarce. Chen and Liu [14] analyse the heat transfer and the airflow in a room at laboratory scale, with a sunspace and a heat storing system in the floor in winter conditions. Olivetti et al., [18] study a sunspace with a vertical heat storage system. Owrak et al., [3] analyse the thermal performance of a sunspace located in Iran, including heat-storing porous floor bed and water tanks. Typically, these studies show that the heat storing systems improve the energy efficiency and the comfort of the sunspace, increasing the energy savings.

Referring to the economic evaluation, there are not many papers. Roach and Kirschner [19] present an economic study of an attached sunspace in a single-family house, taking into account the building cost and the conventional energy price (specifically, natural gas and electricity). They mention that in some cases the recovery of the investment can be achieved in a short period of time. Bakos and Tsagas [20] make an economic analysis of an attached sunspace located in northern Greece. They also state that the energy savings achieved with this system allow recovering the investment in a few years. However, the main factor in these calculations is usually the building cost, for example, Owrak et al., [3] who evaluate the over cost of the sunspace as 5% of total construction cost, found that the recovery time could be up to 20 years.

Finally, several authors point out the overheating problem of the sunspaces during the summer, and how it can be reduced using different passive cooling techniques. Most of them show that a proper ventilation and shading devices can be effective methods, decreasing the temperature inside the sunspace considerably [2,21]. Bataineh and Fayez [17] propose night ventilation and interior curtains and check that these techniques significantly reduce the annual cooling loads. Ignjatovic et al. [6] simulate various scenarios varying the percentage of openings and the shading coefficient of glazing, looking for an equilibrium between heating and cooling loads. Mihalakakou [13] considers that these techniques are not enough and complements them with buried pipes. None of these practices completely eliminates the problem, but they are usually adequate for the sunspace to be sucessfully used throughout the year.

3. Methodology

In this study, the numerical model developed using the CFD code ANSYS 12.1, and validated in [5], will be utilized. This code allows the simultaneous analysis of fluid movement and heat transfer problems, solving the Navier-Stokes equations (including the energy equation), with the finite volumes method.

A three-dimensional geometry with the same dimensions as the real sunspace was solved, including the shape in S of the partially glazed interior partition.

An unstructured mesh was created with triangular prism cells, not only for the fluid zones, but also for the solid materials (opaque and semitransparent). A detail of this grid (with 1,000,000 cells) is shown in Fig. 3.

Turbulent effects were included using a k-epsilon approach (RNG) [22], including buoyancy effects.

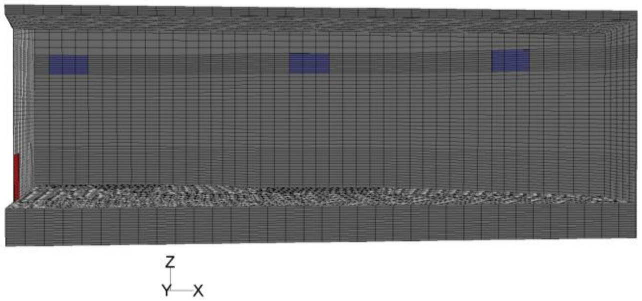

Fig. 3. Attached sunspace in demonstration-container located in the north of Spain viewed from the exterior.

In the sunspace a large part of the heat transfer takes place by radiation. The Discrete Ordinates model [23] has been chosen to determine its effects, because it can simulate the radiation through semi-transparent materials, such as glass. In addition, it allows visible radiation to be differentiated from infrared radiation. For this purpose, two bands were defined, characterized by the wavelength interval (visible radiation waveband from 0.4 to 2.9 mm; infrared radiation waveband from 2.9 to 1000 mm) and by the radiation absorption coefficients for the semi-transparent materials.

The fluid circulating in the sunspace is air, and an ideal gas behaviour is assumed for the calculation of the density and to take into account the buoyancy effects. Regarding the solid materials, the floor and the roof are simulated as a homogenous concrete slab, with a sand layer of 30 cm on the top of the floor.

With respect to the rest of the boundary and simulation conditions:

- Convection and radiation have been taken into account on the glazed surfaces at the contour of the domain. Following UNE-EN-673, the heat convection coefficients were defined as 23 $W/m^2 \cdot K$ for the outer side of the exterior glazing and 8 $W/m^2 \cdot K$ for the glazing in the partition wall.
- The radiation on the interior glazing was considered using the ambient temperature as the external black body temperature.
- For the radiation on the exterior glazing, experimental data have been used together with variables calculated by the ASHRAE method as explained in [5].
- According to the current regulations for buildings in Spain [24], the interior air temperature was considered 21ºC in winter conditions and 26ºC in summer. The exterior air temperature was measured in situ.
- About the air inflow and outflow, a constant pressure was used for the incoming airflow, while the outgoing airflow had a constant velocity boundary condition.

The air temperature, the sun position and solar radiation, both direct and diffuse, were set using a User-Defined Function (UDF). It was developed in C and compiled to integrate it in the CFD code.

About the factors affecting the accuracy of the results, a second order discretization was applied for the equations, and the convergence criterion was that the normalised values of all the residuals were lower than 10^{-5}. To ensure the residuals were below the reference values, the number of iterations were fixed at 80 by time step.

These calculations have been made for a characteristic day in each season. The selected days are the fifteenth of March, June, September and December. To obtain the results on these days, unsteady simulations have been performed, setting the time step at 5 minutes, resulting in 288 time steps per day.

In this part of the research, to study the heat collection, an airflow was imposed from the grille at the exterior lateral wall to the grilles on the top of the interior wall. The air speed was fixed by the rated renovation value of the HVAC equipment (500 m^3/h). The air enters the sunspace at the exterior temperature and the temperature of the outgoing air is one of the results obtained in the simulations.

With these simulations, data have been obtained for three different arrangements: collecting the air during the whole day, collecting only during the night, and without air collection. The last configuration does not retrieve any energy, but it is the passive mode reference state.

4. Heat collection results

4.1. Qualitative analysis

First, a qualitative analysis of the thermal and fluid-dynamic variables is carried out, using the first configuration: collecting the air during the whole day. As an example, Fig. 4 shows the temperature contours in a cross section, situated two meters away from the exterior glazing for a typical spring day: 15 March at 11 am. It can be observed that the sand surface and the opaque walls are hotter than the air, due to the direct impact of the solar radiation. The higher temperatures in the opaque zones produce the convective movements, which prevent the thermal stratification and maintain the air temperature fairly uniform throughout the section. The mean air temperature is 16ºC approximately, 6ºC higher than the exterior temperature. As it is relatively early in the day, it can also be seen that most of the sand mass is cold and only the upper layer has started to heat.

Fig. 4. Temperature contours in a cross section of the sunspace, located two meters away from the exterior glazing; 15 March at 11 am, solar irradiation 597.43 W/m^2, exterior temperature 9.8ºC; configuration: sunspace used as a direct heating system collecting air during the whole day.

As regards the air path within the sunspace, the stream lines on 15 March at 11 am and at midnight (with and without solar radiation) are plotted in Fig. 5. These lines start at the inlet grille and are coloured with the air temperature. The flow moves towards the exterior glazing quickly, and from there, in an encircling movement, it proceeds to sweep the floor and ceiling. In Fig. 5 a, with solar radiation, it can be seen clearly that the air is heated in contact with the glazing, especially in the upper and lower parts, where the photovoltaic modules are installed. The air is hotter in these zones due to the higher opacity and the heat generated by the photovoltaic cells in the energy transformation process. Also, it can be observed that the air flow is heated in contact with the sand, and it is partly cooled in contact with the ceiling. These temperature differences generate currents, which cause quite a chaotic flow in the central volume of the sunspace. When there is no radiation, Fig. 5b, the flow is very similar to the previous situation, but in this case, the glazing is cold and the air flow is heated in contact with the floor, ceiling and walls. The air flow in the interior of the volume maintains a more uniform temperature and it is proportionally colder than in the previous case. It can be supposed that for this reason there is less turbulence.

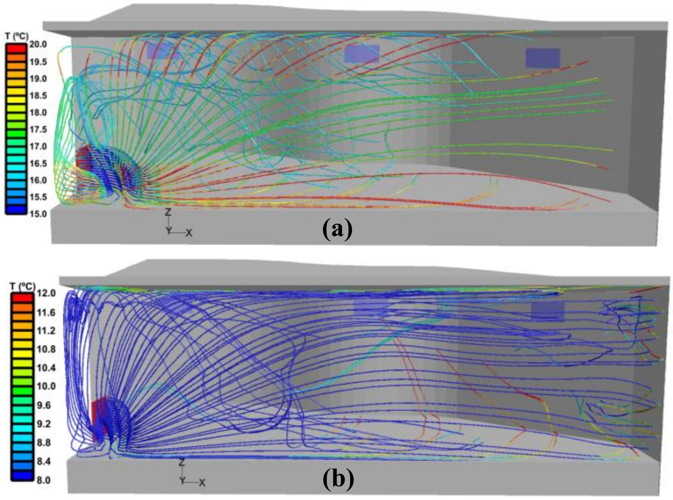

Fig. 5. Stream lines coming out from the grille and coloured with the air temperature; (a) 15 March at 11 am, solar irradiation 597.43 W/m^2, exterior temperature 9.8ºC; (b) 15 March at midnight, without solar irradiation, exterior temperature 5.5ºC; configuration in both cases: sunspace used as a direct heating system collecting air during the whole day.

To summarize the qualitative analysis, it can be seen that during the day the glazing and sand are the zones with the higher heat transference. Also, when there is no solar radiation the glazing stops heating, whereas the sand maintains its temperature. About the other days studied, the behaviour of the flow is basically the same, although there are some differences regarding the temperature values.

4.2. Quantitative analysis

The most important results obtained are the temperatures of the air, sand, etc. throughout the whole day, which are basically function of the solar radiation and the exterior temperature. In this quantitative analysis, the temperatures in the selected days are studied, beginning with the passive mode configuration (without heat recovery), considering it as a reference.

Fig. 6 presents the thermal behaviour of the sunspace without heat collection, in the passive mode, throughout the day on 15th December. It shows the solar radiation, both average and surface temperature of the sand and both exterior and interior air temperature. During the daylight, all temperatures are very influenced by the solar radiation. But, at night the sand acts as an inertia element, releasing the heat stored during the day. This effect has two phases. First, the upper layer of the sand, whose temperature is quite higher than the average, releases the heat in the evening (from 4 to 8 pm), extending the high temperatures produced by the solar radiation. Then, the heat stored in the bulk of the sand is released in a much more progressive way throughout the night, maintaining the interior air temperature substantially above the exterior one. This behaviour of the sand as inertia element has been studied in [5], including the variation of the temperature inside the sand.

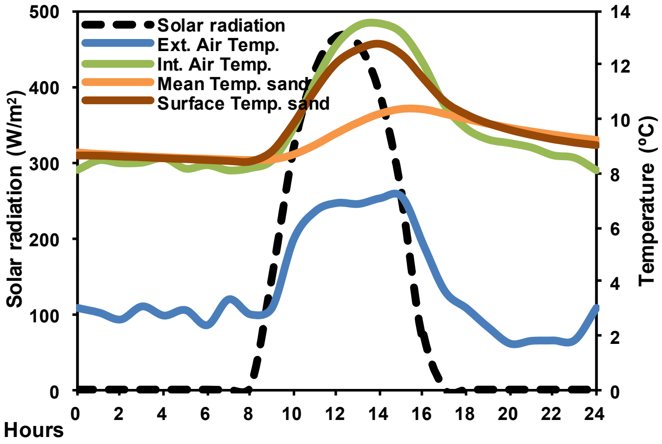

Fig. 6. Solar irradiation, mean temperature of the sand, surface temperature of the sand and both exterior and interior air temperature throughout the day on 15th December; configuration: sunspace used in the passive mode.

This behaviour is basically the same all around the year with differences due to the exterior temperature and the amount of solar radiation received. Fig. 7 presents the interior air temperature throughout the day for each day simulated (15th March, June, September and December), maintaining the same configuration (passive mode). In this figure, the effect of the exterior temperature and the solar radiation reaching the sunspace can be evaluated. The average value is mainly related with the exterior temperature, being between 5ºC and 10ºC higher approximately. The highest increase of the air temperature over the mean value happens in December; this increase is lower in March, then in September and finally in June. This is due to the sun angle and the shading of the roof, which makes the solar radiation effect be effectively larger in winter than in summer.

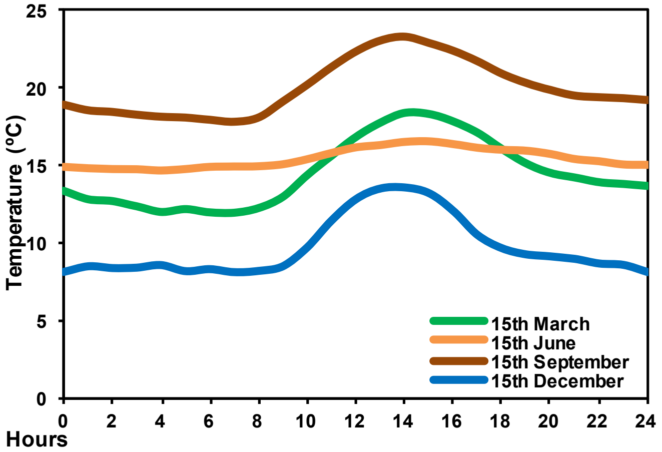

Fig. 7. Interior air temperature throughout all the day for each day simulated (15th March, June, September and December), using the sunspace in the passive mode.

When the sunspace is used to collect the thermal energy, the interior air does not reach temperatures as high as in the passive mode, especially during the night. Also, the sand temperature is lower, but the difference is smaller than with the air. An example of these results is shown in Fig. 8. This figure presents the solar radiation, both inside and outside temperatures and the surface and mean sand temperatures, on 15th December collecting the air during the whole day.

At night, the mean temperature of the sand is 8.61ºC in this configuration, while this value is 8.90ºC in passive mode. In spite of the lower values of the temperatures, they are between 3ºC and 4ºC above the exterior air temperature. The behaviour of the interior air is very similar. At night, the mean temperature of the interior air is approximately 5.7ºC, whereas in passive mode this value is 8.5ºC. About the maximum temperature of the air, in this configuration, the value is 11.09ºC, while it is 13.55ºC when the sunspace works as a passive system. In this configuration, with a flow rate of 500 m^3/h, a thermal power of about 600 W is collected.

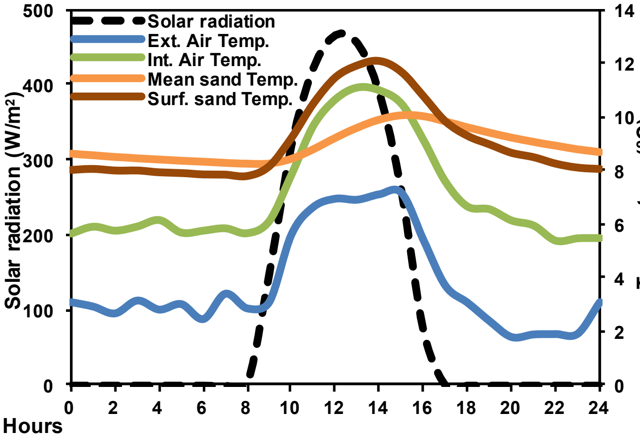

Fig. 8. Solar radiation, both inside and outside temperatures and the surface and mean sand temperatures, on 15th December; configuration: collecting the air during the whole day.

In this case, unlike the passive mode (Fig. 6), the temperature of the sand surface is always higher than the interior air one. So, if night prevalence is wanted, the air could be collected only during the night, allowing a higher heating of the sand during the daylight hours, in order to obtain more thermal power at night. This option is studied in Fig. 9, which shows the inside air temperature in all configurations: passive mode, collecting the air during the whole day and only during the night, on 15th December. It can be seen that when the air is collected only at night, during daylight the temperature inside is practically the same as in the passive configuration. And, at night, this temperature is approximately the same in both configurations collecting the air during the whole day and only at night. This suggests that the partial night collection is not much more effective than the whole day one.

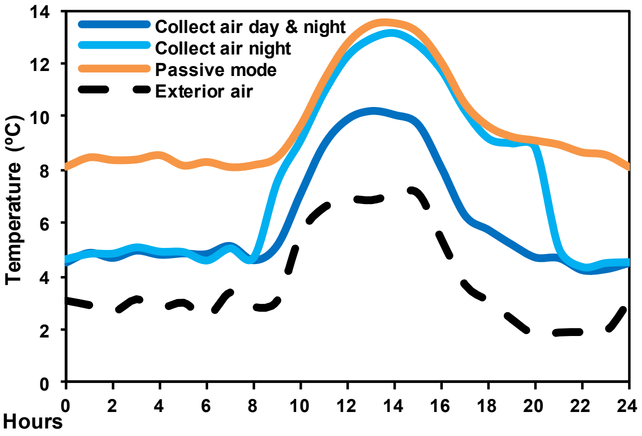

Fig. 9. Exterior air temperature and interior air temperature for all configurations: passive mode, collecting the air during the whole day or only during the night, on 15th December.

In order to detail the energy collected, it has been calculated for each day simulated (15th March, June, September and December), for both configurations: collecting the air during the whole day or only at night (Table 1). For example, with respect to Fig. 9, the energy collected on 15th December, at night is 6606 Wh, when the air is collected during the whole day. Whereas if the air is collected only at night, the energy is only a bit higher, 7192 Wh. This indicates that there is not much more energy stored in this configuration. When the air is collected during the whole day, the energy is 7018 Wh during the daylight. It would be expected that, if the air is only collected at night, the energy during the daylight got stored in the sand, and that the energy collected at night increased substantially. But the data show that it is not true, this energy only increases 10%. So, the diurnal energy not collected is mainly lost. The same has been found for the other characteristic days.

Table 1. Energy collected for each day simulated (15th March, June, September and December), for two configurations: collecting the air during the whole day or only at night.

Configuration	**Collecting air during the whole day**	**Collecting air at night**
March	Energy (Wh)	Energy (Wh)
Daylight	6102	--
Night	8662	9015
Total	**14764**	**9015**
June	Energy (Wh)	Energy (Wh)
Daylight	1985	--
Night	1786	1944
Total	**3771**	**1944**
September	Energy (Wh)	Energy (Wh)
Daylight	3667	--
Night	5205	5417
Total	**8872**	**5417**
December	Energy (Wh)	Energy (Wh)
Daylight	7018	--
Night	6606	7192
Total	**13624**	**7192**

Regarding the data in March, the energy collected during the whole day is 14764 Wh, whereas if the air is collected only at night, this value is 9015 Wh. Comparing March and December, the energy collected in March is higher, 8% during the whole day and 25% only at night, because the hours of solar radiation and the exterior air temperature are greater.

In June, very little energy is collected –3184 Wh during the whole day, and 1944 Wh at night–, even though the exterior air temperature is low. This is mainly due to the sun elevation. In September (considering this month as an average of three summer months), the sunspace is not a good solution during the daylight because the ambient temperatures are relatively high and there is no need for heating. The system is only useful at night, although the energy that could be collected during the daylight is not negligible.

Considering the days analysed as representative, if the air is collected only at night and the data are extrapolated throughout the year, the total energy collected will be 2169.75 kWh. Whereas, if the air is collected during the whole day only in March, June and December and at night in September, the energy obtained will be 4622.67 kWh (more than twice higher).

4.3. Economical evaluation

This analysis demonstrates that an attached sunspace similar to this one could substantially contribute to save energy and therefore, to preserve the environment. However, translating this saving into money, there are many factors to be considered, such as the dimensions of the adjacent rooms and the sunspace, their insulation and the price of the energy used. To give a comprehensive conclusion, a comparison has been made employing the customary building specifications for this location (north of Spain).

The cost of a normally-built sunspace has been offered by a local builder at around 700 €/m^2. This sunspace has a surface of 50 m^2, so its cost would be 34650 €. The heat collected in the sunspace throughout the year was between 2170 kWh and 4623 kWh depending on the configuration. If the energy used is electricity, whose price is about 0.15 €/kWh nowadays, the saving would be between 325.50 and 693.45 €/year, respectively.

If the extra insulation provided by the sunspace is also considered, this saving is even higher. In order to perform an approximate calculation of this insulation, it can be assumed that the temperature in the sunspace is on average around 3.5ºC above the exterior temperature, considering that the interior partition has an overall heat transfer coefficient of 4.40 W/m^2·K and a surface of 40 m^2, the energy loss would be 955 kWh less per year approximately. If the electricity is used as energy source, this saving is about 143.21 € per year. Taking into account these possible savings, recovering the sunspace investment would take at least 41 years. In addition, other uses of the sunspace can be taken into account, such as leisure, aesthetic reasons and so on. However, the economic value of this last consideration is difficult to measure.

The previous calculations have not taken into account the increase in the asset value of the property. This increase is quite difficult to evaluate due to the applicable legal rules mainly concerning the habitability. However, if the sunspace can be considered as a liveable space, the property gain is usually higher than the construction cost.

6. Conclusions

In this paper, the sunspace built during the ARFRISOL project has been analysed by using a validated simulation tool for the study of its thermal behaviour. In order to evaluate the possibility of collecting the solar energy and to use it in the HVAC system, a characteristic day in each season has been selected: the fifteenth of March, June, September and December. And three possible configurations of this sunspace have been studied: passive mode, collecting the energy during the whole day and collecting the energy only at night.

Regarding the results, both qualitative and quantitative studies have been performed. In the first one, the temperature distribution and the air path lines within the sunspace with and without radiation have been analysed. It has been seen that during the daylight the glazing and sand were the zones with the higher heat transference. When there was no solar radiation, the glazing stopped heating, whereas the sand maintained its temperature. In the quantitative analysis, the thermal behaviour of this sunspace has been determined varying its configuration –passive mode, collecting the air during the whole day or only at night– and evaluating the effect of the exterior temperature and solar radiation. Furthermore, the effect of the sand inertia has been emphasised distinguishing between the values of the sand surface temperature and the mean ones. It has been found that the inertia effect is quite important because it allows to collect energy throughout the night, but at the same time it is limited because it cannot store much more energy if it is not collected during the daylight hours.

Finally, the energy collected has been calculated throughout the year considering both configurations: collecting the air only at night or during the whole day. In the first configuration, the annual energy is 2.2 MWh, whereas in the second configuration, this value is 4.6 MWh (more than twice higher). Translating this energy collection into money and considering the electricity as the energy used, the economic saving can be between 325 and 693 €/year, respectively. If also the extra insulation provided by the sunspace is considered, then this saving will be increased in about 143 € per year. Taking into account the cost of a normally-built sunspace, its dimensions, the current price of the electricity and the possible savings, the sunspace investment could be recovered in 41 years.

7. Acknowledgments

This work has been carried out in the framework of the Singular Strategic Project ARFRISOL, on bioclimatic architecture and solar cooling (Reference: PS-120000-2005-1), funded by the Spanish Ministry of Education and Science (MEC) and co-funded by ERDF.

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