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Solar heating system's performance for the heating season 2011/12 in Madrid

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Abstract. An experimental solar heating system was used to supply partially the heat demand of a laboratory the winter period of 2011-2012. This heating system worked in a solar energy laboratory located close to Madrid (Spain), 8h/day during the whole season. As the dimensions, thermal load and characteristics of occupancy of the laboratory are similar to a Spanish average house, the experimental results' conclusions could be generalized to national housing.

This period (nov11-apr12) was characterized by exceptionally clear-sky and solar irradiative days with an average atmospheric clarity of 0.59 and maximum values over 0.8. The total solar energy radiated was 926 kWh/m^2. Collector field's efficiency was 29%. All this factors implied enough solar energy to supply the 83% of laboratory's heat demand for the whole season.

Key words

Solar Heating, Thermal demand, Collector efficiency, Seasonal Performance

1. Introduction

Residential sector is a key sector in the current national and European energetic context due to the importance of the energetic demand, which adds up to 17% of Spanish energy consumption and to 25% in EU.

Focusing on house heating, it is disclosed as the main fraction of the energy consumption. Specifically, it represents the 47% of houses' consumption in Spain, furthermore it rise up to 55.3% at Madrid's continentalized climate [1].

Introducing renewable energies on the housing sector should lead to energy savings. To consider a solar space heating system's efficiency, optimum sizing and feasibility, its performance during a whole heating period should be analysed. However, there are few examples of it in the available scientific literature, which are focused on district heating and heat storage [2]. In addition, depending on the incident solar irradiance the same solar space heating system could cover a different fraction of the energetic demand during different winters. So a solar heating system's performance should be studied and compared among different seasons. In the early years of solar heating technology, long-term performance of solar houses were studied [3] but they cannot be compared as the collectors technology and efficiency has improved in the last decades.

A seasonal study of our heating system was done in the period 2008-09 [4], but in the aim of improving its precision, different seasons' analysis were considered necessary. For deepen in this sense, heating season 2011-12 was studied. Moreover, after its analysis, it resulted to be the most solar energetic heating season in the last 20 years, becoming a significant and relevant seasonal study.

During the official winter season in Spain, from November 1st 2011 to April 30th 2012 the solar space heating system located in the Spanish National Research Council's Experimental Solar Energy Plant at La Poveda, Arganda del Rey, Madrid, partially satisfied the energetic demand of the laboratory. Laboratory's dimensions, thermal load and characteristics of occupancy are similar to a Spanish average house, therefore, results could be generalized to housing sector.

The first week of November was used to set and correct measurement and scheduling system, so in the present paper, the period from November 7th 2011 to 30th April 2012 will be discussed. More specifically, the solar heating facility, the meteorological characteristics of this winter, system's energy balance, and experimental results for the whole period (176 days) and for two representative days in depth will be presented.

Fig. 1 Solar collectors and storage tank's overall view.

2. Solar Heating facility's description

The solar heating system was divided in 3 circuits, as detailed in Fig.2.

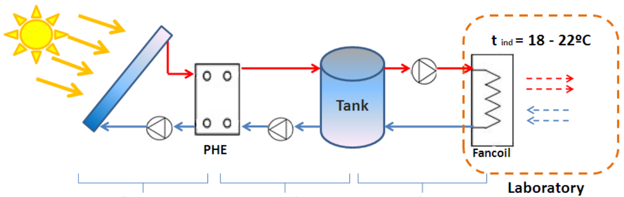

Fig.2. Solar heating system's diagram

A. *Primary circuit*

It is composed of a field of 24 vacuum flat plate solar collectors (net area of 42 m^2), as is described by [4], and a booster that pumps thermal fluid (with a mean flow of 27.5 l/min) to the hot side of a plate heat exchanger (PHE), where heat is transferred to the secondary circuit.

B. *Secondary circuit*

In this circuit, the heat transferred to the cold side of the PHE is pumped (with a mean flow of 19.26 l/min) to an insulated 1500 l storage tank.

C. *Tertiary circuit*

In the last circuit, the thermal liquid is pumped from the storage tank to a fan-coil system inside the laboratory (with a mean flow of 7.8 l/min).

D. *Laboratory, as thermal load*

Thermal energy from the collectors stored in the tank was supplied to the fan-coil for heating the whole laboratory building (80 m^2) up to 21°C, design temperature, as the Spanish Regulation indicates [5]. The laboratory was heated during 9 hours, 8:00-17:00h, every day of the heating period, whenever there was thermal energy stored available.

The area of the laboratory is equivalent to the area of a Spanish average house. It was occupied by three people, around 8 hours/day and 75% of the time.

The calculus for the thermal and internal loads is discussed in section 4.

3. Meteorological variables

The meteorological variables were recorded at the weather station located at the Experimental Solar Energy Plant.

The present paper focuses on the seasonal evolution of outdoor dry bulb temperature and solar radiation.

Figure 3 shows the daily insolation received on 30º tilted surface. It was a highly energetic season, when 926.4 kWh/m^2 was radiated along 176 days. In fact, the highest value during heating season in 20 years.

Extraterrestrial insolation, H_{ext}, for each day of the heating period can be estimated as described by [6], calculating the daily sky clearness index, as the ratio of daily insolation on horizontal surface H_0 (measured by the weather station) to the extraterrestrial radiation:

$$K_T = \frac{H_0}{H_{ext}} \quad (1)$$

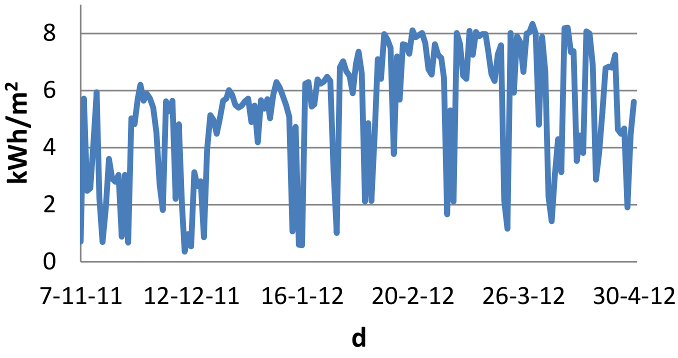

Fig.3 Daily solar energy radiated on 30º tilted m^2.

The average sky clearness index for the whole period revealed 0.58. Even in a continentalized Mediterranean climate as the one in Madrid, it is an unusual high value, as it can be seen comparing the average clearness index of the last 20 heating periods, in Figure 4.

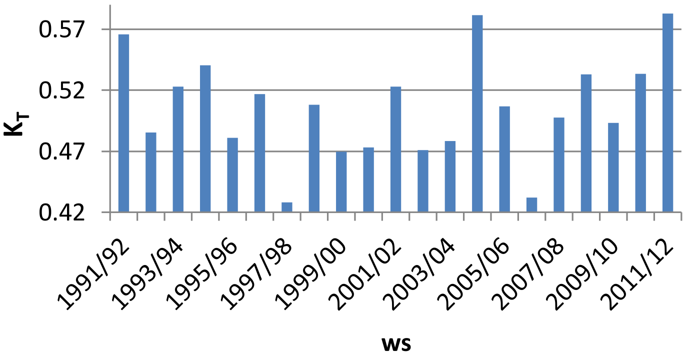

Fig.4. Last 20 years' seasonal average sky clearness index.

This high insolation levels were accompanied by several cold and clear days. Figure 5 shows the seasonal evolution of the daily maximum and minimum outdoors temperatures. According to the State Meteorology Agency (AEMET), the December-February period was extremely dry and colder than usual in Spain [7].

In the present paper, a very cold day (12/2/2012) and a cold day (5/3/2012) and are studied in depth. The outdoor dry bulb temperature and solar radiation during both days are shown on Figures 6 and 7.

Both days were clear sky ones, with a maximum solar radiation on tilted surface over 1100 W/m^2.

February 12th 2012 was one of the coldest days of the season (min. -8.5ºC, max. 7.2ºC). Instead, March 5th 2012 was not so cold (min. 3.1ºC, max 14.9ºC).

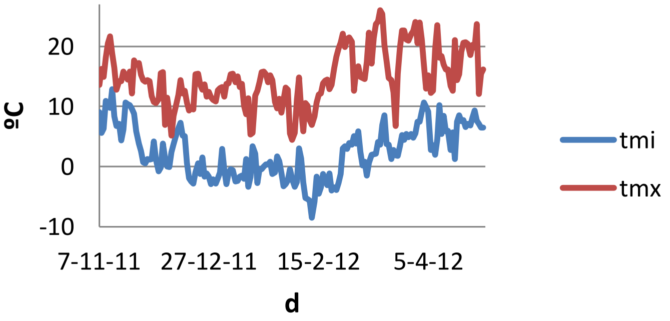

Fig 5. Seasonal maximum and minimum outdoor temperatures.

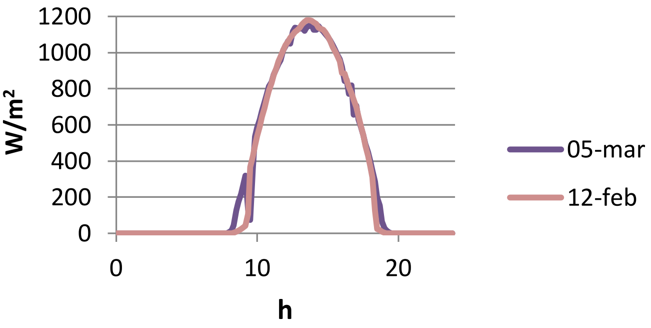

Fig. 6 Solar radiation on 12/2/2012 and 5/3/2012.

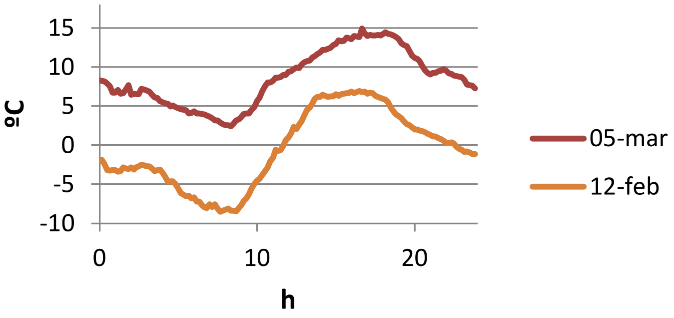

Fig. 7 Outdoor dry bulb temperature on 12/2/2012 and 5/3/2012.

4. Energy balance

The different circuits' power, heat exchange processes' efficiency between them and daily transferred energies were calculated for everyday of the season.
Primary circuit's power:

$$P_{pri} = m_{pri} C_{Ppri} (t_{cwi} - t_{cwo}) \quad (2)$$

As data from the flow meters and circuit's temperatures were recorded every Δt =1 min, daily energy that had been supplied in each heat transfer process *j* was estimated as:

$$E_j = \sum_{i=1}^{1440} P_{ji} \Delta t \quad (3)$$

The daily efficiencies would be:

$$\eta_j = \frac{E_j}{H_t . A_c} \quad (4)$$

So for the primary circuit:

$$E_{pri} = \sum_{i=1}^{1440} P_{pri} . \Delta t \quad (5)$$

And collector efficiency was calculated as the quotient between the capacity received by the fluid as it crossed the collectors and the overall insolation on the collectors' surface:

$$\eta_c = \frac{E_{pri}}{H_t . A_c} \quad (6)$$

Calculating, in analogue way, the heat transfer to the tank by the secondary circuit (P_{sec}, E_{sec}) and the heat delivered to the fan-coil system (P_{fc}, E_{fc}) were obtained.

The thermal load of the space to be heated was calculated considering an $U_g A_{lab}$=460$\frac{W}{ºC}$ factor, for the transmitted heat:

$$P_{trans} = U_g A_{lab} (t_{des} - t_{dbo}) \quad (7)$$

And a mean internal load of $P_{int} = 500\ W$.
So, building's thermal load was considered:

$$ThL = P_{trans} - P_{int} \quad (8)$$

And the daily energy demand:

$$E_d = \sum_{i=1}^{1440} ThL_i . \Delta t \quad (9)$$

The thermal load was assumed to be null out of the testing hours and when the outdoor dry bulb was higher than 17ºC. Whenever the ThL was satisfied and indoor temperature rose over 21ºC, the P_{fc} was matched to the ThL. In these cases, the extra energy used to overheat the laboratory just for comfort reasons of the occupying people was not taken in consideration for the energy balance calculations. The full heat power of the fan-coil was defined as gross heating power ($P_{fcg)}$., however, for the seasonal energy balance, it was just considered the net heat power ($P_{fcn)}$ necessary to reach the target temperature. In the experimental results, the difference between gross and net heating power is shown, as example, on February 12th.

The Solar Fraction, SF, was considered as the quotient between the daily net heat transferred by the fan-coil to the building and its energy demand:

$$SF = \frac{E_{fcn}}{E_d} \quad (10)$$

5. Experimental results

In the present section, daily and seasonal results are shown.

A. Daily results

System’s working temperatures, powers and supplied energies will be detailed for chosen days. Due to length limitations of the present paper, the daily results discussed will be focused on the secondary and tertiary circuit.

1) February 12th 2012

On this very cold day, solar radiation lasted 10.38 hours, reaching the maximum value, 49.5 kW, at 13:40, and providing 327.2 kWh/day over 42m^2 collectors’ surface, from which 81.5 kWh/day was delivered to the tank (Figure 8).

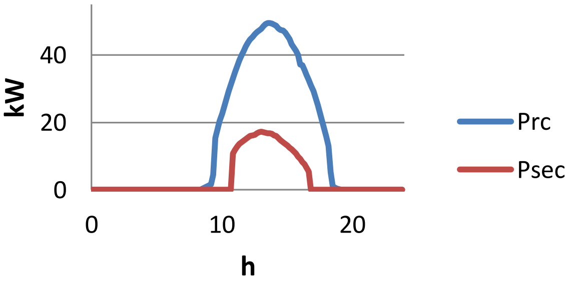

Fig.8. Radiation over the collectors and useful power transferred to the tank on 12/2/2012.

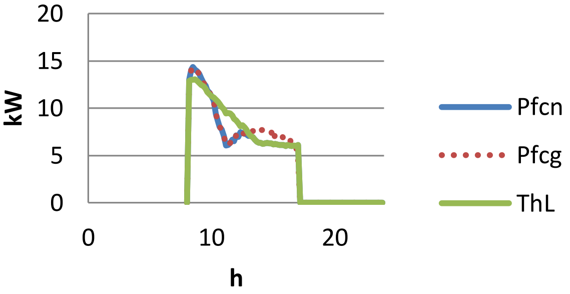

Fig.9. Gross and net heating capacity and thermal load on 12/2/2012.

Figure 9 shows how thermal load reached its maximum value of 13 kW at 8:00, and since the fan-coil turned on and outdoor temperature increased, it started decreasing. Whole day operation period’s energy demand was 77.6 kWh. Gross heat supplied by the fan-coil was 76.6 kWh, however, the net heat considered was 73.4 kWh (94.6% of the demand was covered by solar heating system), 33.4 kWh of which had been stored days before.

Focusing on system’s temperatures (Figure 10), the storage tank’s liquid was near 50ºC before the tertiary circuit started. From 8:00 hours, fan-coil’s working temperatures started dropping as it did tank’s outlet temperature, until it started to receive thermal energy from the collectors at 10:40 (when the secondary circuit turned on), and temperatures rose until its maximum fan-coil inlet temperature of 58.8ºC at 14:50. After that moment, it decreased as the solar radiation did, until 17:00 when the tertiary circuit stopped and tank’s outlet temperature kept near 50ºC for the day after . On the other hand, the indoor temperature increased during all the fan-coil working time, keeping over 18ºC from 11:00 to 18:53 hours.

2) March 5th 2012

On this day, solar heating facility worked similarly. However, as sunlight lasted longer and outdoor temperatures were not so low, a different performance was obtained as it can be seen on figures 11, 12 and 13.

Solar radiation lasted 11:32 hours, providing 336.6 kWh/day over 42m^2 collectors’ surface, from which 101.3 kWh/day was delivered to the tank (Figure 11). On Figure 12, laboratory’s thermal energy demand was 43.2 kWh, and fan-coil supplied 32.8 kWh (76.0 % of the demand was covered by solar heating system), 3.8 kWh of which had been stored days before. Although the energy demand was 44% lower than in February 12th, the Solar Fraction was lower. This decrease is because of the stored available energy at starting time was 88% lower too. In fact, in March 4th, the daily insolation was just 2.1 kWh/m^2, so most of the stored energy was used to heat the laboratory.

The supply air temperature was lower than 30ºC until 10:30 hours, which adversely affects the indoor comfort condition. It was tolerated and considered as useful heat, because the indoor temperature had got colder during the night and occupancy factor was low that day at the beginning of the working period. The indoor temperature reached 18ºC quickly, keeping over 21ºC from 10:54 to 18:05 hours, as it can be seen on Figure 13. Since this target temperature was reached, fan-coil’s thermostat worked the rest of the day turning on/off whenever the temperature increased or decreased around 21ºC. That’s the reason of the constant fluctuations on fan-coil’s outlet temperature and supply air temperature.

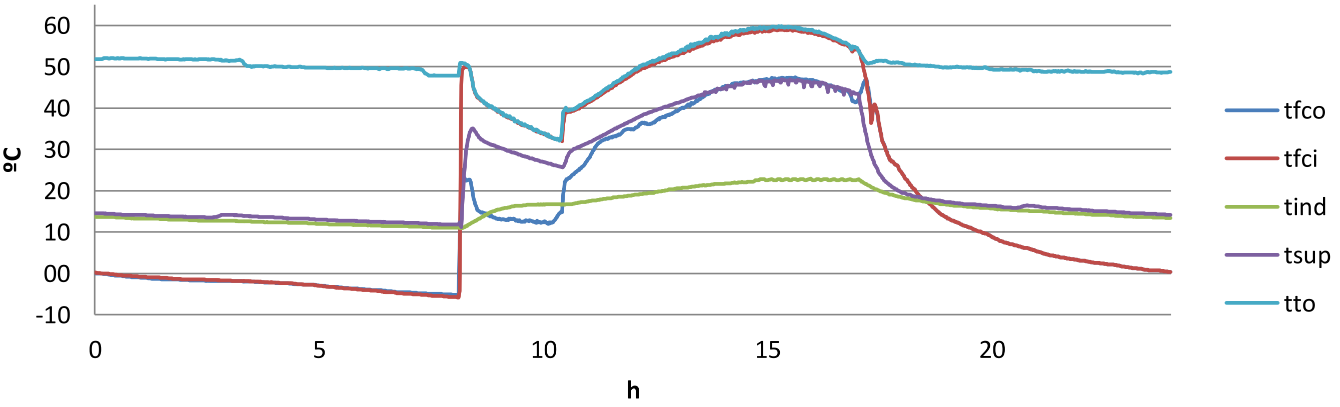

Fig.10 Tertiary circuit’s and indoor temperatures on 12/2/2012.

B. Seasonal results

Performing the daily analysis for the whole heating season and summarizing them, seasonal energy balances are obtained. Figure 14 shows the daily solar energy radiated over collectors' surface, the useful thermal energy transferred to the storage tank by the secondary circuit and the net energy supplied to the fan-coil for space heating.

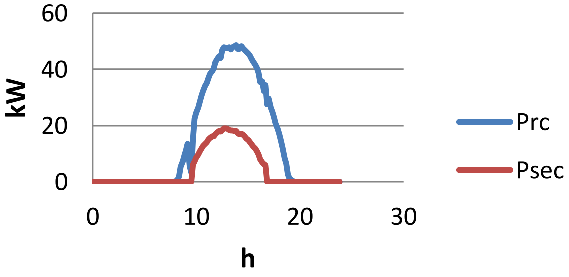

Fig. 11 Radiation over the collectors and useful power transferred to the tank on 5/3/2012.

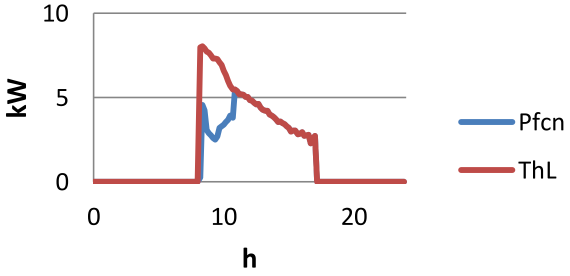

Fig.12 Net heating capacity and thermal load on 5/3/2012.

Along the whole heating season, 38.9 MWh were radiated over the solar collectors, from which 10.3 MWh were transferred to the storage tank and 6.1 MWh were consumed for space heating by the fan-coil.

The seasonal building's energy demand for heating was 7.4 MWh. Therefore, the solar heating system covered the 83% of the demand. Figure 15 shows the SF for every day of the season. The mean SF was 0.84 and there were 82 days when 100% of the demand was supplied by the solar system.

On Figure 16, the efficiency of the primary circuit or collectors' efficiency and the efficiency of the tertiary circuit or global efficiency are shown. Collectors had a seasonal efficiency of 0.29, with short oscillations. By the other hand, the global efficiency fluctuated widely, due to the storage system. In a period with consecutive cold and clear days the global efficiency had a mean value of 0.24. However, in a low insolation day after a clear period, most of the heat transferred to the fan-coil had been, actually, stored in the tank the days before. Consequently, the quotient between the heat used at the fan-coil and the solar insolation over collectors' surface that day increased, and some efficiency peaks appeared. Moreover, most of the days in March and April, the laboratory had lower energy demand, so the global efficiency decreased as the solar energy available exceed the thermal needs of the facility in a bigger fraction.

6. Conclusions

The present article exposes the experimental results of a solar system for a whole laboratory's heating season (6 months). It has been considered, because of dwelling's characteristic, as a thermal simulator of a Spanish average house.

During this period, in 42m^2 of solar collectors, 38.9 MWh were radiated, from which 6.1 MWh were used by the fan-coil system to heat the laboratory up to 21ºC. Such a so irradiative meteorological conditions allowed to reach a seasonal solar fraction of 83% for covering laboratory's seasonal heat demand.

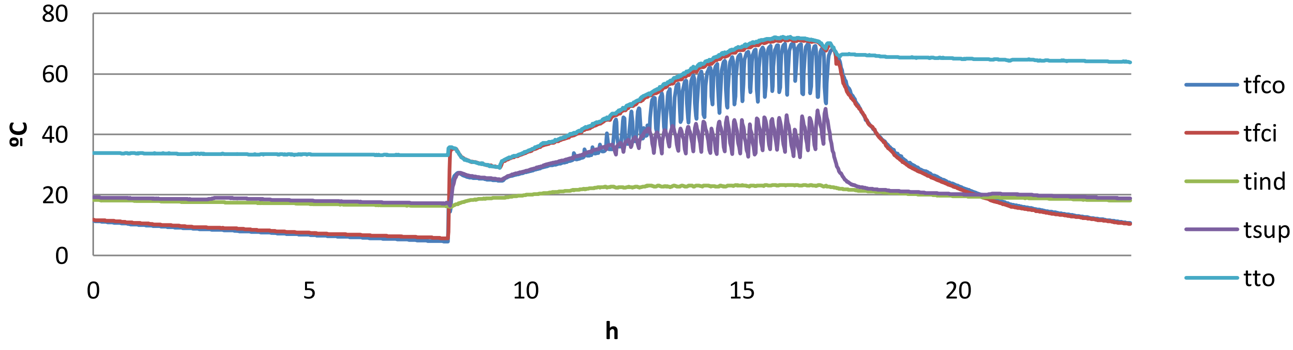

Fig.13 Tertiary circuit's and indoor temperatures on 5/3/2012.

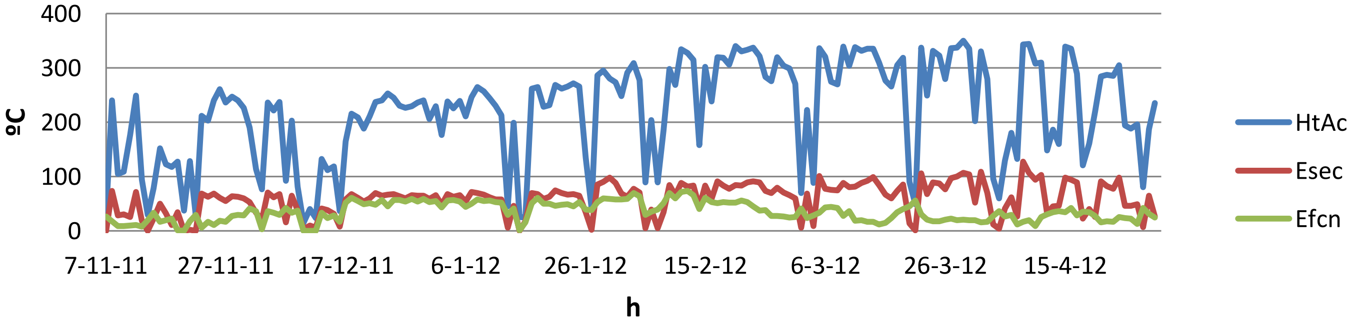

Fig. 14. Daily insolation over collectors' surface, energy transferred by the secondary circuit and fan-coil's heating energy.

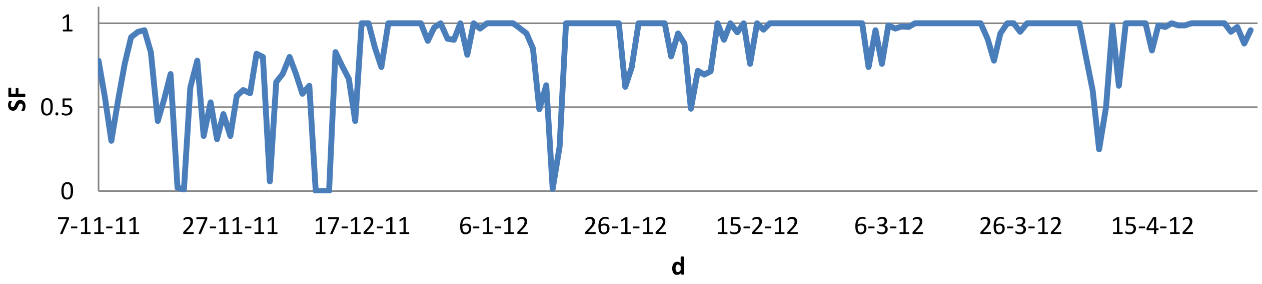

Fig. 15 Daily Solar Fraction along the season.

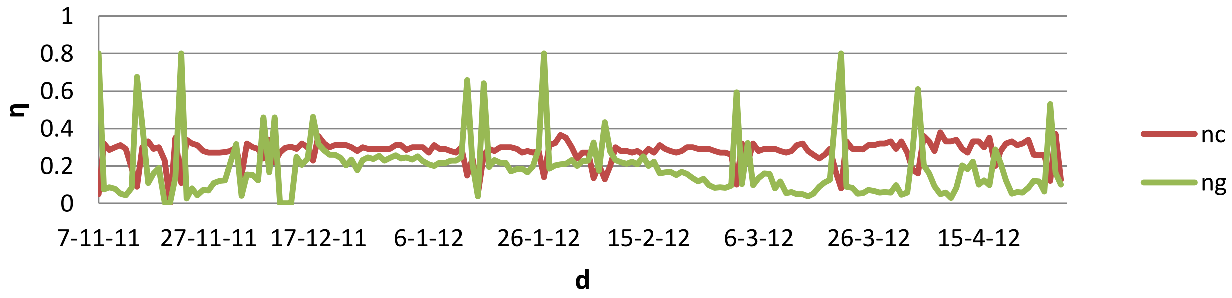

Fig. 16 Collectors' efficiency and system's global efficiency.

It was the clearest and most energetic heating season in 20 years in Arganda del Rey, Madrid. Under unfavorable meteorological conditions, the seasonal solar fraction for the same solar heating system may decrease. Moreover, system's behavior may change under different types of climate or latitudes, even in Spain.

Nomenclature

A: area (m^2)
C_P: fluid's specific heat capacity (J/kg.K)
d: days
E: energy (Wh)
H: daily insolation (Wh/m2)
h: hours
K_T: sky clearness index
P: power (W)
SF: Solar Fraction
t: temperature (ºC)
ThL: Thermal Load (W)
U: heat transmission coefficient (W/m^2.K)
η: efficiency

Subscripts
0: horizontal
c: collectors
cwi: collectors' water inlet
cwo: collectors' water outlet
d: demand
dbo: dry bulb outdoor
des: desing
ext: extraterrestrial
fcg: fan-coil's gross
fci: fan-coil's water inlet
fcn: fan-coil's net
fco: fan-coil's water outlet
g: global
ind: indoor
int: internal
lab: laboratory
mi: minimum
mx: maximum
pri: primary circuit
rc: solar radiation on collectors' surface
sec secondary circuit
sup: air supply
t: heat losses by transmission
t: tilted at 30º
to: tank's outlet

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