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A new design of roof-integrated water solar collector for domestic heating and cooling

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Abstract

A new design of roof-integrated water solar collector is presented. It takes advantage of new synergies found between collector and roof. Its main concept is based on the use of water redistribution for changing the roof configuration. This design provides a low-cost system for household heating and cooling that could be even cheaper than conventional roofs with similar thermal qualities, by using fully its configurable property. In this sense, this design could help us to modify the deeply-rooted paradigm of the classic roof.

Keywords: Roof solar collector; Passive solar heating; Passive cooling

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1. Introduction

Many feasible designs of roof-integrated solar collectors have been developed in the last 50 years. It is possible that the oil price increase will prompt their applications in the future, but at present, high costs have delayed their massive application (Belusko et al., 2004). In recent years, many roof-integrated collectors have been proposed, such as hybrid systems with photovoltaic (Vokas et al., 2003) or thermoelectric (Maneewan et al., 2005) panels, intended to overcome this limitation. These integrated designs have obtained modest cost reductions, but they contributed to improved collector performance. For example, the photovoltaic-panel efficiency is improved by lowering its operating temperature using water cooling. But in spite of their success, they did not change the actual roof paradigm. Ohere are few designs proposing substantial changes to the basic roof concept, leading to further cost reductions.

Solar collectors use water or air. Water systems are more expensive but have better performance than those with air due to their higher energy density (Khedari et al., 1996). It is common knowledge that a small solar collector (*i.e.* 4 m^2), can satisfy the domestic hot water demand in many places worldwide. Hence, we can expect that extending the collector onto the whole roof could provide the household with heating as well. As Hassan and Beliveau (2007) have demonstrated, this can still apply close to 40° latitude. However, at present, large solar collectors are rarely used due to the high costs.

The use of water ponds on roofs for house cooling in arid regions is well known (Nahar et al., 1999; Jiang et al., 2001; Jain, 2006). The water is cooled during the night by evaporation and radiation heat losses, and is protected against solar irradiation by a scrollable cover. Contradicting prior observations of Nahar et al. (1999) and Jain (2006) state that a shallow water depth of 5 cm is enough. Jain also suggests that the inverse procedure could be used for household heating in winter.

In the pioneer work of Harold Hay (1977) and his patented Skytherm system, water bags are mounted over a simple metallic roof that is protected by a folding cover

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with good thermal insulation. This system provides the household with heating by infrared radiation in winter, and cooling by free convection in summer. As Hay showed in his own house in California in the 1970s, this system can provide a comfortable temperature all year even in arid climates (Hay and Yellott, 1969).

Hay's design works under four configurations, combining the summer–winter and day–night options. By just moving the insulator cover it collects or stores solar energy during the day or night respectively in winter, and does the opposite in summer. Although Hay could be considered a pioneer in this field, he did not see one potential of his innovative idea, and neither did his followers, like Hammon (Alves and Milligan, 1978), who were more interested in improving details in Hay's design, such as the folding cover. One of the main drawbacks of the Skytherm was the extremely high cost of its movable cover and thick insulation layer mounted over a very bulky mechanical system. According to the actual climate where it is applied and its low graduation ability, other disadvantages of Skytherm that can arise are: the uncomfortable effects causes by the infrared heating overhead in winter, and by vapor condensation on the cold ceiling in summer. This point will be further discussed in Section 6.

Medved et al. (2003) predicted the possibility of heating a swimming pool of 600 m^3 by using a 600 m^2 collector for a monthly insolation of 165 kWh/m^2 over an unglazed roof-integrated solar collector. In addition his work shows efforts in designing water-coil collectors integrated to the undulatory roof, as we shall propose here.

In this work an innovative design for a solar roof is presented. It is based on the original combination of many concepts of the previous designs. This design is expected to satisfy the demand of household heating and cooling in many low and medium-latitude locations, with lower costs than standard roofs with similar thermal quality. This last condition is achieved by using common building elements, so that this type of roof can be massively applied. In addition, it could serve as an inspiration for other researchers to develop new environmentally friendly buildings. This design was recently patented (Juanicó, 2006).

2. Analyses of different roof techniques

2.1. The classic roof concept

Consider the evolution of conventional roof designs along with developments of new materials and building techniques. At present, a metallic roof is assembled by using sheets of customized lengths to avoid overlapping of short sheets common in previous methods. Instead of the old flat plates, undulatory or trapezoidal profiles are now used to increase mechanical resistance. These changes have produced significant improvements in construction techniques, including costs and time. Among these are:

- Roof surface is reduced by using gentler slopes (20° against 45° required by previous designs to prevent rain filtrating between overlapped plates).
- Construction time on site is reduced because fewer unions, seals and supports are needed for assembly.
- New finishes now make sheets more resistant to corrosion.
- Since metal sheets can become a self-supporting roof, a wider space can be left between braces or these can even be left out completely.
- In some trapezoidal systems, contiguous metal sheets are joined to adjacent sheets by means of welded joints. This system provides an excellent water-tight roof and an upper step several centimeters higher useful for our objective.

This technological evolution in roof systems opens an opportunity window for new designs. In contrast, the classic concept of roof has prevailed without changes for a very long time. Classic roofs are designed following two main goals:

- To prevent rain or snow infiltration.
- To provide good thermal insulation.

The traditional way to fulfill these objectives in high quality roofs has been to overlap several internal layers of different materials (low thermal conductivity, high reflectivity, etc.) between air gaps or chambers, under the waterproof exterior layer. This whole system constitutes a good-quality roof; but at high costs in relation to materials and labor. On the other hand, low quality roofs (with fewer intermediate insulating layers) usually have lower costs but are "warm in summer and cool in winter", as they do not reach the "almost adiabatic" category of the previous ones.

Summarizing, the traditional roof concept can be described as a fixed roof in which the greatest adiabatic degree is intended, and in which the investment made is directly proportional to the objective achieved. This fits the current architectural trend to design low-energy buildings, but with the drawback of having to pay high costs in order to achieve this adiabatic goal (Wall, 2006; Smeds and Wall, 2007). We, on the other hand, are proposing to maximize the degree of adaptability of the building to the environment.

Note that new piping technologies (continuous lines, fittings without elbows, etc.) can be used to minimize leakage problems. Therefore, at present, the application of multipipe systems within the construction of new buildings does not imply excessive costs in materials and labor. In addition, new developments in low-conductivity windows (triple glazing filled with low-conductivity gases, low-emissivity coating, new low-conductivity transparent materials, etc.) provides a way to obtain very good insulation by using multiple-glass windows. There are in the market triple-glazing windows with global conductivity coefficient U of 0.6 W/m^2 K, (www.efficientwindows.org) and new triple vacuum glazing achieving up to 0.2 W/m^2 K (Manz et al., 2006). Note that while all technologies developed for windows can be useful here, we can also explore other material choices, since we do not need to satisfy the requirement of good optical property, as the window does. Thus, for example, some multilayer Mylar windows recently developed can be applied for maximizing the roof insulation (Tsilingiris, 2003). Other technologies available now are: (1) high reflectivity and low-emissivity covers (such as aluminum foils), which provides a useful way to minimize the infrared radiation losses from roof to the environment, and for solar blockage; (2) low-cost transparent plastic material with good mechanical resistance and water proofing used now in solar collectors, such as UV inhibited polyethylene at 5 U\$D/m^2 (Fernandez Gonzalez, 2005). Finally, note that the problem of minimizing heat transfer across horizontal parallel plates (such as this roof) is lower than for vertical ones (windows), since the vertical position enhances the free convection mechanism involved. This point will be further discussed in Section 4.

The combination of these techniques offers a starting point for the new design presented here. This design combines new materials and construction techniques available for developing an innovative roof system. It fully uses water redistribution for changing the roof configuration, creating a deeply configurable system. Although other solar collector systems that use flowing water connected to heating and cooling systems were developed in the past, such as Thomason's designs, and recently, the Cool-Cell™ and Di-Thermal of Baer and Mingenbach (2002), they belong to a different category. The approach common to these designs is to mount a device onto the roof, but they do not change the present roof concept; neither do they achieve new synergies between collector and roof.

2.2. General description of the new concept

Fig. 1a presents a flat-plate solar collector and a conventional roof. Observe that both have essentially a black metallic layer with a back layer for insulation. But whereas the collector has several glass layers and air cavities in order to achieve good thermal insulation, the roof is places the insulation and air cavities *below* the metallic layer. These alternative designs can be joined by reorientating one of them, as we have done. Our present approach is illustrated in Fig. 1b. It consists of substituting the roof with the collector, joining both in a single system making the internal insulation layers unnecessary. In addition, the expensive water-coil collector is replaced by an inexpensive water pond obtained by using a metallic roof with a trapezoidal profile. Moreover, eliminating internal insulation layers reduces the cost while allowing the utilization of the metallic roof as a heat interchange device for the household indoor space, as does the Skytherm.

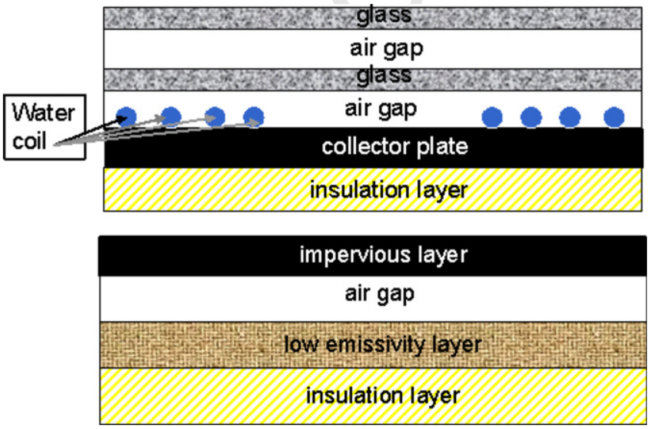

Fig. 1a. Schematic drawing of a flat-plate and conventional roof.

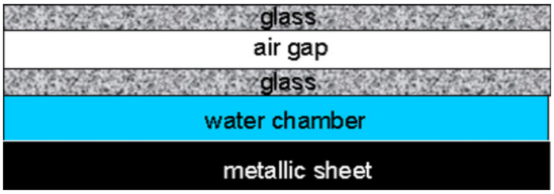

Fig. 1b. Schematic drawing of the new roof-integrated solar collector.

Fig. 2 illustrates the general operational scheme of the system under the winter-day configuration, and Fig. 3 shows a transversal cut of the roof. In Fig. 3, metal sheets with "*U*" profile are shown, as are typical in some new roof systems (such as the zip-rip one) in which a single wide chamber is obtained among two neighbor sheets, joined at the upper rung by means of a deformation weld. This single water chamber in each sheet would be more convenient for our purpose that the multiple chambers in other types of sheets (such as trapezoidal), since a minor number of waterproof endings are needed.

This system consists of (numbers in text and figure match):

- A metallic base (#1) with a "*U*" profile so that it provides an upper-level step (#2) (rung). All the joints of the roof are made on this upper level, and thus, we get a waterproof base for the main water chamber (#3). For example, if braces are needed, they can be installed and attached under this upper level step (#2), to avoid having to drill holes (for nails or screws) within the main (lower) base (#1).
- This water chamber is covered with a first glass (#4) placed at an intermediate level between the previous two, providing us with a water-tight chamber by simply keeping the water level below that of the glass. This glass rests between two special omega-shape pieces (#5) placed on the neighboring steps, as shown in Fig. 3. As the water level will always be lower than these joints, they do not need to be waterproof.
- A second glass layer (#6) will rest on the previous upper rung forming a double-glass water collector.

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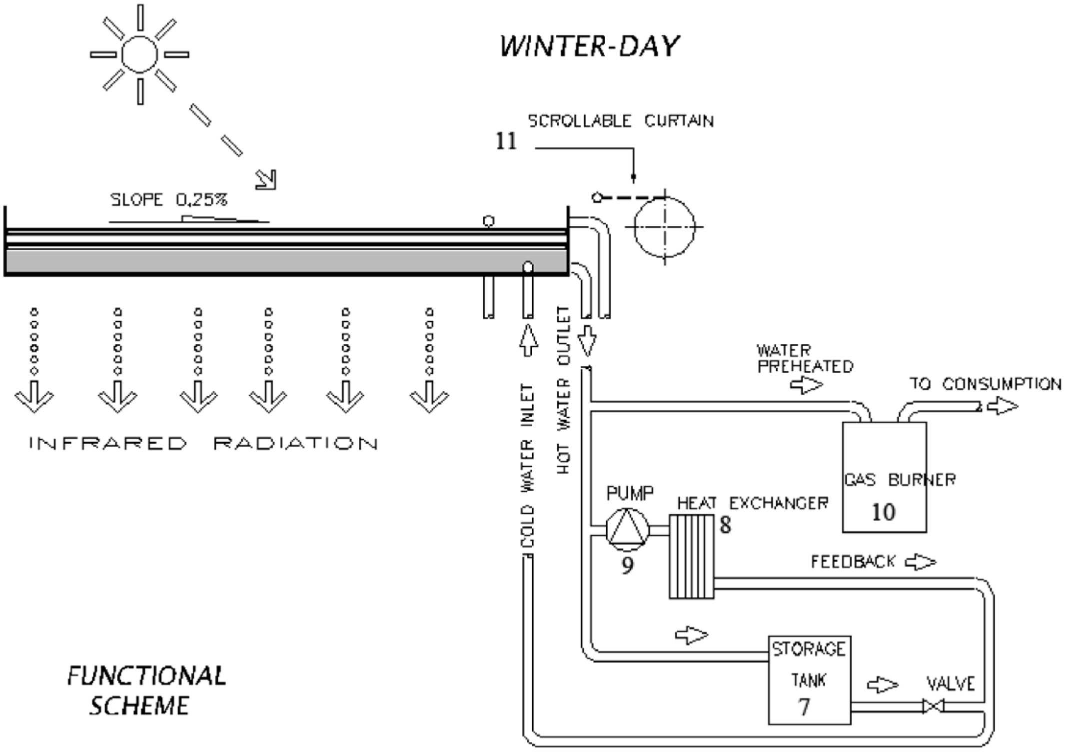

Fig. 2. General scheme of roof system with accessories.

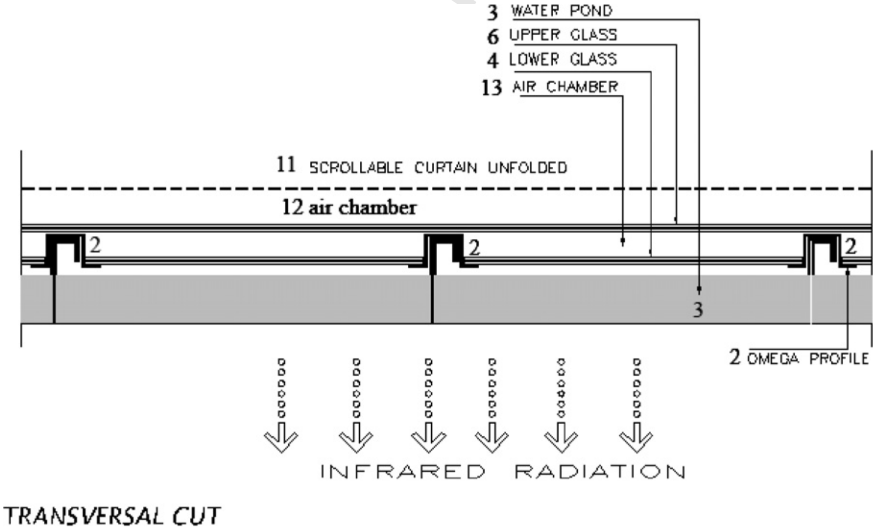

Fig. 3. Cross section drawing. It shows the "*U*" profile that supports two parallel glasses.

- A shallow water layer (#3) contained between the metallic roof and the first glass will capture the solar energy absorbed by its metallic base (with a high-absorptivity surface).
- The water layer (for example, for 5 cm water depth and a 100 m2 roof surface, a water volume of 5000 l is obtained) is connected by piping with the:
- Storage tank (#7) located inside or near the house (for example, in an adjacent greenhouse). This tank feeds into:
- The system of circulating hot water (#8) used to heat the house (preferably a floor with radiant heat). Normally, this system has:
- A standard pump (#9) that will also serve in this case to pump the stored water to the roof. On cloudy days when solar energy collected is not sufficient, the system is supplemented with a:
- Standard water boiler (#10) connected before the point of household hot water distribution.

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- A rolling awning (#11) is arranged above the previous assemblage. Then, another air chamber (#12) above the second glass (#6) is created when the awning is extended, that together with the air chamber between glasses (#13) provides the overall heat insulation. It's important to note that this awning does not need to have thermal insulation, as was the case in Hay's Skytherm.

This general description represents only one practical manner of build the present design approach. For example, the omega-shape pieces (#5) can be eliminated by assembling both glasses within a single window frame, useful also for tying the glasses structure to the roof. Another option is to replace one or both glasses with a transparent plastic material, such as polyethylene. This choice could have many advantages: plastic covers can be handled more easily, can be mounted in larger sheets, have better mechanical properties and are cheaper than glass. In this case, a light expanded metal of open mesh can be mounted over this plastic cover, providing a barrier against external projectiles (like stones) and tying the whole assembly.

The metallic ceiling can heat the house by infrared radiation, as Hay has shown. Paints with different emissivity can be chosen to enhance this heating method in each room. This heating method is quite remarkable as the ceiling could reach temperatures of up to 80 °C in winter, or else this can be minimized, according to the emissivity of the ceiling. This last option and other special features of this design will be further discussed in Section 6.

Although the horizontal design developed here minimizes the roof area, (and cost as well), this concept could be easily adapted to inclined roofs by ensuring the water tightness of the main water chamber.

3. Different configurations of the new system

3.1. Winter-day

The water pond (#3) generated between the first glass and the metallic base collects solar energy and simultaneously warms up the indoor by radiation during winter days (see Fig. 4). Considering a daily solar flux of 3600 W/m^2, this water can reach around 70 °C at sunset, as we shall see in Section 4.

3.2. Winter-night

This warm water is sent in the twilight hours towards the storage tank (#7) and from there it is pumped and recirculated through a standard hot water system for household heating (#8), preferably by infloor hot water radiation. Together with the unfolded rolling awning (#11), (see Fig. 5) three air chambers are created plus an infrared radiation barrier, providing good thermal insulation during the night. However, if it is necessary, we can also pump a small amount of hot water onto the metallic roof in order to keep the ceiling temperature above the minimum comfort level (20 °C). A detailed calculation about the degree of heat insulation obtained by this way will be developed in Section 4.

3.3. Summer-nights

During summer-nights (see Fig. 6) a shallow water pond (#14) is generated onto the upper glass, (open to the environment), in order to cool it by evaporation, and by thermal radiation emitted to the sky. In this way the temperature can drop up to 10 °C below ambient tempera-

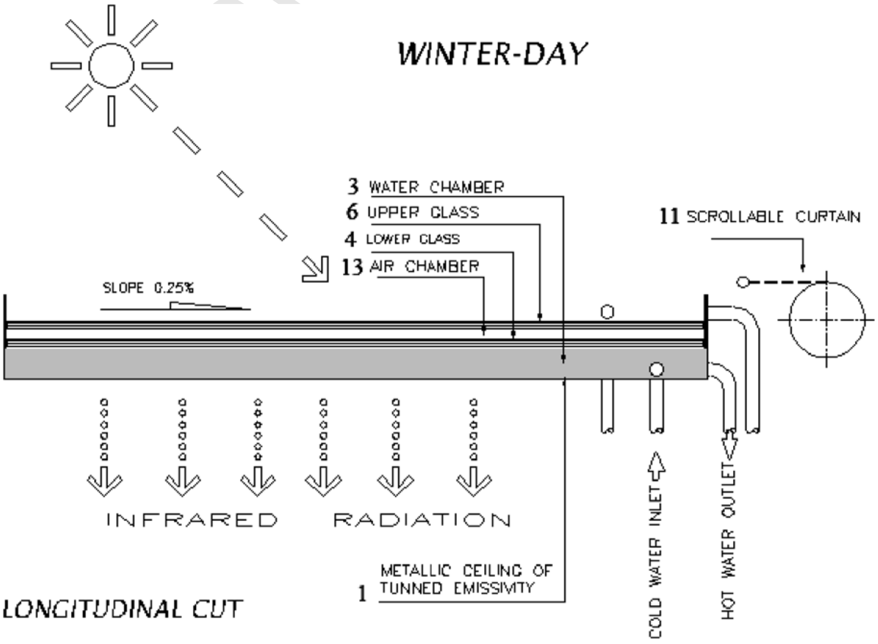

Fig. 4. Scheme in the winter-day configuration.

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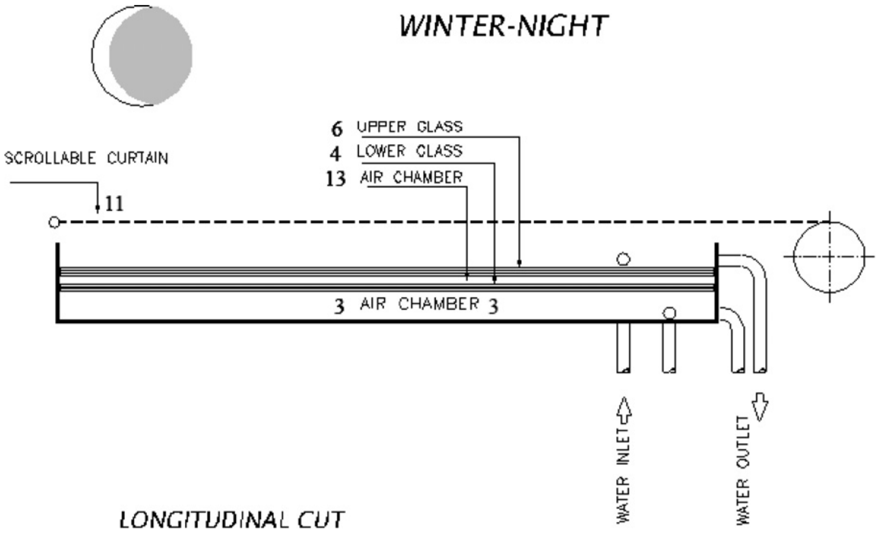

Fig. 5. Scheme (longitudinal section) in the winter-night configuration.

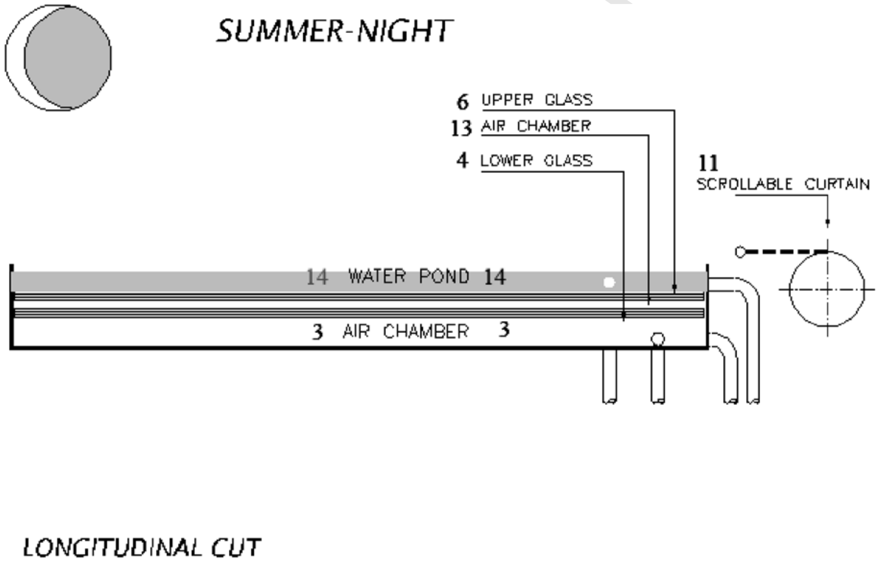

Fig. 6. Scheme (longitudinal section) in the summer-night configuration.

ture (Nahar et al., 1999). The water tightness of this upper chamber whose floor is formed by glass sheets (#6) can be obtained by sticking sticky tapes between adjacent glasses, etc. However, we can realize that actually this condition is not necessary. In this case, the water would drain toward the main chamber collector (#3) through leaks, from where it could be pumped back to the upper chamber. On the other hand, large plastic covers could be used instead of glasses sheets.

3.4. Summer-day

During the day the water cooled at night is pumped to the main chamber (#3) to provide indoor cooling by free convection as shown in Fig. 7. Meanwhile, this water pond is protected from solar radiation by extending the rolling awning (#11); in this way more than 50% of the house heat load can be reduced, as Jain pointed out (2006). According to Jain a shallow 5 cm water pond can provide enough cooling power to satisfy the household demand. The rolling awning can also protect the glass roof from hail.

It could be expected that the water might overheat during the day due to the high temperature difference between the water and the ambient. However, we point out three issues that help us:(1) the awning can be equipped with a low-emissivity surface in order to minimize the infrared radiation from the hot curtain to the water pond; (2) both glass layers provide an infrared barrier too; (3) since the hottest surface is on the top position, the convective heat transfer downstream is insignificant.

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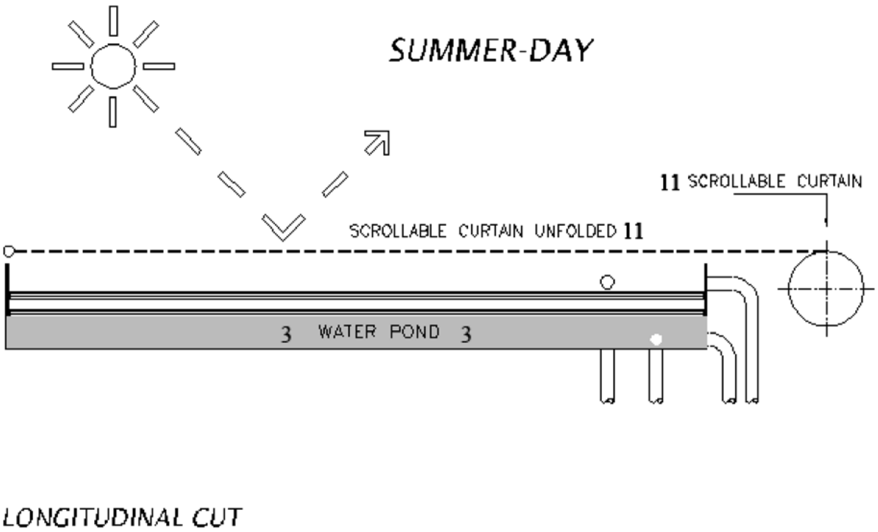

Fig. 7. Scheme in the summer-day configuration.

4. Energy analysis

Let us first analyze the energetic behavior of the solar collector. It can be performed with modest efforts (following the conceptual level of this work), based on the great number of scientific literature available. The study of Vokas et al. (2003) on integrated solar collectors was used in order to determine the solar collector performance for a specific location. Vokas studied the yield of a hybrid PV-solar collector for Athens (38°N latitude), taking an average monthly solar radiation incidence on the flat collector of $G'' = 143\ \mathrm{kWh/m^2}$. Thus, we can calculate: (1) the average daily energy absorbed, E_d, and (2) the annual energy, E_a, as:

$$E_d = G'' \cos\theta \xi A/30 = 187\ \mathrm{kWh} = 0.68\ \mathrm{GJ} \tag{1}$$

$$E_a = 365 E_d = 247\ \mathrm{GJ} \tag{2}$$

where ξ is the overall efficiency (an average bibliography value of 0.5 was taken, as Vokas used) of the solar collector, A is the total roof surface (selected as $100\ \mathrm{m^2}$ for this case) and an average insolation angle $\theta = 38°$ must be considered due to the horizontal position of this roof.

Calculating E_d for the lowest-irradiation month ($90\ \mathrm{kWh/m^2}$ in December according to Vokas), it yields a value of $118\ \mathrm{kWh} = 0.43\ \mathrm{GJ}$, equivalent to 155 GJ/year. Even this lower amount of energy could be enough to satisfy the heating demand for an average house. For example, even in higher latitudes, as Stockholm, Sweden (57°N), there was an average heating demand of only 53 GJ/year in one-family houses (Carlsson-Kanyama et al., 2005).

The energy balance of the water inventory for the diurnal cycle is given by:

$$E_d = M_c \Delta T \tag{3}$$

where M is the mass of water (5000 kg) of heat capacity c, and ΔT is its maximum temperature jump obtained from sunrise to sunset. By taking the annual average E_d (0.68 GJ), it yields $\Delta T = 33\ °\mathrm{C}$. So, starting with initial values of 37 °C in the morning, we will obtain a final temperature of 70 °C in the evening, enough for hot water radiator heating systems and very good for floors with radiant heat. Of course, higher final temperatures can be obtained by choosing smaller volumes of water. The daily energy balance of the water will determine its average temperature, as we shall see in next subsections.

The performance of the roof as a heating and cooling device can be studied by using the one dimensional thermal resistant approach, considering the well known problem of heat transfer by air free convection between parallel plates (Incropera and DeWitt, 2007). As glass is usually very thin (and others expensive low-conductivity materials should be avoided), its thermal resistance is small compared with the resistance of air cavities, and hence, insulation effect of glass can be neglected. Therefore, the total thermal resistance R can be calculated from known convection coefficients h ($\mathrm{W/m^2\,K}$) for the air cavity between glasses (h_g) and the air cavity between the upper glass and the curtain (h_c) as $R = 1/h_g + 1/h_c$, according to this model of resistances in series. Radiation and convective resistances in parallel will be omitted here, since low-emissivity coatings can be applied to minimize radiant losses.

4.1. Summer case

In this case the heating is provided from the top plate, minimizing convective force (Incropera and DeWitt, 2007). The heat transfer is driven only by conduction through two air layers, and convection coefficients can be calculated as the quotient between the gap thickness, t, and the air conductivity, k, being $R = k/t_g + k/t_c$. Hence, the heat transfer can be minimized by setting both air gaps as thick as possible. It should seem to be a good choice, but we must keep in mind that actually an opposite behavior is

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performed during winter conditions, in which the heating plate is at bottom. A good design can be achieved to satisfy both configurations by choosing the optimal t_g for the winter case (0.01 m), and a conveniently large t_c (0.2 m) for the summer case.

Our first concern is the over heating of the cold water chamber (#3) considering it remains on the roof during the diurnal cycle and only two air cavities separate it from the outdoor hot ambient. In this case we obtain $R = 8.0\ \mathrm{m}^2\ \mathrm{K/W}$, equivalent to a global transfer coefficient $U = 1/R = 0.125\ \mathrm{W/m}^2\ \mathrm{K}$. Hence, the heat power from the environment, Q_{ce}, can be calculated for a given outdoor (T_o) and water (T_w) temperatures, as:

$$Q_{ce} = AU(T_o - T_w) \tag{4}$$

For example, integrating the energy loss during a 24-h cycle for $T_o = 36\ °\mathrm{C}$ and $T_w = 16\ °\mathrm{C}$, a total 6 kWh is obtained. Thus, using Eq. (3) to calculate the water temperature increase, a modest increase of 1.0 °C is reached for the 5000 l inventory.

On the other hand, the cooling power provided to the indoor ambient at T_i can be estimated using the proper correlation for the free convection configuration (bottom side of a cold plate) in turbulent flow, reflected by Eq. (5) (Incropera and DeWitt, 2007):

$$Nu_L = 0.15 Ra_L^{1/3} \quad \text{if } 10^7 < Ra_L < 10^{11} \tag{5}$$

where Nu_L and Ra_L are the non-dimensional Nusselt and Rayleigh numbers of the flow respectively, being $Ra_L = g\beta\Delta T L^3/(\alpha\sigma)$, where α, σ, β and ρ are respectively: the thermal diffusivity ($=k/\rho \cdot c$), the kinetic viscosity, the compressibility module and the density of the ambient air, L is the characteristic length of the cooling plate (fixed in 3 m) and $\Delta T = T_i - T_w$. From Eq. (5), the convection coefficient to the indoor ambient h_i can be calculated as:

$$h_i = Nu_L k/L \tag{6}$$

Hence, the space cooling power to the indoor ambient, Q_{ci} can be estimated as:

$$Q_{ci} = Ah_i(T_i - T_w) \tag{7}$$

Thus, the water temperature increase during the diurnal cycle, ΔT_{ci}, can be calculated from Eq. (3), using the total heat power on the water inventory: $Q_{ci} + Q_{ce}$.

On the other hand the nocturnal cycle is used for cooling the water by vaporization and by infrared losses to sky. The infrared loss power Q_{il} is function of the equivalent sky temperature T_{sky}, which falls in the 230–285 K range according to the environmental conditions (Incropera and DeWitt, 2007), being Q_{il}:

$$Q_{il} = A\phi(\varepsilon T_w^4 - T_{sky}^4) \tag{8}$$

where $\varepsilon = 0.97$ is the total emissivity of water at 300 K and φ is the Stefan–Boltzmann constant ($=5.67 \times 10^{-8}\ \mathrm{W/K^4\ m^2}$). Taking a fixed value of 250 K for T_{sky} and neglected the heat loosed by water vaporization (in a conservative approximation), the Q_{il} power can be estimated for a given T_w, and so, the water temperature decreasing during the nocturnal 12-h cycle, ΔT_{cd}, can be calculated from the water energy balance, Eq. (3). The water will be heating and cooling following the daily cycle, according with a periodical stationary process in which:

$$\Delta T_{ci} = \Delta T_{cd} \tag{9}$$

From a given set of ambient temperatures (T_o,T_i) and other problem parameters, the set of Eqs. (3)–(9) allows us to estimated the average water temperature, and the average space cooling power provided to the household. For example, for $T_o = 40\ °\mathrm{C}$, $T_i = 25\ °\mathrm{C}$, a 18 h of cooling cycle and a 8 h of radiant losses cycle (both cycles can be superposed if we used simultaneously both water chambers during night), an average $T_w = 11\ °\mathrm{C}$ is obtained and thus, the average cooling power is 6 kW for this 100 m^2 ceiling. This could be enough to satisfy the total cooling demand of an average house, considering that solar radiation will also be blocked.

4.2. Winter case

A similar reasoning can be performed for winter. In this case, we heating the indoor by free convection from a top plate, and so, Eq. (5) must be substituted by the proper correlation:

$$Nu_L = 0.27 Ra_L^{1/4} \quad \text{if } 10^5 < Ra_L < 10^{11} \tag{10}$$

Hence, calculating the right Rayleigh number, the actual h_i and the convective heating power Q_{hi} can be calculated again by Eq. (6) and (7) similarly to the summer case. But now, the infrared heating must be included, especially if high emissivity paints are chosen for the ceiling. The radiation heating power can be calculated again by using Eq. (8), substituted T_{sky} now by T_i. This heating can be very large if the water temperature is very hot, causing discomfort. This was a major disadvantage of fixed water ponds, as the Skytherm, with little control of radiation. For example, for a water temperature of 70 °C, this power can reach up to 35 kW on a 100 m^2 ceiling. Of course, in this case the heat losses to the environment will be very noticeable too, and hence, the system efficiency will be lower. Calculating the losses from the water chamber to the environment by using proper correlations similarly to the summer case, a value of $U = 1.65\ \mathrm{W/m}^2\ \mathrm{K}$ is obtained for $T_w = 70\ °\mathrm{C}$. This high value causes very noticeable losses of heat (8.3 kW). Instead of using a thick insulation layer in order to minimize losses, our design uses a standard infloor water heating or water radiator system to provide household heating in a more convenient way. In addition, when the water temperature is too low to satisfy the heating demand on these standard heating systems, we can choose the roof heating mode (pumping the water onto the roof), making useful its huge surface. For example, for $T_w = 40\ °\mathrm{C}$, $T_i = 22\ °\mathrm{C}$ and $T_o = 0\ °\mathrm{C}$, we can obtain convective and infrared heating powers of 2 kW and 11.5 kW respectively, and lower heat losses (5.0 kW) than the previous case, reflecting the

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minor temperature jump and *U*-value (1.25 W/m^2 K). So, the water temperature only decreases 0.9 °C/h due to losses, against 2 °C on the previous case. Besides, by duplicating the thin double-glass cavity (for example, using many inner layers of Mylar) the total losses can be noticeably reduced. The addition of just one more transparent layer allows us to obtain a roof with $U = 0.78$ W/m^2 K, or 0.58 W/m^2 K by adding two layers. Indeed, this new roof does not need to equal the very good insulation of traditional roofs ($U \cong 0.4$ W/m^2 K) in order to provide similar thermal behavior. For example, we can assure that the ceiling temperature remains above the comfort level (20 °C) by pumping a very thin water layer onto the metallic roof. In this case, we obtain a third air chamber that improves the insulation capacity of the roof (the *U* factor decreases to 0.75 W/m^2 K for the original double-glass configuration, and it decreases to 0.45 W/m^2 K by adding the double Mylar layer). We can calculate the water inventory that needs to be pumped for assuring the ceiling temperature above 20 °C. For a case with: $U = 0.75$ W/m^2 K, $T_o = 0$ °C and $T_i = 20$ °C, the heat loss to the environment is 1.5 kW, and the water flow (from an initial $T_w = 70$ °C) necessary to control the ceiling temperature is only 26 kg/h.

5. Study of costs

Based on actual roofs built in Argentina (with good thermal insulation, $U = 0.4$ W/m^2 K) for a 100 m^2 indoor area, we found costs from 120 to 170 U$D/m^2, including labor on site (3 workers/15 days, 45 U$/m^2). Considering besides an average value of 30° for the roof inclination and a household standard air conditioned system of U$D2000 (or 20 U$/m^2), this conventional option has total specific costs from 160 to 220 U$D/m^2 of living area. On the other hand, the specific cost of the new design is estimated at about U$D200/m^2, taking one third of the construction time (that represents 15 U$/m^2). This estimation includes the cost of a trapezoidal metallic roof like the one previously described (40 U$/m^2) plus a double-glass window of metallic frame with only one low-emissivity coating (80 U$/m^2), and a standard motorized rolling awning (60 U$/m^2). No braces are included, since the metallic roof can provide a self-supporting base, enough to support the whole system. The total cost of the new roof could be reduced to about 150 U$/m^2 if plastic covers were used instead of the glass, as was mentioned previously. Other special pieces (storage tank, piping, microcontroller unit), would add around 5% of the total cost. Costs of standard heating equipment (gas boiler, radiators, and pump) are not considered in this comparison since they must be included in both options. The water proofing of the lower chamber (#3) should be a major concern, as in any solar plate collector, since the perimeter would be very large. But indeed, this issue can be minimized due to the trapezoidal profile of the metallic roof (#1), that provides a continuous rung for the lateral sides (parallel to the sheet length). The waterproofing on both headers (when the long sheets ends) can be appreciably reduced if every sheet is cut about 10 cm deep on both edges of the lower base, cutting a bottom lapel that can be bent upwards to vertical position, in order to build a waterproof boundary. Additionally by making a similar cut in the upper edge of the rung, we can obtain another lapel that can be bent 90° downwards and superposed with the previous lapel, in order to limit the leak problem.

Additionally, the new system could satisfy the household demand of heating and cooling, which represents many thousand dollars per year. Note that the energy consumption in this buildings is about half of the total energy consumed in OECD countries.

6. Comparative analysis between the Skytherm and new design

It is useful to further discuss other features of this design approach, in comparison to the well known Skytherm design. I hope this discussion is stimulating and gives us a wider perspective for future designs to develop within the main concept presented here.

6.1. Ability on power graduation

The Skytherm cannot graduate the thermal power provided to the household (as heating or cooling); for example, if the cooling power become very high during a particular summer day, it cannot be disconnected, total or partially, in order to adapt it to the environmental changes.

On the other hand, this new design is fully capable to graduate the thermal power by modifying the water mass pumped onto the roof, while the rest is kept within the reserve tank.

6.2. Ability to control heat delivery

The Skytherm cannot delay the thermal power provided to the household. This feature would be useful in order to match the maximum heating power to the household maximum demand. Instead, the daily cycle of the thermal power is almost opposite to the demand cycle. The heating power in winter will be maximum at the sunset and minimum at the sunrise, the moment of highest demand. The same mismatched behavior is observed for summer conditions.

On the other hand, this design can tune the heating power according to the demand curve. For example, the storage system could be designed by using many water tanks. The heated water accumulated in each tank could be pumped (or drained) alternatively to the roof during the night, according to the demand curve. In this sense, smart managements could be developed and programmed on a standard microcontroller, (monitoring the environment conditions and every tank's water temperature, etc.) in order to adapt to the variable environmental conditions.

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6.3. Ability of spatial graduation

The Skytherm cannot optimize the thermal power to the variable spatial needs of the household. For example, in winter during midnight and early hours of the day, the heating power can not be focused on the bedroom area. However, there was a proposal for adapting Skytherm using a fan coil connected to the ponds to overcome this limitation (Haggard Kenneth et al., 1978).

In contrast, this new roof is essentially one built with different spatial zones. Every water chamber (#3) is separated from its neighbors by two rungs and can be considered as an individual water collector, which can be independently filled and drained with water. The cost and technical problems relating to this more complex configuration are low; it would need only to add a few controlled on-off valves. Moreover, if the house layout were planned conveniently, we could focus the heating power on the bedrooms, for example. This new feature would be useful for the summer condition too.

6.4. Compromise solution between infrared and convective heating

The Skytherm only provides heating by infrared radiation from roof. This is appropriate for low water temperatures as with the Skytherm, but it could be an uncomfortable way of heating living areas if we want to achieve high water temperatures. Moreover, we are forced to select ceiling surfaces of high emissivity in order to optimize this heating mode. Therefore, and for the summer condition, if the insulated cover cannot keep the water pond cool, we will experience undesirable radiant heating from roof. Since the water pond has to remain on the roof all day, and it is protected against the solar radiation and the hot environment only by the insulation cover, this case could be easily imagined. Thus, we must choose a compromise solution for the ceiling emissivity between the ideal one for winter ($\varepsilon = 1$) and for summer ($\varepsilon = 0$). These opposite conditions force us to build a very special cover, with the highest insulation capability available, in order to guarantee that it works well under both summer and winter conditions.

In this new design we are not forced to choose a ceiling of high emissivity, since winter heating can be performed by using infloor hot water radiation system. Hence, ceilings of lower emissivity are preferable in order to minimize the infrared heating during summers. Indeed, also heating by free convection can be minimized due to the top position of the hot source. In this sense, total heat flux through roof as low as 10 W/m^2 could be achieved. Moreover, from this result, we can modify our design for the summer-day condition. Instead of creating a water pond on the roof all day, we drain all the water from the roof, similar to the winter-night configuration. In this way, an additional air chamber is obtained, and so, a better-insulated roof. Additionally, the cold water inventory could be pumped into the infloor heating system, working now as a cooling system.

The cold water storage will be better preserved in this new configuration, since it is kept under less exigent conditions than on the roof. The ceiling temperature will increase during the day, but it does not introduce appreciable heating loads At the right moment (maybe in the afternoon, at the highest cooling demand), and applying the appropriate spatial pattern, the cold water inventory could be pumped onto the roof, in order to provide an appreciable cooling power by free convection.

6.5. Hot water supply

This new design could provide a simple way to obtain domestic hot water during winter, unlike the Skytherm.

6.6. Mechanical design of the unfoldable cover

As discussed previously, the protective cover of the Skytherm design has a strong thermal requirement. This influences the mechanical design, requiring a more complex and expensive device. In this new design the protective cover can be as simple as a high-reflectivity rolling awning that blocks solar radiation and infrared radiation emitted from the roof. Note that this less restrictive requirement for the awning could encourage exploring some different designs, such as aluminum awnings with controllable (adjustable) fins. This last option provides a very strong awning, suitable for windy locations.

6.7. Ability of water temperature graduation

The Skytherm uses water essentially as a way to provide good thermal inertia, smoothing the high temperature difference between night and day, characteristic of arid regions. The water temperature variation is not controlled. We have demonstrated that this design allows us to set the water temperature (by using the water inventory pumped onto the roof). This feature can be very useful. For exam-

Table 1
Comparison of features for different designs

	Change the standard roof?	Is a cooling device?	Use flowing water?	Spatial graduation?	Power graduation?
Proposed design	Yes	Yes	Yes	Yes	Yes
Skytherm	Yes	Yes	No	No	No
Thomason	No	No	Yes	No	Yes
Cool-Cell	No	Yes	Yes	No	Yes

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ple, a higher water temperature (desirable for hot water production and for indoor water heating systems) could be obtained in winter without high infrared heating, if low-emissivity ceilings are chosen. Moreover, we could provide simultaneously cold and hot water in summer using different roof zones and different tank reservoirs.

Table 1 summarizes the differences between the designs discussed in the paper.

7. Conclusions

An innovative concept of a solar roof that could satisfy the domestic heating and cooling demand is presented. Being a new concept, it will certainly require additional work and analysis in the future. Nevertheless, the vast bibliography available allows us to extrapolate its performance in this first-order study, having a good chance of success in locations with low-latitude to mid-latitude climates, and even in some high-latitude climates if inclined roofs are developed.

Natural cooling from water roofs in low-latitude climates as well as solar heating from Skytherm roofs in mid-latitude climates has already been thoroughly demonstrated. In both cases, success is due to the large areas of roof involved. This key feature is shared with the proposed new roof design. But this new design is much more configurable than that of the Skytherm, as we have already discussed. Hence, it has a chance to succeed at high-latitude as well if inclined roofs are adopted, in which higher solar ray inclination can be balanced with higher roof inclination and with the higher roof surface. Other relatively high-tech and high-investment solutions, like Baer's and Thomason's, can obtain similar success at lower-latitudes, since their higher efficiencies can compensate for their higher specific U\$D/m^2 cost, but, they have difficulty at higher-latitudes.

This innovative design takes advantage of new synergies proposed between the collector and the roof. Its main concept is based on the use of water redistribution to change the roof configuration in a simple and practical manner. In addition, the rolling awning does not require thermal insulation and so mechanical solutions that are simpler and cheaper can be used.

This design could lead to low-cost roofs that also provide passive heating and cooling, even cheaper than conventional roofs. As we have pointed out, the main drawback of large solar collectors is their high cost. This design provides a solution to this problem that could be widely applied.

The option of the horizontal roof is certainly the least efficient from the solar collector point of view, but it provides a cheaper system than inclined roofs. We did not develop this design from the collector point of view; we thought of it as the whole roof system. We have designed following a holistic approach to achieve a new roof paradigm. In this sense, this design is well adapted to a new generation of environmentally friendly buildings.

I believe that the generalized use of the *U*-factor as the main parameter for characterizing thermally the building envelopes reflects the conventional design criterion. The *U*-factor would reflect properly the heat flux across a building surface only under stationary conditions. But Nature lives along cycles: summer and winter, day and night, and so, environmental conditions impose strong cycles on our buildings. Why use a stationary factor as the main thermal parameter? A fixed passive roof can achieve better thermal performance only by means of better thermal insulation; but for new dimensions of configurable design there are many ways to achieve a better thermal performance, as we have demonstrated here.

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