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# The pulsed-flow design: A new low-cost solar collector

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ABSTRACT

A new pulsed-flow design of hose-based solar collector is presented, which uses a long hose connected to district-grid water in the same way that the basic hose design does. But on contrary that this last, here the exit is not connected directly to consumption and instead the hot water flow is controlled by a thermostat that purges the hose to an insulated tank every time it reaches the desired temperature. So, this water-pond collector works close its maximum efficiency along the day and minimizes nocturnal cooling effect, improving noticeably the performance of the original hose design. As was demonstrated by thermal modeling, this new pulsed-flow design could satisfy the domestic demand of sanitary hot water even in high-latitude locations and furthermore, its performance could be noticeably improved by adding a smart microcontroller. The economic analysis shows this design could be highly competitive applied to large hot-water demands and relatively good for single family demands.


## 1. Introduction

It is well known that a small vacuum-tube solar collector can satisfy the family demand of hot water around worldwide. This design is suitable for cold high-latitudes developed countries that represent more than two-thirds of worldwide market. On the other hand the scenario is quite different in developing countries in which prices usually increases markedly due to extra costs like freight, technician's installation and insurances that are all very high in countries with low population density and small solar markets. Certainly in this case there are barriers not solved for the vacuum-tube technology and its complexity. However, recently has been proposed a simple solar collector based on a long hose, intended to solve this challenge by offering a low-cost home-made system [1]. It consists in a single black LDPE hose wrapped by transparent air-packed polyethylene film, which is connected directly between district water grid and consumption, as Fig. 1 illustrates. This way, by choosing a large-diameter long hose a good flow is provided to consumption meanwhile the full water inventory is simultaneously heated within the hose. Despite its simplicity, this collector achieves good diurnal efficiencies according to both, their large solar area and water-pond characteristics. The water pond scheme obtains higher efficiencies relates to conventional natural-convection scheme in which a few liters is overheated into the collecting unit, as it was used by previous designs of water-pond roofs [2–4]. This key behavior will be presented briefly here; a full discussion was previously provided [1].

### 1.1. Thermal analysis of the water-pond solar collector

Thermal efficiency ($\eta$) of any solar collector can be approximated by a linear function:

$$\eta = a0 - a1 \frac{(Tm - Ta)}{I_n} \tag{1}$$

where $a_0$ is the optical efficiency, $a_1$ (W/m$^2$ °C) is the heat-losses coefficient, $I_n$ is the normal flux of solar irradiance (W/m$^2$) and $T_a$ is the ambient temperature. The mean temperature ($T_m$) in a flat collector is the average between the cold inlet ($T_c$) and the hot exit ($T_h$) temperatures, and this difference $\Delta T = T_h - T_c$ easily rises 40 °C during the day since natural convection is the unique driven force on the cooling circuit [5–7]. For illustrative purpose, let us considered a collector working at $\Delta T$ = 40 °C and $T_a$ = 20 °C in which the tank water is heated to 30 °C, and so, $T_c$ = 30 °C. Hence, a set of: $T_h$ = 70 °C, $T_m$ = 50 °C and $T_m$−$T_a$ = 30 °C is obtained. On the other hand, a water-pond collector working on the same condition has: $T_c$=$T_h$=$T_m$ = 30 °C and thus $T_m$−$T_a$ = 10 °C, a third of the previous one. Hence, according to Eq. (1) the efficiency of the water-pond collector is noticeable higher than the flat one of

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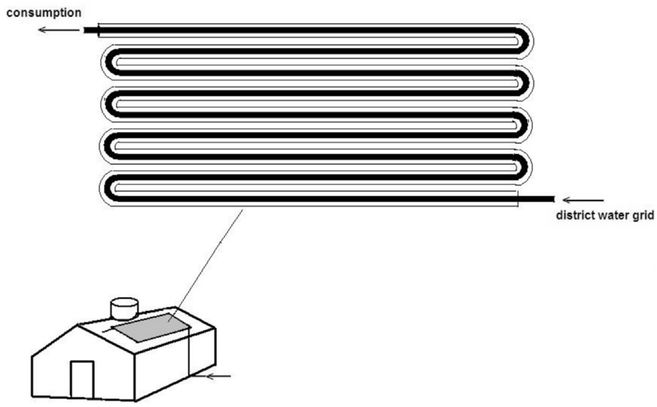


**Fig. 1.** Schematic drawing of the basic hose collector.

similar quality (that is, having same $a_1$ and $a_0$) since its heat losses is a third than the standard collector's ones.

The thermal performance of this hose-based collector working on a temperate maritime-climate location (Buenos Aires, 35° south latitude) was recently studied [8]. It was designed by using new transparent materials as thermal insulation [9–11]. It was observed that a 1.5″ LDPE hose (double-wrapped with double air-packed polyethylene film, being so $a_0 = 0.8$ and $a_1 = 14$ W/m$^2$ °C) could satisfy the diurnal household demand of sanitary water most part of year. This behavior is illustrates in Figs. 2 and 3 showing the daily evolution of the collector's (mounted onto a 30° inclined roof) temperature and efficiency for different seasonal conditions (see Table 1). From here, three clearly different behaviors can be observed:

a) Temperature increases sharply from sunrise to noon, and reaches useful levels at early morning accordingly to high efficiencies obtained during this period, in which they are close to its maximum ($a_0$) value.
b) Temperature barely keeps its level from noon to sunset following a sum-zero process in which small (positive and negative) efficiencies are observed. In this case and on contrary than previous one, the high temperatures reached cause a noticeable decreasing on efficiency.
c) Temperature decreases very sharp during the night. Here, the large area of hose becomes a major disadvantage of this system that works clearly worse than a conventional collector using an isolated tank.

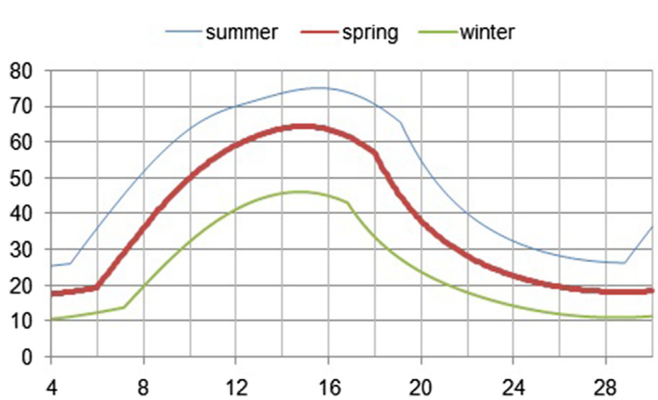


**Fig. 2.** Daily evolution of temperature (°C) on a 1.5″ hose collector during winter, spring and summer cases (see Table 1) for average conditions in Buenos Aires (35°S); time of day (in hours) on the X axis.

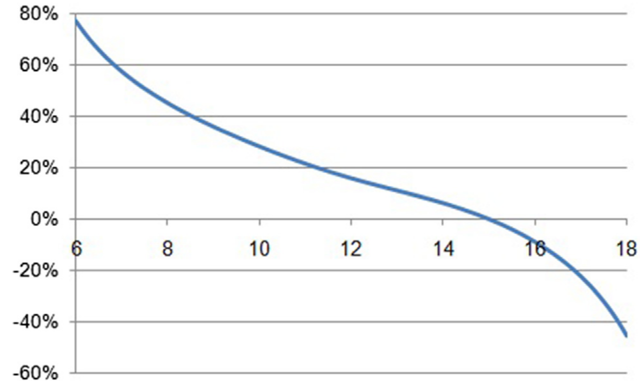


**Fig. 3.** Daily evolution of collector's efficiency (Eq. (1)) for the previous spring case.

**Table 1**
Climatic parameters for Buenos Aires (35°S) [12].

| Date/Season | $G''$ (kWh/m$^2$) | $I_n$ (W/m$^2$) | $T_a$ (°C) |
|---|---|---|---|
| 1st January/Summer | 6.5 | 745 | 30 ± 5 |
| 21 Sept./Spring | 4.5 | 720 | 22 ± 5 |
| 1st July/Winter | 2.0 | 600 | 15 ± 5 |

Summarizing, we can conclude that the water-pond collector works very well during mornings and poorly during afternoon, but decidedly it has bad performance during nights. Furthermore, this system cannot storage any plus of energy absorbed during sunny days in order to be used on next cloudy days, since the energy gained during the day is always losses during night. These behaviors are maybe the reasons why this kind of collectors (extensively proposed by solar enthusiasts) has been ignored for scientists. However and as was proposed recently, this concept can be enhanced by using a “mixed” system assembled with a thinner hose in parallel with a thicker one [8] or by using a very thick vertical tube with reinforced insulation [13]. This way, this collector works reasonable in tropical and templates climates, but not at all in cold high-latitude locations or/and when the nocturnal demand is the predominant one. Indeed, these are unsolved challenges for every low-cost collector, but now we are intending to solve this lack by means of this new pulsed-flow design.

## 2. The pulsed-flow collector

### 2.1. Conceptual design

This new design proposes two major modifications to the basic hose collector:

1) An automatic temperature-controlled on/off valve is added at exit, like a bimetallic thermostat. So, every time the water within hose reaches the desired pre-set temperature (typically between 35 °C and 45 °C), this valve is opened and the hot water flows out the system until the “cold front” from inlet comes to exit. So, the valve is closed and then a new warming cycle begins.
2) The hose exit is connected to a thermally isolated storage tank, working as an intermediate buffer between collector and consumption. On the contrary that on a standard collector working on a free-convection loop, this tank does not need to be mounted outside onto the roof and so, its insulation can be built noticeably cheaper.

This way a pulse-flow system is obtained, in which the district-grid pressure (connected to the hose inlet) pushes the flow out every time the water is enough hot. At that moment the hose is replenished with cold water that remains stagnancy during the warming cycle until it reaches again the desired temperature and another pulsed flow starts. This new configuration (illustrated in Fig. 4) changes noticeably the previous design, regarding three new characteristics:

- First, the collector works close to its highest efficiency along the whole day, similarly to the basic-hose collector does just during early morning. This is a key to improve the solar gain meanwhile keeping a simple construction.
- Second, the hot water is stored into an isolated tank, similarly to conventional collector does. This way, concerns about negative efficiencies suffered during afternoon and nights are avoided.
- Third, the consumption flow is offline from the pulsed flow.

Regarding these novel characteristics, some dimensions of design are opened by this pulsed concept. In the basic design is mandatory to choose large diameters in order to provide together: 1) a low hydraulic restriction to consumption flow; 2) a large storing capacity; 3) better nocturnal performances. However, in the pulsed design is feasible (and recommended) to use thinner hoses, since the hose only is used to provide a high absorption surface/water volume ratio. From the point of view of the solar efficiency this new collector still works as a water-pond collector (and hence, it inherits the major advantage of the basic hose collector), but the three previous requirements are now all supported by the tank. So, let us study now the improvement obtained by the pulse design over the basic hose collector and after that, the enhancement that could be reached by optimizing their new variables of design.

### 2.2. *Performance of the pulsed collector in Buenos Aires (35°S)*

We will study the thermal performance of the pulsed collector by using the same thermal model previously developed for the basic hose collector [1], but considering now that all the water inventory is discharged every time it reaches 40 °C and the fresh water comes into the hose at mean ambient temperature (the new initial condition). The full description of the model was presented before [1] but a summarized version in presented in the Appendix. Firstly, let us consider the same previous 1.5″-hose collector working on its summer case in the template-climate medium-latitude location of Buenos Aires (35°S). Here the temperature evolution (see Fig. 5) shows a noticeably higher performance than the basic system shown in Fig. 2. This pulsed system is able to

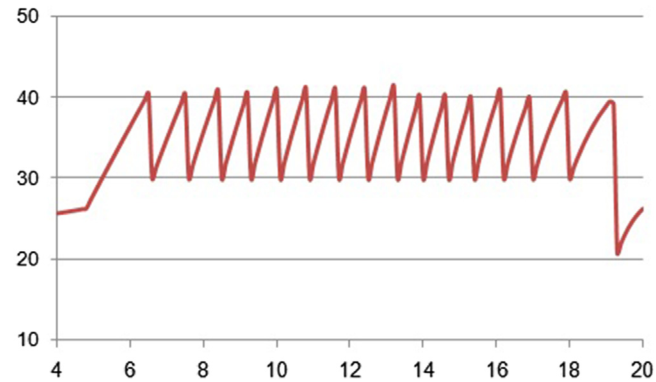


**Fig. 5.** Daily evolution of water temperature (°C) for the previous 1.5″ hose collector, but now water is exchanged every time it reaches 40 °C, for previous summer case. Note that collector is filled in every pulse with fresh water at ambient temperature (30 °C).

regenerate sixteen times the water inventory of the whole hose along the day and therefore, this system supplies a very large amount of water warmed up to 40 °C, (useful for domestic uses) which still remains warm during the whole night. On the contrary, the basic hose configuration (see Fig. 2) could maintain hose hotter than 40°°C for most of the day (from 7am to 10pm on this summer case), but it is then cooled overnight and then, it cannot store hot water for a day another. Despite this well-known drawback of hose collectors that is solved with this new configuration, what is an outstanding improvement achieved by the pulsed-flow configuration is the huge production (sixteen times greater) observed. How it is possible is a key to understand the pulsed-flow concept. So, let us go back to the analysis of the surplus efficiency obtained by the water-pond collector compared to a standard natural-convection flow collector, discussed in section 1.1. Following the example used there, the water-pond collector gets a greater efficiency just because it does not overheat water (into the hose) in order to heat water tank up to 30 °C, and hence, it works always on a lower mean temperature than the standard collector and therefore, on a higher efficiency according to Eq. (1). In the same way and now for the summer case considered here, the hose collector is very efficient to heat water from ambient temperature (30 °C) up to 40 °C along each pulsed cycle, but for example, it has poor efficient for heating water from 60 °C to 70 °C. This behavior is reflected in Fig. 3, since the decreasing of efficiency suffered along the day is due to increasing in the mean temperature (see Fig. 2), as was explained. On this base, we can now understand that the huge (x16)

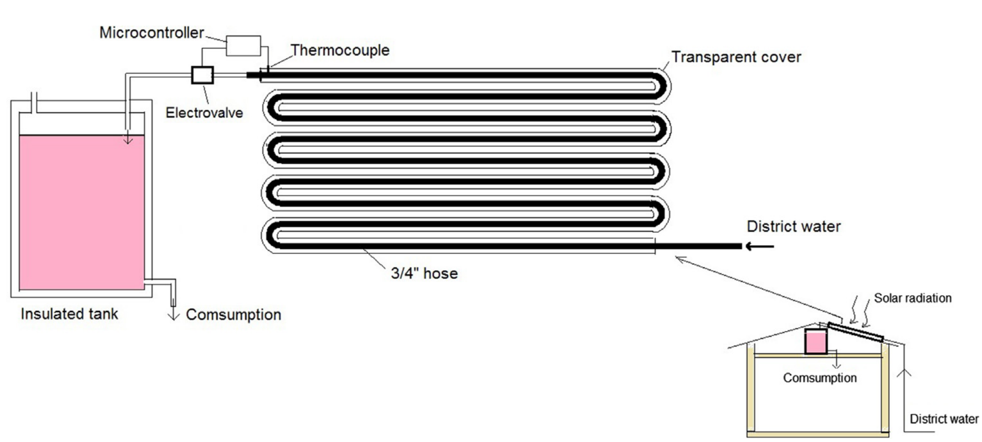


**Fig. 4.** (Above) schematic drawing of the water flow through the pulsed collector and (down) a schematic drawing of the whole system mounted on the house.

production is explained by considering the different efficiencies achieved along the whole day for each case. The pulsed collector starts the day having efficiency of 80% ($=a_0$), and reaches fast (at 7 a.m.) the desired temperature (40 °C) having an average efficiency of 72% during this first pulsed cycle, which mostly remained equal (that is, in every pulse cycle) along the day. On the contrary, the basic hose collector starts the day with the same behavior only up to 7 a.m.; however after that its efficiency is decreased along the day and even worse, it becomes negative during the afternoon, causing an overall efficiency of 14% considering the whole day (from 7 a.m. till 7 p.m.). Let us remark this noticeably improvement was achieved only by changing the controlling logic and not at all the quality of collector itself.

The noticeably improvement found for the pulsed system is repeated also by considering the previous spring and winter cases (obtaining seven and two pulses per day, respectively). Even for this worst (winter) case the pulsed collector duplicates the performance of the basic design and even better, it keeps water around 40 °C along the whole night into the storage tank. This feature is a marked improvement relates to the original system performance (see Fig. 2) that barely reaches a peak of 46 °C at some instant during afternoon, but it is quickly cooled during the night.

Regarding this last trend, since the pulsed design not have to satisfy the consumption flow we can explore the choice of smaller diameters and thus, providing a higher absorption surface/water volume ratio. Table 2 shows the performance of different hoses for the same previous cases. Here it can be observed that smaller the diameter is higher the number of pulses is. Of course, a thinner hose provides less amount of water in each pulse than a thicker one, but this effect could be counterbalanced by using longer hoses, which is feasible taking in account that concerns about hydraulic restriction and nocturnal cooling are avoided.

Let us note the performance during summers is markedly higher than winters, and even it could lead to excessive water production (x33). Hence, it is interesting to study the summer production working on higher temperatures. This trend is considered in Table 3 for the ¾″ hose. As was expected, it is observed that the water production changes noticeably relating to the temperature of pulses and therefore this behavior could be useful to regulate the level of the tank by adding a microcontroller. On the other hand, the opposite effect could be useful during winter (see Table 4); here the water production could be increased by selecting a lower temperature accordingly to the higher efficiencies achieved.

It could be also possible that the customer does not need much water, but the last feature could be further used in cloudy cold days. Fig. 6 compares the evolution of the basic hose and the pulsed (30 °C) hose during a winter day having a half (1.0 kWh/m$^2$/day) of average solar resource. Here is observed that the pulsed collector exchanges three times its water inventory, meanwhile the basic hose barely remains at 30 °C at sunset.

All these behaviors suggest clearly the convenience of using a smart microcontroller in order to gain flexibility and to improve the water production. This choice will be studied in next section, but before let us consider the performance of the pulsed collector working in a cold high-latitude location.

**Table 2**
Number of pulses (40 °C) for different hose diameters on previous cases.

| Hose diameter | Summer (#) | Winter (#) |
|---|---|---|
| 1.5″ | 16 | 2 |
| 1″ | 22 | 3 |
| ¾″ | 26 | 4 |
| ½″ | 33 | 5 |

**Table 3**
Number of daily pulses by using a ¾″ hose according to the selected temperature of pulses for the previous summer case.

| Temp. (°C) | Pulses# |
|---|---|
| 40 | 22 |
| 50 | 13 |
| 60 | 7 |
| 70 | 3 |

**Table 4**
Number of daily pulses by using a ¾″ hose according to the selected temperature of pulses for the previous winter case.

| Temp. (°C) | Pulses (#) | Efficiency (%) |
|---|---|---|
| 40 | 3 | 40 |
| 35 | 6 | 54 |
| 30 | 9 | 63 |

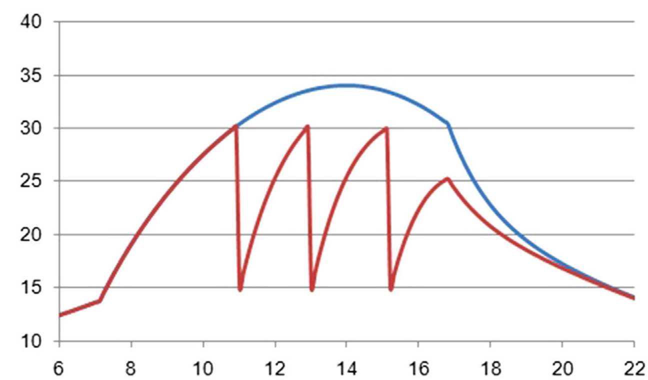


**Fig. 6.** Daily evolution of water temperature (°C) for two ¾″ hoses during a cloudy winter day showing both, the basic hose and the pulsed flow configurations.

### 2.3. *Performance of the pulsed collector in the cold city of Ushuaia (55°S)*

Let us study the performance of this pulsed collector in the Argentinean more southern city of Ushuaia (55°S), which ambient conditions are summarized in Table 5 [12]. According to the previous analysis, we will consider again thin hoses double wrapped with air-packed polyethylene film ($a_0 = 0.8$ and $a_1 = 14$ W/m$^2$ °C) mounted onto step inclined roofs (70° tilt angle) which are usually employed in this snowing location. The performance of these configurations for the winter condition is summarized in Table 6. Regarding the basic ¾″ hose collector, which reaches a peak of 31 °C but quickly decreases to 4 °C at 6 p.m., the pulsed collector obtains outstanding results; it can work as useful pre-heater providing warm water during the whole night. Here is observed again that thinner hoses provide higher performances; of course this trend is common to any hose collector, but the pulsed configuration allows us to decouple the diurnal performance (better for thin hoses) and the nocturnal one (better for thick hoses).

**Table 5**
Climatic average parameters on Ushuaia (55°S) [12].

| Date/Season | $G''$ (kWh/m$^2$) | $I_n$ (W/m$^2$) | $T_a$ (°C) |
|---|---|---|---|
| 1st January/Summer | 5.5 | 580 | 14 ± 8 |
| 1st July/Winter | 0.5 | 530 | −2 ± 4 |

**Table 6**
Number of daily pulses obtained for the winter case (see Table 5) in Ushuaia.

| Diameter | 20 °C | 25 °C | 30 °C | 35 °C |
|---|---|---|---|---|
| ½″ | 6 | 4 | 2 | 0 |
| ¾″ | 4 | 3 | 1 | 0 |

**Table 7**
Number of daily pulses obtained for summer case (see Table 5) in Ushuaia.

| Diameter | 35 °C | 40 °C | 45 °C | 50 °C |
|---|---|---|---|---|
| ½″ | 16 | 11 | 7 | 2 |
| ¾″ | 11 | 8 | 5 | 1 |

On the other hand, the pulsed collector could work on high temperatures (up to 50 °C) during summer average days, as is reflected in Table 7. For example it is outstanding that this simple collector can provide a large 40 °C production in this cold high-latitude location; a 300-m ½″ double-wrapped hose would produce 400 L of enough-hot water per day. However, in cloudy days (having half solar resource) its performance is markedly poorer (see Table 8) suggesting that lower pulsed temperatures are recommended; following the previous example our system would produce in this case, 290 L on 30 °C or 72 L on 35 °C. These results show their high sensitivity relating the pulsed temperature and therefore, suggesting again the convenience of using a smart controlling system in order to improve production any time. On the other hand, the basic ½″ hose works clearly worse that the pulsed design, as is observed in Fig. 7.

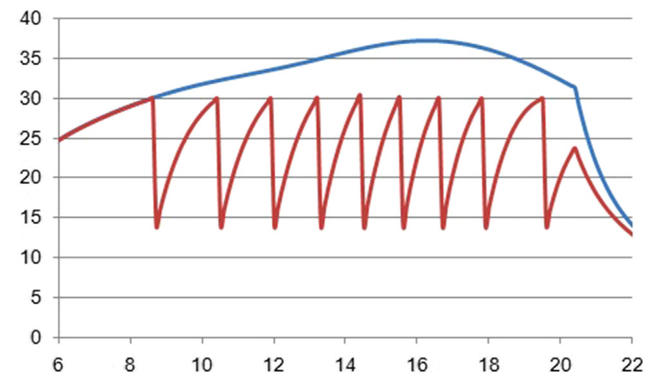


**Fig. 7.** Daily evolution of water temperature (°C) for ½″ hose collectors (basic and pulsed configurations) for a cloudy summer day in Ushuaia.

### 2.4. Designing a smart controlling system

The previous thermal analysis has shown the performance of collector could be noticeably improved by using a smart controller. Of course, to develop a smart system is probably a completely new task considering issues as: weather forecast and special user demands by internet connections, fuzzy logic algorithms that could learn from user's demand pattern, etc., but now in this first work we want to illustrate the way as a microcontroller could solve some special working cases. First, let us checking the input variables that could be monitored from external sensors:

1) Temperature of water at hose exit.
2) Temperature of water at hose inlet.
3) Temperature of water into the tank.
4) Ambient temperature.
5) Water level indicator into the tank.
6) Solar irradiance.

The microcontroller could also be programmed with data of each specific application:

1) Tilt angle of roof.
2) Latitude of location.

In addition, there are other variables that can be calculated by the microcontroller itself:

1) Hour of day.
2) Day of year.
3) Historical records: for example, recording the number and temperature of pulses during last week.
4) Present records: the number and temperature of pulses during the present day.

This list of dozen input variables could be reduced (or enlarged) regarding the degree of complexity intended for the logic of control. Although to fully perform this task is out of scope for this initial work in which we have presented the pulsed design by first time, we shall discuss a simple strategy in order to demonstrate the feasibility of this concept. Firstly, let us note the last half-dozen variables listed are internally calculated by microcontroller, and that combining data from these inputs, the controller could estimate the actual solar irradiance without using properly a solar metering, which is a more complex sensor regarding maintenance and durability concerns. Second, the water level into the tank could be performed by means of a complex continuous sensor, or maybe it could be performed by using some simple on/off sensors (for example, four on/off sensors on: 10%, 30%, 60% and 99% levels). Thus, when water level is lower than 10% the controller should trigger to a “reinforced-production strategy” in which the pulsed temperature ($T_p$) should be minimized; on the contrary as much as the water level increases across intermediate levels the microcontroller should increase $T_p$ and finally, when the water level overpasses 99% level the microcontroller should trigger to a “non-pulses strategy” to prevent tank flooding. Following this scheme, to set $T_p$ within the intermediate range is certainly the most complex algorithm. This selected temperature should take in account many variables; just in a first glance we can guest some ideas:

1) The season: increasing $T_p$ in summer and decreasing in winter.
2) The hour: increasing $T_p$ during morning (when is expected that solar resource is growing) and conversely, decreasing $T_p$ during evenings.
3) The present solar resource: increasing $T_p$ in a shinny day and decreasing $T_p$ in a cloudy day, remembering that this quality could be inferred from historical data.
4) The water level of tank: increasing $T_p$ when this level is low and decreasing $T_p$ when this level is high.

Regarding to water level and volume of the tank, let us note a remarkable and special feature of this pulsed design. In any standard collector we could hypothetically choose any size of tank, but in fact this variable is very linked to the size of the collecting surface. For example, if a too large tank is selected, the water

**Table 8**
Number of daily pulses obtained for summer cloudy days in Ushuaia.

| Diameter | 25 °C | 30 °C | 35 °C | 40 °C |
|---|---|---|---|---|
| ½″ | 17 | 8 | 2 | 0 |
| ¾″ | 12 | 6 | 2 | 0 |

temperature achieved would be too low; in addition the tank size could be conveniently selected for average days, but in this way the water temperature would be penalized in cloudy days. On the contrary, in this pulsed scheme the size of tank is fully independent of the water temperature stored; thus we could select a larger tank in order to gain more flexibility in the operation scheme meanwhile the water temperature is function of the selected $T_p$. This key and novel feature leads us to adopt a smart controller.

*2.4.1. Special designs: summer and winter holidays*

A special case that deserves our attention is on summer's holidays. In this special case can be expected no consumption during a long period such as the tank is full and so, the microcontroller could not use the pulsed flow to limit the hose overheating (which is a simple strategy) and hence, to avoid the risk of material (regarding the fact that LDEP hoses has been proposed) failure. This concern is a serious problem because this collector could be built with better insulation quality and/or be exposed to hottest climates that were studied here, reaching easily temperatures above the point of risk ($\approx 75$ °C) for LDPE. Of course we could build the collector by using materials of better qualities (as HDPE) that could withstand higher temperatures. However, despite the fact this choice is more expensive we want now to show a different solution emerged from the design. Fig. 8 illustrates a recirculation loop (with a small pump) added between the tank and the hose collector, connected with two on/off valves. This auxiliary circuit can be used during holidays in order to interchange the water of hose and tank, every time the hose is extremely hot. Although in this way the temperature of tank would increase day by day, this trend could be counterbalanced by using also nocturnal recirculation and so, using the collector as a cooling device.

This recirculation loop could be useful also for reheating water into the tank. Suppose that we come back home after winter holidays and we find the tank full of template water, not convenient for using directly but warmer than grid water. A simple choice could be to discharge the water tank (a forbidden choice in many developed countries), but instead, the recirculation loop could be used (instead of the pulsed scheme) up to the tank reaches the desirable warm temperature.

## 3. Analysis of engineering and costs

Let us estimate the engineering and total cost of this system applied on the template location of Buenos Aires for: 1) a single family; 2) a large building.

*3.1. Single family application*

We will choose the simplest engineering for this case. Thus, we select a reinforced hose material that can withstand temperature peaks during summer holidays, like HDPE. This way the recirculation loop is eliminated and the number of remote-controlled on/off valves is minimized to one. The cost of this simplest system can be estimated as: a simple microcontroller, 100 U$D; two temperature sensor, 20 U$D; 3 on/off water tank level, 50U$D; a remote-controlled on/off ¾″ valve, 50 U$D, 300 m of ¾″ HDPE hose (80 L per pulse) 90 U$D, a plastic tank of 400 L, 70 USD; thick thermal insulation for tank is estimated around 20U$D considering that is not necessary to use impervious layers when the tank is placed under the roof. According to the previous thermal analysis, this system could provide 240 L@40 °C in average winter days (or 480 L@35 °C) and about 560 L@60 °C in average summer days. This system could really be constructed by end-users by purchasing a kit of special elements (microcontroller, remote-controlled on/off valve, water tank level and temperature sensors) and buying locally the largest elements (hose, tank, insulation materials) reducing noticeably freight costs and having a total cost about 400 dollars. This cost is very competitive regarding this outstanding performance; for example an imported small vacuum-tube collector costs about 800 dollars in Argentina. Moreover, this cost analysis shows that most part of costs are related to fixed units, and therefore we can expect that specific cost (U$D/liter) is reduced on large systems.

*3.2. Large building application*

Let us consider a large building, in which a daily consumption of 50,000 L is demanded. Extrapolating the previous performance (see Table 4), this consumption can be supplied by using 31.500 m of ¾″ hose during winter days (35 °C), the most limiting condition. In this case, the recirculation loop allows us to choose a low-cost LDPE hose, for which the cost is 3500 dollars including a plastic manifold used to split this very long hose in many parallel lines used to reduce the hydraulic restriction. The extra cost related to the recirculation loop (two on/off valves and a small pump) is largely balanced by the saving cost on hose material, since HDPE hoses cost twice that LDPE ones.

The design of the huge tank deserves some special consideration. Firstly, let us remark again the advantage of this system, in which the tank does not need to be installed onto the roof and so, concerns related to mechanic loads over the roof structure can be avoided. Second, this large volume could be provided by two tanks instead of a single one; the complexity introduced is minor and can be counterbalanced by the higher flexibility obtained; for example one tank could be used for keeping a larger water inventory on lower temperature and the other for storing a smaller inventory of hotter water. This configuration is suggested by the great difference in performance obtained regarding to $T_p$.

The total cost of the system is estimated (without tank) in less than 5000 dollars. The cost of tank is dependable of the pattern of using. For example a school with fully diurnal demand would

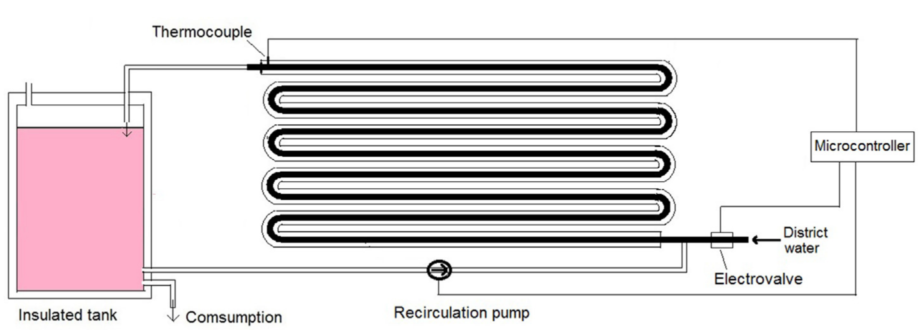


**Fig. 8.** Schematic drawing of the pulsed-flow collector with a recirculation loop.

require the smallest tank meanwhile an apartment building with fully nocturnal demand would require the largest one, costing less than 5000 dollars for a 50,000 L plastic tank. So, the total cost is estimated down 10,000 for the more expensive case, which is very cheap. For example, it could be compared with the application of many vacuum-tube solar collectors, in which we can roughly estimate that a quantity about 400 of small (~2 $m^2$) units (~800 dollars each one) should be used and so, a total cost of 320,000 dollars is expected, that is thirty-two times greater.

Let us note this collector reaches winter temperatures (35 °C–40 °C) suitable to supply also the infloor space heating demand; for this last case the tank size could be reduced noticeably since the large water inventory of the infloor system itself could be used as tank. The very small cost of the hose system suggests to use a larger hose system, in order to supply both (sanitary and space heating) demands. Of course, this possibility is limited by the roof surface available; this 31.500 m ¾″ hose needs (considering a gap of two diameters between contiguous hoses) a minimum of 1.700 $m^2$, which is reasonable for this application.

On the other hand, the performance of this system during summer is very impressive and can be again extrapolated from previous results (see Table 3); it can daily produce 185,000 L at 40 °C or almost 60,000 L at 60 °C. This large spread out in the yield suggests that the two-tank scheme could be a good choice for this case. Moreover, it demonstrates that this large collector could be used to supply other applications like for example, to extend the seasonal operation of a swimming pool or to use on space heating systems by using heat seasonal storage.

## 4. Conclusions

In this paper is presented a new design of low-cost solar collector. It was developed intending to fit the lack of a simple collector suitable for self-installation by end-users, a key for getting success on most developing countries. To achieve simultaneously all these goals, a new thermal-hydraulic paradigm was created on which this collector take advantages of new plastic and tubing technologies. Although the basic hose collector is a well known design, this pulsed-flow design has decidedly brought this concept to a higher level. On the other hand, since the concept of pulsed-flow collector is not a novelty (for example, this is used for heat-pipe collectors), the mixing of a hose water-pond scheme with a pulsed-flow design is an original concept. However, we can appoint three main conceptual differences between both solutions: 1) in the heat-pipe collector the heat is transferred by using a closed loop instead of an open loop, 2) in the heat-pipe collector the recirculation flow it is driven by a pump, not by district-grid pressure, and 3) The heat pipe collector uses the pulsed-flow concept solely for matching the characteristic flow curve of the pump and the heat pipe thermal cycle, meanwhile this new scheme uses the pulsed flow in order to maximize solar collecting efficiency.

This collector can work well on different template and cold climates with medium and high latitude locations, based on their water-pond characteristic and innovative pulsed-flow design. The originality of this collector is conceptual, since it changes the deeply-rooted thermal-hydraulic paradigm of conventional collectors. The improved efficiency of the new pulsed scheme is a key for achieving low-cost collectors but even working well in temperate climates. In this sense, this design starts a new family of very cheap solar collectors that could even work in high-latitude climates.

The cost of this system could be attractive also for single homes, but its strength is found clearly on large applications. Other special features of this concept are their flexibility and modular design, their simplicity, high durability, and its open design and accessible technology, for which this system could be built in almost any place around the world by using locally made materials and simple construction techniques. This way, this new concept could be universally implemented in a short time.

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## Appendix

Let us study the dynamic modeling of a water-pond solar collector in order to determine the daily evolution of temperature and then, the evolution of efficiency according to Eq. (1). Firstly, let us consider the daily evolution of the normal solar flux ($I_n$); for a cylinder whose generatrix has a north-south orientation, its normal surface $S_n$ exposed to sun rays is independent of the azimuthal *(ψ)* solar angle and is only related to the altitude solar angle *(α)* and the roof title angle *(β)* according to:

$$S_n = DLsin(\alpha+\beta)\ ,\ \text{if } \alpha>0(\text{during day}),\ \text{or } S_n = 0 \text{ if } \alpha<0(\text{during night}) \tag{A1}$$

where for any hour *(t)* of a given day *(d)*, the solar altitude at a certain latitude *(Θ)* location having a $\delta$ declination angle can be calculated going through Eqs. (A2–A8):

$$\delta = 23.45sin(360(d-81)/365) \quad \text{for } d=1,2\ldots365 \tag{A2}$$

$$\psi = 360^\circ t/24h - 180^\circ \quad \text{for } 0<t<24\text{h} \tag{A3}$$

$$C_1 = sin(\theta)sin(\delta) \tag{A4}$$

$$C_2 = cos(\theta)cos(\delta) \tag{A5}$$

$$S_1 = C_1 + C_2cos(\psi) \tag{A6}$$

$$S_2 = \sqrt{1-C_1^2} \tag{A7}$$

$$\alpha = arc\ tan(S_1/S_2) \tag{A8}$$

From here we can calculate the "ideal" (on a sunny day) solar power $P_{irrad}$ received in any instant, as:

$$P_{irrad} = S_n I_n \quad \text{if } \alpha>0 \tag{A9}$$

The energy absorbed by the collector and the heat losses are both considered within the efficiency Eq. (1). So, the net power gained in any instant is:

$$P_{net} = P_{irrad}\eta = S_n I_n(a_0 - a_1(T-T_a)/I_n) \tag{A10}$$

Hence, the dynamic energy-balance equation for a hose-based collector can be numerically calculated by approximating the temperature rate by its differential increment ($T_n$–$T_{n-1}$) on the *n-sime* time step *(Δt)* as:

$$mc_p\frac{dT}{dt} \approx mc_p\frac{T_n - T_{n-1}}{\Delta t} = P_{net} \tag{A11}$$

where $m$ and $c_p$ are mass and heat capacity of water, respectively. From here, the temperature of collector in the *n-sime* time step can be derived as:

$$T_n = \frac{S_n a_0 I + DLa_1 T_a + \frac{mc_p T_{n-1}}{\Delta t}}{\frac{mc_p}{\Delta t} + DLa_1} \tag{A12}$$

So, the evolution of temperature can be numerically simulated by using this last equation during the day or modified for night use (by setting $S_n = 0$) and by setting $T = T_a$ during the earliest hours before sunrise. For this study the irradiance flux from the sun reaching the Earth's surface ($I$) is considered as constant along the day despite changes induced by atmospheric conditions, and this constant $I$ value is estimated from average data of the daily total irradiance $G''$ on a level surface, available from local solar maps.

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