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Full thermal-hydraulic and solar modeling to study low-cost solar collectors based on a single long LDPE hose

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ABSTRACT

A comprehensive analysis of low-cost solar collectors based on a single long plastic LDPE hose resting on a roof and working by thermosiphon is performed. This lay-out involves two challenging issues, high hydraulic resistances and low tilt angles, which shall be solved. We have developed a full thermal-hydraulic and thermal-solar modeling to optimize the collector's parameters to achieve a good performance under thermosiphon conditions. This modeling leads to strong coupling effects between the variables, showing that thermal-hydraulic mechanisms are as important as thermal-solar phenomena. We have investigated several cases comprising variation in the collector's parameters: hose diameter and length, tank height and volume, number and quality of glazing layers, roof tilt angle and climatic conditions. It is found that, all year round, this collector can provide 150 l of sanitary hot water at minimum 45 °C in tropical and temperate climates by using a 100-meter 1.5″-diameter LDPE hose, for roofs tilted 20° or more. In addition, for horizontal roofs, the desired goal could be achieved with a 2″-diameter hose instead. On the other hand, the model also shows that using longer hoses and many wrapping layers lead to worse performances, meanwhile to raise the tank causes slight improvements. The proposed modeling, comprising three coupled phenomena, makes possible to design a simple and robust collector that can be locally manufactured using materials available in hardware store. Due to cost and maintenance feasibility, we find that this option could be useful for developing countries with temperate and tropical climates.

1. Introduction

Energy demand for sanitary hot water represents only 15% of the total household energy in developed countries with cold climate, but it increases up to 40% in developing countries with temperate climate [1] and even more in tropical ones. It is quite a paradox that, whereas solar collectors have large and growing markets in developed countries [2], they are almost unknown in many developing countries, which are in more need of energy solutions. This paradox has a correlation regarding its technological evolution.

The modern vacuum-tube solar collector is suitable for cold high-latitude locations since it minimizes heat losses [3]. Nowadays more than 80% of the worldwide market is supplied by Chinese manufactures, reaching final prices of 500 USD, considering installation and freight costs for households in developed countries [4]. On the other hand, the scenario is quite different in developing countries, where final prices paid by users are generally doubled or tripled due to the low scale of market, higher freight and installation costs, which are more relevant in countries with low population density and weak transportation networks [4]. Besides, other concerns discourage the use of commercial solar collectors in these countries:

1. Lack of national regulations that guarantee the collector performance;
2. Lack of trained technicians that guarantee the proper collector's installation and maintenance. Often technicians are found in large cities.
3. Risk of destruction by hail in warm and humid climates. Hail often occurs in vast regions of developing countries.

Extensive regions of underdeveloped countries require finding appropriate technologies that can be locally afforded, due to both costs and maintenance. Carlsson et al. pointed out at this by stating: "To take into account all the relevant factors for materials selection in designing a solar heating system, it would be best to take a holistic view. This would allow for simultaneously considering not only functional quality

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and cost effectiveness, but also reliability, long-term performance, ecological soundness, and recoverability" [5]. Previous works have studied the barriers to implement renewable energy options in rural and underdeveloped areas. For instance, in India, it was found that, in spite of large efforts of various programs based on extensive research, there is low acceptance of renewable energy technologies and a lack of popularity at a grass root level [6]. Barriers related to investment costs and feasibility of government subsidies have been investigated recently for Thailand [7]. Solving energy shortages in populations under poverty requires government and international aids in the form of subsidy's programs. In Mexico, it was found that international financial assistance caused renewable energy projects to be directed to certain regions [8]. In Latin America, the failure of programs has been identified either on the sustainability of the systems [9], and on the influence of users' behavior [10,11]. In addition, engagement of local communities is also a key factor for successfully implementing programs [12].

Therefore, in a context of barriers, performance failures, user's acceptability, dependency on subsidies and financial aids, the case of solar water heaters that can be made with locally available materials and knowledge, is an interesting option to be fully investigated. Certainly, there are barriers for the enlargement of solar markets in developing countries not solved by the vacuum-tube technology and its complexity [4].

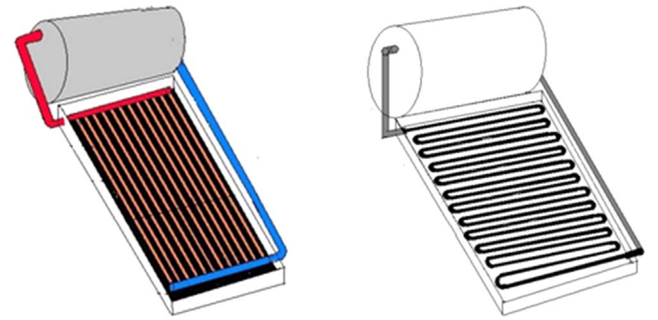
On the other hand the demand for low temperature sanitary hot water (below 45 °C) in temperate and tropical countries is a good niche market for simple low-cost collectors [4]. Within this low temperature range, the efficiency of a simple collector is competitive with high-tech solutions. Our approach to provide a solution consists in:

1. To use a simple design.
2. To use low-cost materials available in local hardware stores.
3. To create a robust reliable device that minimizes operation & maintenance issues.
4. To promote local labor to build the equipment as far as possible.

Operational concerns are related to dilatation of the solar coil due to high temperature thermal expansion, which could lead to dangerous overpressures [2]. Maintenance concerns are related to glazing reposition (for instance due to hail damage) and revision of auxiliary supporting system. Regarding these issues, our goal is to investigate a design for a robust and simple solar collector which could even be homemade.

At first glance, plastic tubes appear as an excellent choice [13,14]; however, the most common grid-type design does not support this choice due to the large number of connectors needed. Instead, a single long LDPE (Low Density Polyethylene) hose is proposed [4,15]. To limit heat losses, the LDPE hose is wrapped in a transparent bubbled plastic which at the same time is the collecting surface, glazing and backside insulation. This design has been traditionally avoided due to thermal-hydraulic concerns related to water recirculation by natural convection (thermosiphon).

To solve this problem we have developed a thermal, hydraulic and solar (THS) model based on numerical explicit equations, which allows optimizing length and diameter of hose, water column height and tilt angle. The model can be performed on a spreadsheet. The coupled energy and momentum equations have been traditionally solved by implicit numerical schemes supported on complex CFD codes (Computer Fluid Dynamic) [16], used as a "black box". On the contrary, in the present method, based on explicit numerical scheme, all variables can be visualized by the user. This modeling leads to interesting coupling effects between the variables, showing that thermal and hydraulic mechanisms are as important as solar phenomena. As far as we know, this is the first time that this kind of tool is used in order to optimize a hose collector working on natural-convection recirculation. A collector based on a single long plastic LDPE hose



a. Schematic drawing of a grid-type flat collector. b. Schematic drawing of a single-hose collector.

Fig. 1. (a) Schematic drawing of a grid-type flat collector. (b) Schematic drawing of a single-hose collector.

resting on a roof and working by thermosiphon has two challenging issues, high hydraulic resistances and low tilt angles, which will be solved by using a THS modeling. We have investigated several cases comprising the collector's parameters: hose diameter and length, tank height and volume, number and quality of glazing layers, roof tilt angle and climatic conditions.

2. Discussion on free-convection solar collectors

Natural convection solar collectors have been traditionally designed from the beginning of solar technology as flat-plate collectors [17]. These are basically an assembly of many parallel short tubes (grid-type), placed on a black plate absorbing solar radiation and connected to an upper tank by a thermosiphon loop (Fig. 1a). The use of many parallel tubes is mandatory for minimizing hydraulic losses, since the difference of densities can barely pump the coolant flow. For example, for a tank placed one meter above the collector and a temperature difference of 30 °C, the buoyancy force gives a pressure difference of just one centimeter of water column. This very low force can barely drive the recirculation flow, which in turn causes this high jump on the collector's temperature and so decreasing the collector's efficiency by increasing heat losses. A detail study and sensitivity analysis of this coupled thermal-hydraulic effect has been traditionally overlooked in the developing of the collector's solar technology.

Often researchers have focused on thermal-solar phenomena related to the collector itself, but neglected thermal-hydraulic phenomena related to the thermosiphon loop. For instance, in a recent review [2] Buker and Riffat have pointed out that: "Thermal performance characteristics of flat solar collectors mainly depend on the transmittance, absorption and conduction of solar energy and good conductivity of the working fluid" and similar conclusions can be found in other reviews [18–20]. In addition, in a recent field study comparing different kind of flat solar collectors [21], the authors have avoided any mention (and further analysis) about the tank height. For instance, if the tank had been raised, the collector's performance would have been improved, as this measure increases the recirculation flow. Furthermore, this effect could not affect similarly to different collectors. In other words, and it will be discussed in detail below, the efficiency is always related to the whole collector, which includes its thermosiphon loop.

The natural-convection grid-type collector is still in much preference for low-cost collectors, but actually leads to strong limitations regarding opportunities created by new plastic materials. One option to take advantage of new materials is to use a long bended hose (Fig. 1b), but this choice does not work within the natural-convection approach due to its higher hydraulic resistance. For instance, a collector based on a 100-meter hose has a hydraulic restriction 10,000 times larger than an array of one hundred one-meter parallel tubes. On the other hand, the grid of several tubes requires numerous sealed fittings that imply major concerns regarding a plastic collector.

Despite great advances in plastic tubing, there are still few options for fittings, which can be classified into three kinds:

1) Barb fittings. These fittings are used with elastic tubing, like LDPE. With variations in temperature it provides a medium-quality fitting. In addition, barb fittings require large space and so it is not suitable for assembling tube grids in a limited space. However, high-quality compression fittings are available but at much higher prices [22] about 10 dollars. So, this choice is feasible within the long hose configuration rather than the grid-type one.
2) Threaded pipe joints. These fittings are used on more rigid materials, like PVC. It provides a good-quality fitting, but considering the grid scheme it implies many overlapping joints (double-threaded joints and change-of-section joints). So, the increase in number of fittings increases the risk of failure, as well as costs.
3) Thermo fusion joints. The HDPE (High Density Polyethylene) pipes can be joined by thermal fusion to form a joint that is as strong as the pipe itself, but its application to the grid layout is too cumbersome since it would require welding simultaneously all parallel tubes to each flow collector.

The use of LDPE hoses, though, presents four interesting advantages:

1. Its high elasticity can withstand dilatations due to thermal dilatation of water inventory, which in turn avoid the need of a pressure control system;
2. It has a high UV and mechanical resistances;
3. There is commercial availability of long hoses and large diameters;
4. It provides a flexible hydraulic path which can be adapted in different shapes to buildings' envelopes.

In addition, we will propose a novel glazing solution, which is based on air-packed bubbles on LDPE film, which is also a good UV-resistance and low-cost solution. Transparent materials traditionally used for solar collectors (mostly polycarbonate) are plastics which have become more rigid by enlarging several orders of magnitudes the molecular size. This process increases noticeably the scattering section that in turns causes solar aging. On the contrary, LDPE films have small-size molecules and present a low scattering section; therefore an inherent high resistance to UV radiation [23].

Due to the aforementioned, the application of plastic tubing to grid-type collectors has strong limitations that blurred their inherent advantages which can be enhanced by changing the collector's design. For instance, a single long LDPE hose could provide a large and cheap solar area (from 5 U$D/m^2), along with a reliable mechanical and cost-effective solution, whilst its hydraulic restriction must be solved on a new thermal-hydraulic paradigm.

3. Background on hose collectors and thermosiphon

Although the general idea of constructing a solar collector based on a single long hose has been extensively adopted by solar enthusiasts, scientific literature is scarce about this issue, which for example is not mentioned in any of the many available reviews [24,25]. In two previous works [26,27], we have proposed the simplest hose-based design, which consist of a single long LDPE hose connected in series to the district water supply. The collector is completed with transparent layers wrapping the hose and simply resting onto the roof (see Fig. 2). This highly-restricted hydraulic configuration was solved by using the district water pressure as driving force, which is much larger (about 1000 times) than the buoyancy force provided by water–temperature difference. This type of collector has shown good performance in tropical climates [27] and moderate performance in temperate locations [28]. However, due to its water-pond configuration (that is, all the water inventory is always kept within the hose mounted onto the roof), it suffers fast cooling during evenings and so, it cannot satisfy nocturnal demands.

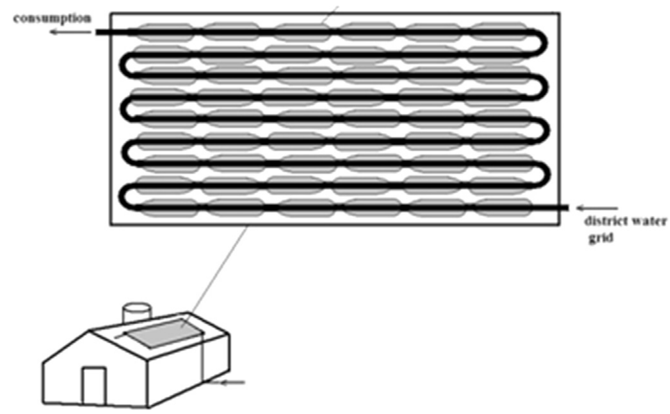


Fig. 2. Schematic drawing of the hose collector (using plastic bottles as glazing).

Thus, in a recent work [4] we have proposed to add a temperature-controlling device to hose collectors for solving its major drawback. On the simplest practical resolution, it consists in a thermostat (regulated about 45 °C) installed on the hose exit so that the water inventory is discharged to an isolated tank. Although this solution moderates nocturnal cooling it has drawbacks during winter in temperate climates due to low water yield and in addition, it could lead to tank flooding during summer.

In the present work, we propose a new approach to solve both the hydraulic resistance and the heat loss during nights. The long single hose is now connected to a traditional upper tank and recirculation is done by a thermosiphon loop. The very low buoyancy force is the challenging task, fulfilled by a thermal-hydraulic and solar modeling performed to obtain a feasible configuration.

The study of the thermosiphon optimization has been overlooked in the literature [29–31]. Although this mechanism have been of course considered within the portfolio of numerical tools used for modeling flat solar collectors, like TRANSYS and other codes [32–34], most studies have been focused on improving the performance of the collector device itself, forgetting that the optimization of the thermosiphon mechanism could improve the collector's performance too. There is a lack of sensitivity analysis on major parameters of thermosiphon, like the water tank height and water mass, and the length and diameter of hydraulic connections, all of which affect the recirculation flow that in turns affects the collector efficiency by means of its working mean temperature. This underestimation of the thermosiphon phenomenon has a correlation regarding most experimental studies. For instance, the flow is commonly measured by injecting a dye trace into one main piping section] and estimated an error of ± 30% [21,31]. On the contrary, on these works the temperature measurements have been done with an accuracy of ± 0.05 °C, which represents a relative error of just 0.1%. Since both variables, flow and temperature, are directly proportional to the calculated fraction of solar power absorbed by the collector, and therefore both are major variables for estimating the efficiency curve, their measurements are obtained with a huge difference of accuracy. The discussion of this controversy is out of the scope of this work, but we shall discuss in detail the thermosiphon optimization here.

4. Materials and methods

4.1. Hydraulic modeling

The recirculation flow is determined by balancing buoyancy pressure drop (Δp_b) with the total frictional pressure drop (Δp_f) along the flow path. This is the first closure condition (Eq. (1)), needed for approximating the solution given by the numerical code. The total frictional pressure drop is the sum of concentrated and distributed losses related to mean flow velocity, V, the length (L) and diameter (D) of the hose, and the concentrated (k_c) and frictional (f) coefficients, and it is given by Eq. (2) [35]. A fixed mean density (ρ_O) is assumed following the well known Boussinesq's approximation [35]. The frictional Darcy's coefficient f is related to flow Reynolds number Re (Eq. (3)) where we use constant values of dynamic viscosity (ν_O=0.0008 Ns/m) and density (ρ_O=996 kg/m^3) of water at 30 °C; for laminar (Re < 3000) or turbulent (Re > 3000) flows, it can be estimated by Eqn. 4 [35].

$$\Delta p_b = \Delta p_f \tag{1}$$

$$\Delta p_f = \frac{1}{2}\left(k_c + f\frac{L}{D}\right)\rho_o V^2 \tag{2}$$

$$Re = VD\rho_0/\nu_0 \tag{3}$$

$$f = 64/Re \qquad if\ Re < 3,000 \tag{4a}$$

$$f = 0,316Re^{-1/4} \qquad if\ Re > 3,000 \tag{4b}$$

The k_c value is related to the geometry of restriction. For example, considering a 100-m hose mounted on a roof of a 10 m slope which is bent with a normal radius curve (k_c=3) along roof edges, a total k_c=30 is obtained; since this is much lower than total distributed coefficient (k_f=$f\ L/D$) in all cases, we will set this value.

The recirculation mass flow (m') is related to the mean flow velocity and hydraulic section of the hose by Eq. (5):

$$m' = \rho_0\ V(\pi D^2/4) \tag{5}$$

For a given m' and ρ_O, the frictional term Δp_f can be calculated going through Eqs. 2 to 5. On the other hand, the buoyancy term Δp_b is caused by the difference in water densities between the cold (T_c) and hot (T_h) temperatures, the average height between collector and water tank level (Δh), and the Earth´s gravity constant (g), by Eq. (6).

$$\Delta p_b = [\rho(T)_c - \rho(T)h]\Delta h\ \ g \tag{6}$$

Hence, by using the well-known engineering correlation given in Eq. (7) [35], the buoyancy term can be calculated from a given (T_c, T_h) pair. Meanwhile T_c is always equal to the bulk temperature of tank (T_k) and can be considered as a given parameter by now, T_h, or more properly the collector's gradient (T_h–T_c), is related to the balance of energy of collector and thus, it must be derived from the thermal model described in next section.

$$\rho[kg/m^3] = 1000*(1 - (T + 288.9414)/(508929.2*(T + 68.12963)) *(T - 3.9863)^2),\ T\ in\ °C \tag{7}$$

4.2. Thermal modeling

In the thermal model the mass flow m', the hot temperature T_h, and the collector's efficiency will be calculated for a given pair (I_n, T_k), where I_n is the normal irradiance flux [W/m^2]. In Section 3.3 (solar model) the actual I_n flux along the day will be obtained. Then, the evolution of the temperature T_k along the day is obtained by the energy balance in the water tank.

The thermal efficiency (μ) for any solar collector can be defined as:

$$\mu = a_0 - a_1(T_m - T_a)/I_n \tag{8}$$

where a_O is the "optical" efficiency obtained for non-heat-losses condition, T_m is the mean collector's temperature (Eq. (9)), T_a is the external ambient temperature, a_1 [W/m^2°C] is the collector's coefficient of total heat losses.

$$T_m = (T_h + T_c)/2 \tag{9}$$

For a given pair of climatic conditions (I_n, T_a), the efficiency is a function of T_m, which in turn is related to T_h for a given T_c=T_k. On the other hand, the collector´s gradient (T_h-T_c) is related to the collector's energy balance given by Eq. (10), in which the net solar energy absorbed is balanced by the energy transferred to the cooling circuit, which is a function of the mass flow and the collector´s gradient.

$$I_n S_n \mu = m' c_{p0}(T_h - T_c) \tag{10}$$

Where S_n is the normal solar surface projected to sun's rays and c_{pO} is the heat capacity of water, assumed as constant.

The coupling between momentum and energy equations is described by this nested logic. By using two closure conditions an explicit numerical scheme can be solved. Thus, for a given set of collector´s parameters (D, L, Δh, a_O, a_1) and climatic conditions (T_a, T_k =T_c, I_n), we start by an initial pair of values (m', μ). An initial Δp_f is calculated going through Eqs. (2) to (5) and then an initial T_h is calculated from Eq. (10). Hence, an initial buoyancy term Δp_b is calculated from Eqs. (6) and (7), and m' is iterated until the first closure condition (Eq. (1)) is reached. After that, a new μ is calculated from Eqs. (8) and (9), and it is substituted on the previous value (related to Eq. (10)), creating a secondary iterative process until both efficiencies become equal. The whole process ends when both closure conditions are simultaneously achieved.

4.3. Solar modeling

For a cylinder with axis oriented north-south, the projected normal surface S_n is independent of the azimuthal solar angle and is related to the altitudinal solar angle *(α)* and to the roof tilt angle *(β)* (Eq. (11)). For any hour *(t)* of a given day *(d),* the solar altitude at a certain latitude (θ) location having a δ declination angle can be calculated going through Eqs. (12) to (18):

$$S_n = D\ L\ sin(\alpha + \beta),\ if\ \alpha > 0(day),\ or\ S_n = 0\ if\ \alpha < 0(night) \tag{11}$$

$$\delta = 23.45\ sin(360(d - 81)/365)\ for\ d = 1, 2\ldots365 \tag{12}$$

$$\psi = 360°t/24h{-}180° \quad for\ 0 < t < 24h \tag{13}$$

$$C_1 = sin\ (q)\ sin\ (\delta) \tag{14}$$

$$C_2 = cos(q)cos(\delta) \tag{15}$$

$$S_1 = C_1 + C_2 cos\ (\psi) \tag{16}$$

$$S_2 = \sqrt{1 - C_1^2} \tag{17}$$

$$\alpha = arc\ tan\ (S_1/S_2) \tag{18}$$

From here, and by using the obtained S_n value (Eq. (11)), the Eq. (10) can be rewritten as:

$$I\ S_n\mu = m' c_p(T_h - T_c) \tag{19}$$

Where I is the total solar irradiance (not only its normal component) assumed as constant along the day. This assumption is very good on an "ideal shiny" day and worse in cloudy days. However, this helps us to estimate$I$values from average statistical data of daily total irradiance G'' on ground level surface, which are commonly available from solar maps. Therefore, this assumption is reasonable for the purpose intended here, which is to define a realistic average curve of solar irradiance along the day. From here, the balance of energy in the water tank (assumed as ideally insulated) allow us to calculate the evolution of its temperature along the day starting with an initial condition (*i.e.*, *$T_k(0)$=T_a*), according to:

$$M_k c_p \frac{T_{k,n+1} - T_{k,n}}{\Delta t} \approx M_k\ c_p \frac{dT_k}{dt} = m' c_p(T_h - T_c) = IS_n\mu \tag{20}$$

Where M_k is the mass of water stored in tank, and the temporal variation of the tank temperature dT_k/dt is numerically approximated by using a large time step (~1 h) so that the whole process not be a large time-consuming task, but it still provides good results for this sensitivity study. Following this explicit one-step numerical scheme, the tank temperature on the *n+1* time step ($T_{k,n+1}$) is calculated from its known value on the *n* time step ($T_{k,n}$) and two magnitudes (I, S_n) known in the present *(n+1)* time step that are calculated by using this model. To be more realistic a daily evolution of T_a is used, defined by a cosine function with their mean value ($T_{a,m}$) and variation (ΔT_a), and having a peak at 3 p.m., by:

$$T_a(t) = T_{a,m} + \Delta T_a \cos(\pi(t-15)/12) \tag{21}$$

The Eqs. (1)–(21) comprise a fully thermal-hydraulic and solar modeling of solar collectors. As we shall see, this is useful for performing sensitivity analysis on many parameters, for instance sizing, L, D, M_k; layout, β, Δh; climatic, I, T_a; latitude; date; and collector´s quality, a_O, a_1.

5. Results and discussion

5.1. Preliminary analysis of natural-convection hose collectors

Let us considered the natural-convection hose collector illustrates in Fig. 1b, mounted onto the roof as in Fig. 2. It is assembled by a 100-meter black LDPE hose double wrapped by air-packed polyethylene film, for which their collector's parameters as it have been previously determined: a_O=0.8 and a_1=14 W/m^2°C [4,15]. For a temperate-climate location like Buenos Aires (35°S) whose climatic parameters are summarized in Table 1 [36], this system is intended for providing hot water for sanitary demands (up to 45 °C) along the whole year mounted on common roofs or vertical walls. This objective would be a great goal, considering this very cheap collector could be home-made assembled, but it would provide nocturnal demands too.

Firstly, let us use the partial thermal-hydraulic (TH) model on a simple hose collector mounted onto an average roof (L=100 m, Δh=1 m) to perform a sensitivity analysis regarding three main parameters: (1) D; (2) $\Delta T_{ak}=T_a-T_k$; (3) I_n, which results are summarized in Tables 2–4. This preliminary analysis (valid for a given instantaneous condition) is independent of the solar model, but by fixing I_n these results comprise different sets of: β, latitude, hour, seasonal (d, t) and weather conditions (T_a). Besides, in this way ΔT_{ak} is the only parameter of temperature involved and this preliminary analysis is also independent of M_k. So, this simpler model comprises many different cases in a few parameters, and so it is useful for a preliminary analysis in order to realize the coupling effects between different parameters.

From here, several behaviors are observed:

1) The reduction on efficiency is proportional to the diameter reduction; by changing D from 1" to 1/2" the efficiency is reduced to half. This reduction in D causes that mass flow is reduced eight times and therefore the collector's temperature jump (T_h-T_c) is doubled, which in turn causes efficiency reduction, according to Eq. (10). So, the collector's performance is very sensitive to variation of D.
2) The reduction on efficiency is approximately proportional to I_n reduction. By reducing I_n 30% (700 W/m^2 to 500 W/m^2) the efficiency is reduced between 25% and 38%. Hence, and according to the increase of the tank temperature T_k along the day and the common curve of I_n (showing a peak at noon), we can expect two different behaviors:
   a. <u>During the morning:</u> both, I_n and T_k are increased. Both effects are opposite and therefore the collector roughly keeps its efficiency. For example for a 1″ hose, going from 500 W/m^2@10–700 W/m^2@20 °C the efficiency varies from 29.7% to 24.4%.
   b. <u>During the afternoon</u>: I_n is reduced and T_k is increased. Both effects diminish the collector's performance and so, the efficiency drops quickly to zero. For the same example, going from 700 W/m^2@20–600 W/m^2@30 °C the efficiency dramatically drops from 24.4% to 3.7%. Thus, the collector cannot take almost anything of solar energy received during afternoon. Regarding the winter condition (T_a=15 °C) an increase ΔT_{ak} of 30 °C should be necessary to get enough hot water and thus, if this

Table 1
Climatic parameters considered for Buenos Aires (35°S).

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

Table 2
Partial TH model results for ΔT_{ak} =10 °C.

D	Flow (liters/min)	T_h-T_c (°C)	Efficiency (%)
for I_n=700 W/m^2			
1″	0.505	21.2	38.8
¾"	0.237	28.5	31.5
½"	0.074	40.4	19.6
for I_n=600 W/m^2			
1″	0.439	18.7	34.8
¾"	0.202	25.0	27.7
½"	0.061	34.7	16.2
for I_n=500 W/m^2			
1″	0.367	15.9	29.7
¾"	0.165	21.0	22.6
½"	0.0475	28.3	12.3

Table 3
Partial TH model results for ΔT_{ak} =20 °C.

D	Flow (liters/min)	T_h-T_c (°C)	Efficiency (%)
for I_n=700 W/m^2			
1″	0.429	15.7	24.4
¾"	0.194	21.0	19.0
½"	0.057	29.0	10.8
for I_n=600 W/m^2			
1″	0.344	12.7	18.5
¾"	0.151	13.8	13.8
½"	0.042	7.2	7.2
for I_n=500 W/m^2			
1″	0.242	9.1	11.2
¾"	0.101	11.6	7.7
½"	0.026	14.6	3.5

Table 4
Partial TH model results for ΔT_{ak}=30 °C.

D	Flow (liters/min)	T_h-T_c (°C)	Efficiency (%)
for I_n=700 W/m^2			
1″	0.297	9.7	10.4
¾"	0.126	12.5	7.4
½"	0.034	16.3	3.7
for I_n=600 W/m^2			
1″	0.163	5.4	3.7
¾"	0.064	6.6	2.3
½"	0.015	7.7	0.9
for I_n=500 W/m^2→No solution			

Table 5
Sensitivity analysis of Δh and D for ΔT_{ak}=20 °C, I_n=700 W/m^2.

D	Δh (m)	Flow (liters/min)	T_h–T_c (°C)	Efficiency (%)
1″	1	0.43	15.7	24.4
1″	10	1.45	6.4	33.6
1.5″	1	1.21	9.9	30.0
1.5″	10	3.62	3.6	36.0

goal cannot be achieved at noon, it hardly will be obtained during afternoon.

3) The efficiency is strongly inversed to ΔT_{ak}. By doubling ΔT_{ak} from 10 °C to 20 °C the efficiency is reduced about to half; but, when higher (30 °C) ΔT_{ak} are needed the efficiency is reduced to almost zero. This behavior is characteristic of low-quality collectors (that is, having large a_1 values), and so we will reduce the a_1 value as a manner to reach higher temperatures. This can be obtained by putting more layers of glazing around the hose or by using different plastic materials, as we shall see.

Regarding the previous results, the use of larger hose diameters is strongly recommended to enhance natural-convection mechanisms and so, we will consider larger hose diameters, and besides we consider the sensitivity of column height *(Δh)*, which it is the only way to increase the buoyancy force (that in turns increases mass flow and so, reduces the collector´s working temperature, a manner to improve efficiency). Tables 5 and 6 show results of both sensitivity analyses. Here, several behaviors can be found:

1) By increasing D over 1″ the efficiency is moderately improved (from 7% to 22%).
2) By increasing Δh the efficiency is appreciably improved. For example, by placing the collector over a vertical wall on a 20-meter-height building (Δh=10 m) the performance is improved 48%. This noticeable improve is obtained by increasing the recirculation flow, which in turns decreases the mean working temperature of collector and therefore, leads to a higher efficiency according to Eq. (10).

5.2. Complete study of natural-convection hose collectors

5.2.1. Results for various roof settings

We study now the daily evolution of the hose collector mounted onto different β tilt angles and seasonal conditions. For a single family application and according to previous results, we set M_k=150 kg and 1.5″–100 m hose double wrapped by air-packed polyethylene film (a_O=0.8, a_1=14 W/m^2°C). Let us study both, the most favorable (summer) and unfavorable (winter) conditions, for which four daily curves of I_n (according to *β:* 0°, 20°, 60° and 90°) are illustrates in Figs. 3 and 4 respectively; integrating these curves the calculated daily solar irradiance flux of energy (E_d) is shown in Table 7. Besides their lowest E_d, it is observed that horizontal roof receives a marked peak of irradiance at noon and after decreases sharply along evening, meanwhile the opposite behavior occurs on vertical walls. Thus, the vertical arrangement is most favorable for low-cost solar collectors, in which the T_k and I_n values are key factors related to efficiency and therefore it is desirable to reach higher temperatures in the evening.

Table 6
Idem previous, for ΔT_{ak}=30 °C, I_n=600 W/m^2.

D	Δh (m)	Flow (liters/min)	T_h–T_c (°C)	Efficiency (%)
1″	1	0.16	5.4	3.7
1″	10	0.69	2.5	7.1
1.5″	1	0.53	3.7	5.7
1.5″	10	1.87	1.5	8.2

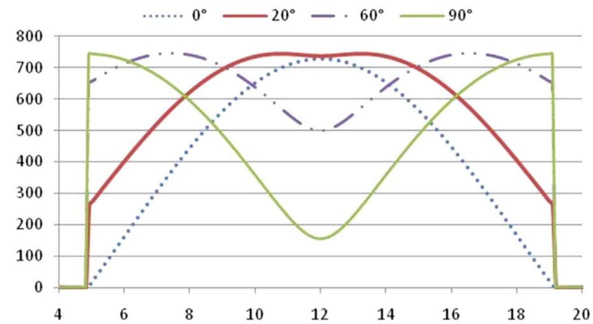


Fig. 3. Daily evolution of I_n (W/m^2) on summer case (Table 1) for different β angles.

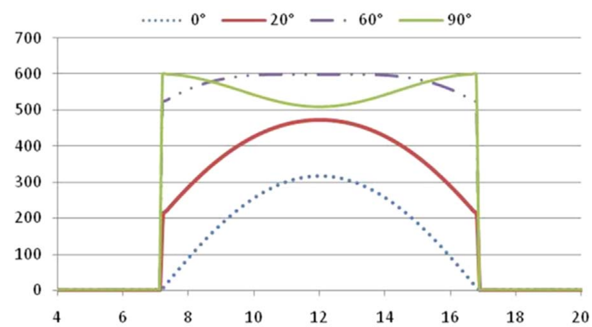


Fig. 4. Daily evolution of I_n (W/m^2) on winter case (Table 1) for different β angles.

Table 7
Total daily irradiance flux (E_d) for summer and winter cases (see Table 1).

β	E_d summer (kWh/m^2)	E_d winter (kWh/m^2)
0°	6.5	2.0
20°	8.6	3.7
60°	9.5	5.7
90°	7.3	5.4

Let us consider three different houses and four cases. For two standard roofs, case A (β=0°) and case B (β=20°) with a short height (Δh=1 m) is considered. On the other hand, higher collectors are considered: case C, for a three-story house by attaching the hose collector (Δh=5 m) to the north wall (β=90°); and case D, (Δh=3.5 m) is considered for a two-story alpine-style cabin attaching the hose collector to the roof (β=60°). Table 8 summarized the final T_k and average efficiency obtained in every case. It is observed that cases C and D can reach the temperature goal all year round, while cases A and B would provide this goal barely half year.

Figs. 5 and 6 illustrate the daily evolution of T_k for summer and winter conditions, respectively. Fig. 5 depicts that roofs having low tilt angles (A and B) show fast heating during the morning (when T_k is cold) and noon (when I_n is maximum), but almost null during the afternoon. On the contrary, cases C and D show high heating during the afternoon but lower at noon. For winter conditions, Fig. 6 shows that

Table 8
Final daily T_k and average efficiencies for summer and winter conditions, M_k=150 kg.

Case-β-Δh	T_k summer (°C)	T_k winter (°C)	μ_{summer}	μ_{winter}
A–0°–1 m	65.0	28.5	28.0%	22.8%
B–20°–1 m	70.0	37.4	24.6%	30.4%
C–60°–3.5 m	71.8	49.2	21.3%	30.4%
D–90°–5 m	66.9	48.2	20.2%	31.0%

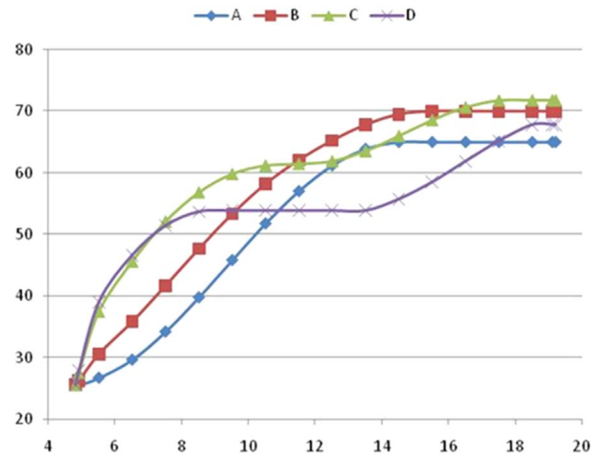


Fig. 5. Daily evolution of T_k in all cases for summer condition.

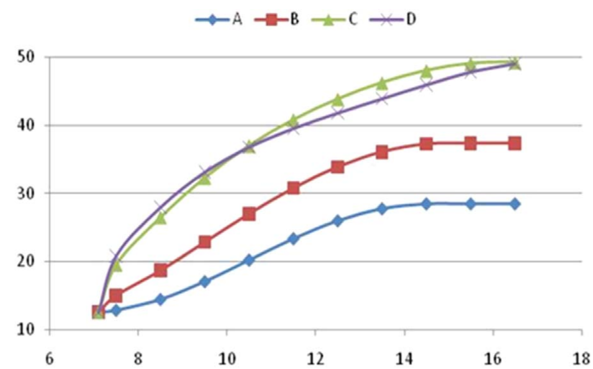


Fig. 6. Daily evolution of T_k in all cases for winter condition.

cases C and D result in steady fast heating during the entire solar day, but it is not the case with cases A and B.

5.2.2. Improving winter performance for collectors on low-tilt roofs

Let us optimize the collector mounted on a low-tilt roof (case B), intending to reach the desired goal in the winter condition previously described in Table 1. We will consider three strategies to improve case B, as follows: B_0, the original case (100 m-1.5″, Δh=1 m); B_1, by using the longest hose available (300 m-1″), which solar area is doubled; B_2, by using the longest hose and increasing the height of the tank (Δh=3.5 m); B_3, the original hose but improving both, Δh=3.5 m and the thermal quality (a_1=10 W/m^2°C), which can be obtained by changing the size of standard air-packed bubbles (10 mm diameter, 3 mm height) on the polyethylene transparent film to a larger one (30 mm diameter, 10 mm height). This plastic with larger air bubbles is used to improve the thermal insulation without reducing the optical (a_O) efficiency. This choice is supported by a recent study [37] showing that the optimal gap in double glazing used on solar collectors is around 10 mm.

Table 9 compares the performance of these options. Case B_1 results in much lower efficiency as a consequence of too high hydraulic resistance, which annuls the initial advantage of doubling the solar

Table 9
Optimization of case B for winter conditions.

Case	T_k (°C)	μ
B_0	37.4	30.4%
B_1	33.3	10.9%
B_2	38.8	14.4%
B_3	45.9	35.5%

Table 10
Optimization of case A for winter conditions.

Case	T_k (°C)	μ
A_0	28.5	22.8%
A_1	36.2	34.0%
A_2	40.2	39.3%
A_3	41.3	42.0%
A_4	39.9	38.7%
A_5	43.3	35.8%

area. Case B_2 improves the performance of B_1 by increasing the tank height, but it is not enough to overcome the drawback of increasing the hydraulic resistance. On the other hand, the improvement applied on transparent glazing in case B_3 causes a noticeable rise in efficiency and in T_k, which reaches the temperature goal. Thus, the basic design of the collector can be improved by generalizing this choice.

5.2.3. Improving winter performance for collectors on horizontal roofs

Let us now study the most challenging (A) case. According to previous results on cases B, we propose now the use of a ticker (2″) hose (case A_1) in order to increase the solar area and the recirculation flow in all cases. Case A_2 considers improving thermal quality (a_1=10 W/m^2°C) by using larger air bubbles as described before. Case A_3 is the same as A_2 but increasing the height of the tank (Δh=3.5 m). Case A_4 considers adding a third wrapping layer of glazing to case A_3, and in this way reducing simultaneously both, a_O (=0.72) and a_1 (=8 W/m^2°C). The last case A_5 is the same as A_2 but reducing the water tank to 120 kg in order to achieve the desired temperature goal.

Table 10 depicts the efficiency and the tank temperature obtained for cases A_0 to A_5. A noticeable effect of increasing the hose diameter and improving the quality of glazing is obtained. The increasing of height (A_3) causes a slight advantage that perhaps could not be justified. In case A_4, the benefit of improving the thermal insulation by adding more wrapping layer is counterbalances by the detriment on the solar transmittance, and therefore this choice does not increase the performance. Case A_5 shows that the only way to reach the desired temperature in to reduce the tank volume.

5.2.4. Relevance of thermal-hydraulic mechanisms

In the last case studied, we have reduced the tank volume to achieve the desired temperature level, following the common strategy of determine the tank volume by considering the most challenging winter condition. Regarding the thermal-hydraulic approach considered in this paper, a strategy useful for improving the collector's performance consists in changing the volume of water in the tank along the year. High temperatures reached during summer are obtained at the expense of poor efficiencies; for example, the collector mounted on roof type C reaches 72 °C during summer with low efficiency (21%), while during winter the efficiency rises to 30.4% for water temperatures around 49 °C. The lower efficiency during summer is directly related to the higher mean collector's temperature, which causes larger heat losses. Hence, it is expected to get better performance if the tank volume would be increased during summer and consequently, reduced during winter. This behavior is not relevant for high quality collectors (like vacuum tube ones) but it is relevant for low-cost collectors, as they are proposed here. This strategy could be easily performed for example, by constructing a double floating inlet line within the tank (one above and another half height) and selecting one of these alternatively, two times a year. A more sophisticated mechanism could be designed by using one on/off inlet valve linked to a microcontroller that senses the temperature and water level into the tank. In this way, the water inventory could be tuned up daily considering the present environmental conditions in order to obtain higher performance.

The thermal-hydraulic parameters of the collector's loop, such as the water mass in the tank and its height relative to the collector, the geometry of hydraulic connections and piping, etc., are seldom considered in order to enhance the collector's performance or even to characterize the whole collector. A possible reason for this trend could be based on the following: the collector's efficiency is fitted by using both, a first parameter (a_O) that determines its optical efficiency, and a second parameter (a_1) that determines its heat losses. Therefore, it is clear that the collector's performance can be enhanced by improving its optical quality and/or its thermal insulation. All thermal-hydraulic parameters affect the efficiency by the recirculation flow, which does cause the temperature jump across the collector and which determines the mean collector's temperature, a key variable regarding the collector's heat losses. The indirect mechanisms for which the thermal-hydraulic parameters of thermoshipon affect the collector's performance (the recirculation flow, the collector's temperature jump and the collector's mean temperature), maybe explain why those input parameters have been traditionally not considered by researches within the portfolio of strategies for improving the collector's performance.

5.2.5. Cost comparison to commercial collectors

Let us compare the cost of the hose collector against a commercial heat-pipe collector in Argentina. The cost of 100-m 1.5″ LDPE hose is 50 USD for the one standing a pressure of 2.5 bar. The transparent air-bubble polyethylene film used for double wrapping glazing adds a cost of 15 USD (0.6 USD/m^2). A standard 200 l plastic water tank costs 60 USD plus 25 dollars more for its thermal insulation (10 cm-thickness, 2 m^2 of polystyrene). The hydraulic connections add 50 dollars, bringing the total cost of materials to 200 dollars. This collector could be made locally and installed by a local technician, taking one day of labor (100 USD), reaching a final cost around 300 USD. This is around half of that for a heat pipe collector installed in developed countries (500 U $D); however, as we has discussed before, the heat pipe collector installed in a rural area of Argentina costs at least 2000 USD. These comparisons illustrate hidden problems leading to barriers in the preferences of commercial solar heat water systems in developing regions. In addition, the advantages of a locally made system extend beyond the cost, and include local maintenance and social appropriation of the technology.

6. Conclusions

A full thermal-hydraulic and thermal-solar modeling applied to natural-convection solar collectors was developed. Although complex CFD codes could be used for this purpose (usually as a “black box”), the present modeling allows to visualize interesting coupling effects between the variables, showing that thermal-hydraulic mechanisms are as important as thermal-solar phenomena.

To demonstrate the relevance of the different phenomena in the functioning of a solar collector, we have investigated a collector based on a single LDPE hose wrapped with bubbled plastic glazing. This configuration avoids difficulties on mechanical assembly with plastic materials; however, it creates challenges regarding the natural-convection mechanism and its high hydraulic resistance, which could be solved by performing a sensitivity analysis on hose diameter and length, tank height and volume, and number and quality of glazing layers.

Although this type of collector has been proposed before, the modeling has proven to be of great value in order to obtain high performance. For instance, it was found that for enlarging the solar area a very long hose is not recommended, while to use larger hose diameters could be a good choice for enlarging both, the solar area and recirculation flow. We have studied the collector set on roofs or walls at different tilt angles, and has shown that the type of collector studied can reach minimum temperatures of 45 °C in a temperate climate all year round. A collector based on a 100-meter 1.5″ LDPE hose and mounted in roofs with tilt angles above 20°, could provide daily at least 150 kg of sanitary hot water all year round. The most challenging condition is a horizontal roof, for which it is found that it could provide daily at least 120 kg of warm water by using a 2″ hose.

All the configurations studied here showed the important fact that thermal-hydraulic mechanisms are as important as thermal-solar phenomena. This characteristic has been usually overlooked for developing solar collectors working on the thermosiphon mechanism. Thus, the modeling and the behaviors found here could be applied to other collector's designs and different climates to optimize working conditions, more so in those cases when solar effects appear to be a limitation.

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