Experiments and simulations on a thermosyphon solar collector with integrated storage

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Abstract. This paper deals with the thermal behaviour of a new type of flat solar collector that integrates the fluid storage tank. Often the main limitation of the solar thermosyphon installations is the prohibition to adopt external storage tanks due to their impact, especially for historical centres of particular architectural significance. To avoid this issue, a new system, that includes the collector and the storage, has been developed. This new apparatus works as a thermosyphon: it is possible to take advantage of the natural convection to avoid using a pump. Experimental tests have been conducted in such a collector with and without the absorbing plate. Furthermore, CFD simulations are reported to analyze in detail the dynamic thermal performance of the innovative solar collector and a good-agreement with the experimental tests has been found. Finally, both in numerical simulations and in experimental data the thermosyphon effect has been verified, obtaining the desired water temperature for domestic applications.

1. Introduction
The solar thermal system is a developed technology that aims at converting the solar radiation into thermal energy available to user. There are numerous designs of solar collector on the market to meet the needs of different locations and areas of applicability, i.e. water and air heating, cooling and electrical power production and so on.

For domestic applications the solar collectors can be, mainly, divided in three groups: forced-circulation, natural convection and integrated collector storage.

The advantage of integrated collector storage solar water heaters (ICSSWHs) is, primarily, an isolated, simple and cheap system with no moving parts, allowing the user to be power grid independent. Furthermore, the collector and the thermal storage are a single unit, so the esthetic impact of the system is reduced as compared to common thermosyphon devices that are prohibited in some particular areas, e.g. old towns, for the presence of the external thermal storage. The ICSSWH configurations are reviewed in detailed by Smyth and coworkers \cite{1} from the first technologies to the recent ones. The main disadvantages, instead, are due to high top heat losses and hot water retention during the night and the not-insolation periods. These performance problems can be limited or overcome with appropriate modifications.

About solar radiation capturing, more systems have been analyzed and optimized from an optical point of view with the concentrating device installation; for example a ICSSWH with compound parabolic concentrator has been studied in detail by Devanarayanan and Kalidas Murugavel \cite{2} when varying geometry of reflectors and number of tanks. A similar study was performed by Tripanagnostopoulos
and Souliotis [3] when varying the position of two tanks inside the solar water heater to analyze its thermal performance.

The key-element of the solar collector is the absorber plate that is designed to maximize the solar radiation absorption with special coating. The absorber plate can be coated with black, semi-selective or selective layer. The selective coating on the absorber plate guarantees a high degree of absorption (>0.95) in the range of ultraviolet and visible region and at the same time a low emissivity factor (<0.1) in the infrared region having low heat losses by radiation to ambient air. A comparison between different coatings has been experimentally analyzed by Del Col et al. [4] for the flat solar collector and Ge and Xie [5] for ICSSWH. In addition, Kumar and Rosen [6] analyzed a ICSSWH corrugated absorber plate to increase the solar radiation collection and improve the heat transfer coefficient. Beside the reflectors application and the treatments on the absorber plate, there are other possibilities to increase the water temperature:

- reducing heat losses by convection (transparent honeycomb layer, Kaushika and Reddy [7] or single/multi glass cover on the top, Kuman and Rosen [8]), by conduction (insulation on the back) and by radiation (type of glass cover and absorber plate);
- choosing the proper ICSSWH geometry, i.e. rectangular size when varying aspect ratios (Henderson et al. [9]), triangular (Kaushik et al. [10]) or trapezoidal one (Smyth and Norton, [1]);
- use of baffles layer inside the ICSSWH.

It is also fundamental to be able to maintain for a long time the water at high temperature inside the ICSSWH avoiding too high heat losses and reversal thermosyphon flow. To retain the fluid temperature at user operating condition the hot water could be withdrawn continuously from the top of the system through constant/intermittent forced flow rate (Kumar and Rosen [6,8]) or through natural one with a ICSSWH geometry subdivided in two parts A and B, exposing part A to solar radiation and well-insulating part B (Kumar and Rosen [11]).

Furthermore, in case of forced flow there has to be a suitable draw-off regime making better use of the water thermal stratification. For this reason, Smyth and co-workers [1] suggest different manifold designs to improve the flow inlet to the ICSSWH.

A lower system efficiency can be due to a reversal thermosyphon flow. This phenomenon takes place when the solar radiation is low or null, i.e. during cloudy sky or night, but it can be prevented by using mechanical devices as reported by Faimal et al. [12].

Another option to maintain a high water temperature is the application of PCM (Phase Change Material) around the thermal storage. Chabaane et al. [13] has performed a comparison between two ICSSWH systems with and without PCM technology. It is worth noting that during the day for the PCM case the water temperature remains almost constant at the maximum value which is nearly equal to the melting temperature of the PCM, allowing a better performance than the sensible heat storage unit.

The objectives of this paper are:

- to verify the natural convection occurring inside the thermosyphon presented here and the achievement of the desired water temperature for domestic applications;
- to analyze in detail the dynamic thermal performance of the innovative solar collector and to validate the CFD simulations with experimental data.

As compared to the past studies, this paper presents an innovative solar thermosyphon which permits:

- to avoid the installation of the external tank;
- to store hot water in the well-insulated side reducing the heat losses to external air and improving thermal stratification;
- to obtain hot water in a compact device with modular configurations, adaptable to the user needs.
2. The new solar panel
A new ICSSWH design is reported in this paper. As compared to the common solar thermosyphon, to compensate the absence of the external tank, the idea is to build a solar collector with the single modular element composed by a small tank, placed below a receiver tube welded to an absorber plate, as shown in figure 1. In this way the big external tank was replaced by a sufficient number of modules in order to satisfy the needs of hot water.

The simple and cheap design of an ICSSWH can be here observed. In fact, the working fluid is tap water and there are not moving parts since the fluid moves under natural convection due to the thermosyphon effect.

This new ICSSWH design allows to heat the water in the receiver tube by the solar radiation and to withdraw the hot water from the receiver tube to the small tank place below it. In this way, the hot water is driven by natural circulation to the small tank where the heat losses are mitigated by a good thermal insulation. This configuration may be similar to that reported by Kumar and Rosen [11].

One disadvantage of the system may be the higher depth (about 6 cm) as compared to traditional solar flat plate collectors, but this aspect should be optimized during industrialization.

During the experimental tests, the section was composed by a single modular element, that was filled with water until the air was completely eliminated. Hereinafter, the experimental tests were performed in no flow conditions, so the device runs as a closed-loop.

In this innovative ICSSWH the tanks are connected directly to the tap water at the inlet and the hot water at the outlet. Hot water is taken directly from the top of the tank, when there is a demand for it, and at the same time the same tank is refilled with cold tap water.

![Figure 1. The design of the new solar thermosyphon.](image1)

![Figure 2. Thermocouples position in the test section.](image2)

3. Experimental data
Three different test sections have been run during the experimental campaign and each one consists of a single solar panel module, properly instrumented. The first two cases were preliminarily tested and then the third one.

The solar irradiance has been simulated through Joule effect by applying an electrical resistance: this allows to carry out indoor tests with simple and fast procedures. In fact, in case of outdoor tests, since the apparatus is exposed directly to solar radiation, the experimental data depend on the climate dynamics, so it becomes fundamental to measure solar radiation and air temperature during the whole test. For the first two tests a cylindrical electric heater of 4 mm diameter and length equal to 1600 mm has been used. This one was applied directly over the receiver pipe, centred along the total length and for its installation the receiver plate has been removed. The receiver tube and the resistance were wrapped with aluminium tape to ensure good thermal contact. The external diameter of the channel is...
8 mm for the first test and 10 mm for the second one. The 10 mm tube was chosen because it is more widely available on the market and therefore cheaper to purchase. For the third test section a heating strip of length equal to 1600 mm has been placed on the absorbent plate using a glue. This configuration, as compared to the one performed for the preliminary tests, ensures a better agreement with the operating conditions of a solar collector. Since the absorber plate is welded on a 10 mm channel, as depicted in figure 1, a conductive paste was used to avoid contact thermal resistances due to air presence between the electrical strip and the absorber plate. With this operation a good thermal contact is guaranteed because the paste will fill the spaces that, otherwise, would be filled by air.

All the test sections were instrumented with six K-type thermocouples (figure 2): S1 at the end of the received tube, S2 about 200 mm from the end of the electrical resistance, S3, S4, S5 respectively at 250 mm from the top, at the centre and at 250 mm from the bottom of the tank and, finally, S6 at the beginning of the received tube. Since all the thermocouples are placed in the fluid, they measure the local water temperature in the point where they are placed, except S2 that is applied on the adsorbed plate. The measurement uncertainty of the K-type thermocouples was ±0.2 °C. The supplied power by the electrical resistance is measured using a power meter LAUGHLIN DMG 700 while the data acquisition system is National Instruments Compact Point File. The measurement uncertainty of the electrical power was ±10 % due to the disturbances in the electrical grid during the experimental tests. The device was insulated with neoprene on any surface to limit heat losses to external air; precisely, the thickness was about 5 mm around the receiver pipe and about 10 mm around the collector tank for the preliminary tests. For the third test section, instead, it has been preferred to insulate only the top of electrical strip and the whole tank with a thickness of 35 mm and of 15 mm respectively. The insulation were made by applying self-adhesive layers of neoprene (thermal conductivity is in the range of 1 ÷ 2.5 W m⁻¹ K⁻¹). In addition, to limit the radiation heat transfer, an aluminium tape has been applied on the last neoprene layer.

It is worth highlighting that, during the experimental test, the top side of absorber plate has been insulated to input the source term avoiding heat losses directly to the ambient; in this way it is possible to know the real source inputted to the solar collector. Furthermore, it has been decided to not insulate the bottom side of absorber plate to work closer to the real performance of the solar panel, where the heat losses to the ambient, primarily, occur through the glass cover. Since the thermosyphonic phenomenon is driven by the natural convection the fluid velocity is very low, i.e. few centimetres per second, for this reason any sensor would affect the measurements and the flow itself, making the data collection very difficult.

The thermal power has been supplied in two different ways. For the first test the heat source has been performed with: an increasing ramp from 0 to 200 W for two hours, a constant value of 200 W for three hours and, finally, a decreasing ramp from 200 to 0 W for two hours. For the second and third test, instead, a constant heating power of 130 W for three hours has been supplied. The first heating power profile has been chosen to study the thermosyphon performance under not-constant supplied power. The second heating power profile has been adopted to analyze the temperature trends inside the solar collector, with a constant power of 800 W m⁻² over the absorber plate.

The experimental data were obtained at varying device tilt angle, precisely, from 15° to 45° for the preliminary tests and 45° for the third one. The solar thermosyphon was filled by water and at the beginning of each test the fluid and device temperature was around 27°C. This experimental apparatus, due to its simplicity, allows to modify its configuration quickly. In fact, it is possible to change the inclination of the circuit and the power supplied to the electrical resistance, simulating different situations: exposure to direct solar radiation during peak hours (power kept constant at a value close to the maximum solar radiation available in Northern Italy latitudes) or the evolution of solar radiation during a typical day, with the characteristic bell-shaped curve of solar power.
4. Experimental results
As depicted in figures 3-5 in all the cases the establishment of natural convection is confirmed. In fact, the temperatures increasing can be observed in time inside the receiver tube, showing that natural circulation causes the water flow and the good operation of the whole system.
Furthermore, it can be confirmed that the average temperature in the collector tank is compatible with the domestic demand of hot water.
From figures 3-4 the effect of collector tilt angle can be evaluated. At higher inclination the temperatures in the upper part of collector, primarily T_S2, T_S1 are lower and the other temperatures, i.e. T_S3 and T_S4, are higher than those at lower inclination. The reason of this behaviour is due to a different buoyancy effect at varying the tilt angle of thermosyphon. Infact, at higher device inclination the buoyancy effect is high and it improves the natural circulation having a better temperature distribution inside the storage tank.
In all the cases it can be noted that although the thermocouple T_S6 is placed near the heated area its value does not increase much in time, because it is more influenced by the cold fluid coming from the collector tank rather than by the conduction on the metal parts of the tube.
From figures 3-4, it can be observed as the temperature trends are strictly influenced by the heating mode. In fact for the first test all the temperatures follow the bell-shaped function of heating power, so three steps occur:
- in the first step the temperatures increase at similar rate of the input power (0-2 h), primarily for T_S1 and T_S due to the short distance from the thermal source;
- in the second step the temperature trends are flatter due a constant heating power (2-5 h);
- finally, when the electrical power decreases the thermocouples records a maximum value, that occurs a different locations inside the thermosyphon, and then the temperatures decrease, except for the T_S6. The temperature trend of T_S6 could be due to a reversal flow of natural circulation inside the device.
In the second and third test the trends are different as compared to the first one except for the third step, where the temperature trend are quite similar. In fact, in figures 4-5 it is worth noting that, at the test beginning, when a constant value of electrical power is supplied, the temperatures increase very rapidly in the first 450 seconds and then the temperature increasing becomes much flatter. This could be due to natural circulation behaviour: when the density gradient between the thermosyphon ends is enough high to improve the flow, i.e. around 450 seconds after the beginning, then the temperature slopes are lower.

Figure 3. Temperatures in the thermosyphon with a 8 mm diameter channel at different tilt angles (Test 1).
Figure 4. Temperatures in the thermosyphon with a 10 mm diameter channel at different tilt angles (Test 2).

Figure 5. Temperatures in the thermosyphon with a 10 mm diameter channel and the absorber plate at 45° of tilt angle (Test 3).

5. Numerical simulations

In this section the comparison between the CFD simulations and the experimental data is reported. The goal of CFD simulations is the detailed description of thermosyphon performance, obtaining the temperature distribution and the velocity field during its operating conditions.

The setting of the CFD simulations is formed by three parts:
- the definition of thermosyphon geometry;
- the setting of the mesh, i.e. type and number of elements, so the mesh refinement;
- the setting of models (i.e. single/multi-phase, turbulence, transient/steady-state…), boundary conditions, materials and solution methods.

The dimensions of the absorber plate were 2037 mm, 106 mm and 1 mm, respectively for the length, the width and the thickness. The material of the absorber plate and the pipe was copper, whereas the material of tank was steel. The external diameter was 8÷10 mm for the pipe and 89 mm for the tank.

Three-dimensional and time-dependent simulations of solar thermosyphon are performed at the same operating condition of test 3. The working fluid is considered incompressible.
To set the thermosyphon effect it is important to apply three conditions to improve the natural convection: a source term (i.e. a constant wall heat flux), a temperature-dependent density of the fluid and the presence of gravity with orientation that depends by the thermosyphon tilt angle. For this reason, all fluid properties (i.e. water) are considered to be temperature-dependent and are interpolated by polynomials computed from NIST Refprop Version 9.0. The initial conditions of simulations are a fluid temperature of 27°C and a mass flow rate equal to zero. Since the convection is natural and not forced the fluid velocity is very low (i.e. centimeters per second), so the fluid flow has been simulated as laminar. The constant value of the heat flux imposed on the absorber plate is 800 W m$^{-2}$.

5.1. Spatial Mesh
The tridimensional domain is discretized into about 4.5 millions of elements. Due to computational efforts and costs two mesh types are chosen and the symmetry condition has been applied. The set up of the mesh is not simple since the domain size is wide. For this reason, in the tank domain the mesh is unstructured and much coarser, while in the copper pipe and absorber plate domains the mesh is structured and much finer, as depicted in figure 6. In this way it is possible to have:
- better accuracy in the zones where the fluid dynamics calculations are more complex;
- computational saving where the fluid properties are almost constant and the fluid dynamics calculations are simpler.
Furthermore, the mesh independence test has been performed. The new mesh was composed by about 5.8 millions of elements. The maximum deviation between the temperature profiles obtained with the two meshes was about 0.5 °C.

5.2. Temporal Mesh
As mentioned above, the simulations are in transient configuration since the phenomenon studied is time-dependent. Each simulation analyzed the thermosyphon performance for a time period equal to 2 hours. The time domain is discretized with two methods:
- for the first ten minutes the time step is five seconds and the results are recorded every minute;
- hereinafter the time step is thirty seconds and the results are recorded every ten minutes.
This procedure is done because the applied heat flux is immediately equal to 800 W m$^{-2}$ and therefore the temperature and velocity profiles of fluid vary rapidly.

Figure 6. A detail of the mesh used for simulations.
5.3. **Boundary Conditions**

During the experimental campaign the most of heat losses occurs at the bottom side of the absorber plate, as described in the previous section, while the upper side is well-insulated with neoprene. So, to evaluate a similar amount of heat losses a heat transfer coefficient of 8 W m\(^{-2}\) K\(^{-1}\) has been applied over the absorber plate to take into account the forced convection with air (i.e. a wind velocity of 1 m s\(^{-1}\)) and the radiation transfer with sky. The air temperature is equal to the initial temperature of the fluid, 27°C.

The heat flux over the absorber plate has been defined as a body source term, i.e. 800 kW m\(^{-3}\), for a volume of 1600 mm x 53 mm x 1 mm (since the symmetry conditions have been applied the width of the volume is equal to the half width of the absorber plate), yielding a heating power of about 130 W. This method has been adopted since in CFD simulations it is not possible to define two different boundary conditions on the same surface.

Furthermore the dimensions used for the body source term are related to the length of the heating resistance, the width (symmetry condition) and the thickness of the absorber plate.

During the experimental tests the solar collector was well-insulating with neoprene, so for numerical simulations the heat losses on the other external surfaces of the thermosyphon are imposed equal to zero (adiabatic boundary).

When the heat losses from the absorber plate to ambient are taken into account, two effects in different periods can be noted:
- in the short term, since the heat flux is not transferred totally to the fluid, the density gradient is lower at the start, and in the first 10 minutes the maximum velocity is lower than that one under completely adiabatic condition;
- in the long term, the heat losses affect on the slope of the temperature profiles.

5.4. **Setting solver**

The commercial CFD code Ansys FLUENT release 14.0 has been used for the unsteady simulations to define the thermosyphonic behavior inside the new apparatus presented here.

An implicit first order time scheme is used to solve the momentum and energy equations and second order upwind schemes are applied for their spatial discretization.

The standard scheme is used for the pressure interpolation, while the pressure-velocity coupling was handled by means of the SIMPLE algorithm. The under-relaxation factors used are the default values presented in the FLUENT code.

6. **Experimental data vs. numerical simulations**

In this section the validation of numerical simulations with experimental data is performed. In figure 7 the temperature trends of both numerical simulations and experimental data using thermocouples readings are reported.

It is worth noting that, at the beginning, the temperature at the end of the copper pipe increases rapidly since it is the nearest to the thermal source term. The heat is applied as a step function at the start of the test, and then the slope of the temperature curve becomes lower and its value is defined by the heat losses to air. In fact, in adiabatic conditions the temperature slope is higher than that one in the simulations presented here, since the heat flux would be completely transferred to the working fluid. A similar trend can be noted for the other temperatures, precisely for T\(_{\text{S3}}\) and T\(_{\text{S4}}\), and it is important note that the rapid increase of temperature occurs at different times with different slope for the different positions of thermocouples in agreement with the experimental data. This behavior of temperature trends highlights the start of natural convection due to buoyancy effects and the presence of a thermal stratification inside the tank, as depicted in figures 7-8.

The different slope of temperature profiles is due to the amount of fluid volume and the fluid velocity in the zone where the thermocouple is placed. In fact, the amount of fluid near the S1 thermocouple (in the copper pipe) is much lower than that one around the S3 thermocouple (at the top of the tank). Furthermore, the fluid velocity in the tank is much lower than that one in the pipe due to the different
external diameter. For these aspects the temperatures in the tank increase more gradually as compared to the temperatures in the pipe. It can be observed that the $T_{S5}$ and the $T_{S6}$ trends are flat, so a time of two hours is not enough to heat the volume of water at the bottom of tank.

**Figure 7.** Comparison between the measured temperatures (Test 3) and numerical simulations.

**Figure 8.** The water temperature distributions obtained by numerical simulations for a tilt angle of 45° and for an external diameter of 10 mm.

The good agreement between numerical simulations and experimental data can be confirmed. Furthermore, it is worth noting that the numerical simulations tend to slightly overpredict the experimental trends. This aspect could be due to different reasons, such as:

- a complex insulation operation of the thermosyphon during the experimental tests due to the short distance between the tank and the copper pipe: this causes more heat losses both from tank and from copper pipe to external;
- difficulties to guarantee a constant heat flux over the absorber plate due to disturbances in the electrical grid during the experimental test;
- a non-optimal thermal contact between the electrical resistance strip and the absorber plate despite of the conductive paste application, so it could create some air bubbles that decrease the local conduction.
Finally, in figure 8 the temperature field inside the thermosyphon is depicted at different times, i.e. at 40, 80 and 120 minutes after the test start. In this figure the thermosyphon phenomenon due to the temperature gradients created in the first moments by the heat sink and the gravity effect can be seen. Over time, this process increases the amount of volume heated and a thermal stratification occurs at top side of the tank.

As depicted in figure 7, the deviations between the experimental temperatures and the numerical ones, that have been calculated at 3600 s, are 1.6 °C, 3.0°C, 1.8°C, 0.5°C, 0.7°C for T_S1, T_S3, T_S4, T_S5 and T_S6, respectively.

7. Conclusions

Experimental tests were carried out on three different test sections at varying operating conditions and the following conclusions can be drawn.

- In all the test sections the presence of the natural convection is confirmed. It is verified with the experimental temperature trends and also by the numerical simulations in figure 7 where the velocity trend inside the pipe is reported.
- A good agreement between the experimental data collected in test 3 and the numerical simulations is found. This validation is very important to define in detail the performance of the solar thermosyphon, obtaining more informations about the temperature distribution and the velocity field inside the solar collector. It is worth highlighting that the flow rate is not measured because the fluid velocity is very low and any sensor would affect the measurement and the flow itself, but this parameter, as mentioned above, can be obtained for the numerical simulations.
- The effect of device inclination has been investigated. It can be observed that at low tilt angle of the solar thermosyphon the temperature values are higher and the thermal stratification is more pronounced. This means a better performance at high tilt angle due to the influence of buoyancy effect with a higher circulation of working fluid and with a higher fraction of heated fluid inside the tank storage. For this reason it would be interesting to analyze experimentally the solar thermosyphon at 90° tilt angle, that is the typical configuration on vertical facades.
- When the heating system is switched off the temperature at the bottom of the pipe increases; this phenomenon could be due to the reversal flow of the fluid. For this reason, it may be fundamental to investigate this problem that would be verified when solar irradiance decreases.

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