# EXPERIMENTAL EVALUATION OF SOLAR COLLECTORS

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Newton G. C. Leite[1], Luiz Carlos B. S. Reis[2] and Maurício A. Zanardi[3]

## ABSTRACT

The purpose of the present work was to investigate the association of two important engineering devices, the two-phase thermosyphon and the solar collector. A cycle to obtain high vacuum was set up to manufacture thermosyphons, which were inserted into evacuated glass tubes to compose the structure of a solar collector prototype. The prototype was operated over a period of eight months, during which two other solar collectors were tested simultaneously for comparison purposes. The other two collectors were purchased on the market, one of which already included the thermosyphons, while the other operated without them. Temperature readings were taken at the manifold inlet and outlet, as well as in the main water supply, and in the storage tank. The temperature data were analyzed and could be condensed into just two 24-hour periods, as they showed reproducible behavior. A calorimeter allowed estimating the amount of stored energy, which in this case used twenty 24 hour periods for analysis. It was concluded that the solar collector that uses the thermosyphon can reach higher temperatures at the manifold outlet, but the storage tank can interfere, causing a decrease in the temperature of the water that reaches the consumer.

**Keywords:** Solar collector. Thermosyphon. Experimental study.

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[1] Department of Mechanics and Energy - DME Center for Renewable Energy Sources - CFRE Faculty of Technology - FAT
Rio de Janeiro State University - UERJ
E-mail: nleite@fat.uerj.br
ORCID: 0000-0001-8570-5218
[2] Department of Mechanics and Energy - DME Center for Renewable Energy Sources - CFRE Faculty of Technology - FAT
Rio de Janeiro State University - UERJ
E-mail: bevilaqua@fat.uerj.br
ORCID: 0000-0002-3176-5546
[3] Department of Mechanics and Energy - DME Center for Renewable Energy Sources - CFRE Faculty of Technology - FAT
Rio de Janeiro State University - UERJ
E-mail: mauricio_zanardi@uol.com.br
ORCID: 0000-0002-0844-6344

## INTRODUCTION

The thermosyphon is a device that can be called a heat superconductor, despite its relatively simple construction. Since the name thermosyphon appeared around 1928, reported by Japkise (1973), this device has been studied and improved, as it presents great potential in heat transport. The literature is extensive and covers both the experimental and theoretical parts, as can be seen in the works of Faghri (1995) and also of Peterson (1994).

Solar collectors are of several types depending on their purpose, as shown in the works of Abdel-Dayem, et al., 1999, Azzolin, et al., 2018, Fan and Furbo (2007), Ismail. et al., 2016, Kalogirou (2003), Kalogirou (2004) and Vejen, et al., 2004. The literature has propagated the benefits offered by renewable sources, as well as the environmental problems related to the use of conventional energy sources and, as part of the solution, the use of various types of collectors such as flat plate, compound parabolic, vacuum tube, parabolic trough, Fresnel lens, etc. Solutions for solar water heating, space heating and cooling, heat in industrial processes, steam generation systems, desalination, chemical applications, among others, are exhaustively studied. As seen, systems that use solar energy can be applied to a wide range of problems and provide significant benefits, so they should be used whenever possible.

This study aims to compare solar collectors that use two-phase thermosyphon technology with conventional collectors. Three collector models were studied, two with the presence of two-phase thermosyphons, one of which was entirely built in the laboratory, while the other was purchased commercially and one did not use the thermosyphon. All collectors used were made of double evacuated glass tubes and had identical storage tanks.

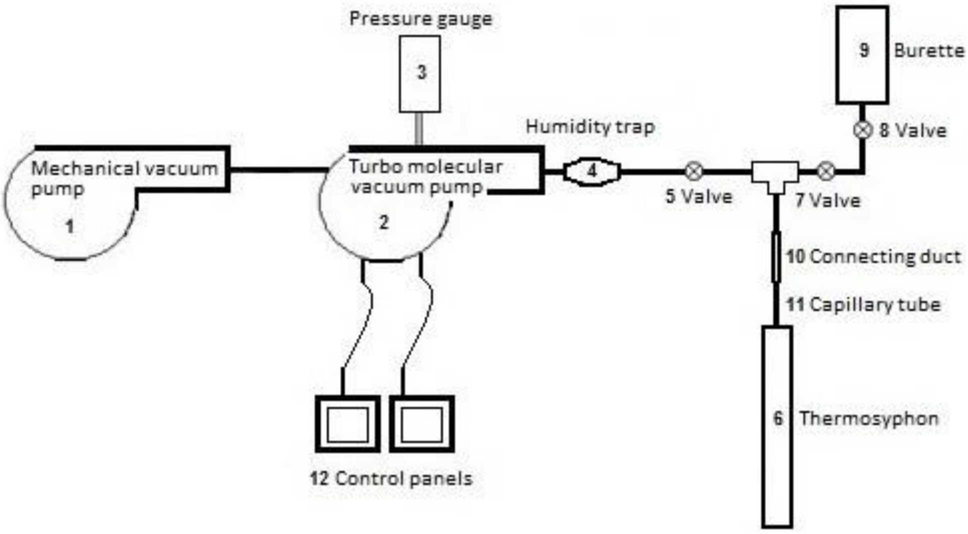
## EXPERIMENTAL APPARATUS

### CONSTRUCTION OF THE VACUUM CIRCUIT

The research project began with the assembly of a system capable of producing high vacuum. This system was assembled using two pumps coupled in series. The Pascal-SD series rotary vane mechanical vacuum pump, model 2005 SD, ADIXEN brand, with double stage and pumping flow of 5.4 $m^3$/h, with final vacuum of 0.2 Pa was connected in series to a drag turbo molecular vacuum pump, model HiPace 80 DN 63 ISO-K, as shown in Fig. 1.

This configuration allowed the internal structure of the turbo molecular pump to be protected during the initial vacuum generation process, up to the safe operating limit of the turbo molecular pump. After activation of the turbo molecular pump, the mechanical pump is manually switched off and then the time required to reach the required vacuum inside the thermosyphon is waited. During this stage, only valve 5 is open. As soon as the suitable vacuum is reached, the turbo molecular vacuum pump is switched off via the control panel and the process of filling the thermosyphon with the working fluid begins. Valve 5 is closed, valve 7 is opened, and valve 8 serves as a level control valve to allow the thermosyphon to be filled with the desired amount of working fluid. After filling, valves 7 and 8 are closed and the capillary tube is clamped by two flat face pliers, the connection sleeve is broken and the capillary tube is sealed with silver solder. The circuit was well optimized, with very interesting engineering solutions such as, for example, the moisture trap, which in more sophisticated systems usually involves expensive techniques where equipment and/or substances lower the temperature of the working fluid in an attempt to freeze it and consequently prevent it from returning to the pump. In this system, a component that caused pressure loss by retaining all the moisture was used, which met the project's needs very well. The entire vacuum circuit was created with the purpose of manufacturing two-phase thermosyphons with a vacuum sufficient for their proper functioning. The lowest vacuum obtained being 0.08 Pa and the highest being 0.1 Pa.

Figure 1. Vacuum circuit.



Source: From author.

## TWO-PHASE THERMOSYPHON CONSTRUCTION

Before the copper tubes were connected to the vacuum circuit, they underwent a rigorous process of manual internal cleaning with acetone to prevent contamination of the working fluid with solid residues. Then, their ends were sealed with appropriate caps using silver solder, and one of the sides received a capillary tube, as shown in Fig. 2, which was responsible for connecting the thermosyphon to the vacuum system. At the end of the filling and sealing process, they had to undergo a check regarding the amount of working fluid that each one received. The check was done by weighing the copper tube before and after filling with the working fluid, using a $5.10^{-7}$ kg precision scale from the KALA brand.

Ten two-phase thermosyphons were built to compose the solar collector that was tested, where each tube was filled with 30% of its total volume with distilled water, which was used as the working fluid. The smallest error in the filling process was 2.2% and the largest was 17.2%. The geometric characteristics of the tubes were: 1.8 m in length; external diameter of $1.21\times10^{-2}$ m and internal volume of $2.1\times10^{-4}$ $m^3$.

Figure 2. Detail of the thermosyphon cap – without external cleaning.

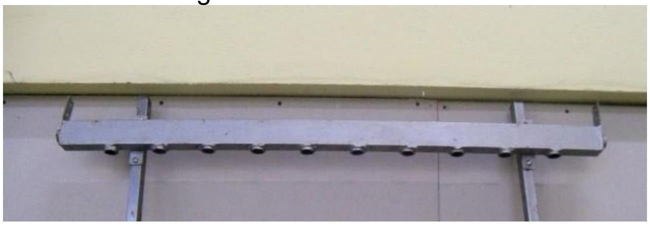
Source: From author.

To test the operation of the constructed two-phase thermosyphons, two procedures were used: first, one end of the tubes was immersed in a boiling water at approximately 100 ºC, while the other end was manually inspected to observe the heating time of the end and the noise caused by the heat exchange process; in the second procedure, the tubes were shaken until they produced a noise similar to two metals colliding. These simple inspection methods proved to be quite reliable, since when these phenomena were not observed during operation of the tubes that presented problems related to leaks.

## SOLAR COLLECTOR CONSTRUCTION

The construction of the prototype began with the assembly of the main steel structure that was responsible for accommodating and supporting the weight of the double vacuum tubes with the two-phase thermosyphons. The internal part of the manifold, which is the region through which the water circulates, shown in Fig. 3, was built with a threaded system, which did not present major assembly problems or leaks. The thermosyphon could be fitted perfectly into the manifold using a threaded ring that was welded to it, as shown in Fig. 4. Next, the collector itself was assembled, starting with the placement of the thermosyphons, checking for leaks in the hot water flow, assembling the double evacuated tubes and, finally, filling the manifold insulation box with expanded polystyrene spray.

Figure 3. Manifold details.



Source: From author.

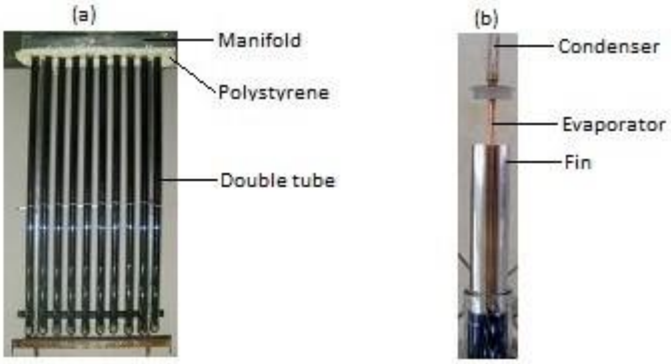
Figure 4. Threaded coupling system.

Source: From author.

The purpose was to build a solar collector with commercially available evacuated double tubes, but adapting two-phase thermosyphons inside it. Fig. 5(a) shows an overview of the prototype that was manufactured, which had its structure modified when compared to those purchased on the market. Fins are generally used to improve the heat exchange performance between the thermosyphon and the internal walls of the double tube, as can be seen in Fig. 5(b), which elucidates the use of an aluminum fin around a heat pipe in the commercially available solar collector. In the prototype, only radiative effects were predominant in the heat exchange process in the region where the evaporator of the two-phase thermosyphon is located, dispensing with the use of a fin that provides an increase in area and heat transport by thermal conduction.

After the prototype assembly process, it was taken to a suitable test station and three models of ASUS solar collectors were carefully installed in the same position. All were mounted facing geographic north with an inclination angle of 28º. The storage tanks used had a volume of 200 liters and all the pipes and connections were properly insulated and maintained a similar lengths and curvatures. After a few hours of operation, all models were monitored with a thermal imaging camera to detect small leaks that could compromise the tests.

Figure 5. Construction details of solar collectors: (a) Prototype and (b) Commercial solar collector.



Source: From author.

When consulting the manuals that accompany collectors sold on the market, it was observed that some of them include the term heat pipes. To resolve the doubt, one of the supposed heat pipes – Fig. 5(b) – was opened and its working fluid was quantified and chemically analyzed by the Chemistry and Environmental Department of UERJ-FAT. A fluid similar to distilled water was found, but mixed with a powder that was identified as a mixture of copper and copper oxide. The liquid part occupied approximately 4.02% of the total volume and the most interesting discovery is that the tube was not a heat pipe as announced in the manufacturer's manual, but rather a two- phase thermosyphon. In this case, it is not clear whether it was simply a confusion on the part of the person who wrote the manuals or whether there is some intrinsic conceptual error in the definition between heat pipe and thermosyphon on the part of the manufacturers.

## DATA ACQUISITION AND STORAGE

To track the data required for collector analysis, thermocouples with compensation wire were manufactured to reduce project costs. The wire used was composed of a Chromel-Alumel alloy, known in the market as conductive wire with the code KX, with a diameter of 1.8 mm, which is suitable for working with type K thermocouples. The records of the water inlet and outlet temperatures in the manifold were made by an eight channel automated data acquisition system – Fieldlogger from Novus Produtos Eletrônicos Ltda.

All thermocouples were calibrated based on the ice melting temperature, ambient temperature (compared with a YOKOGAWA Thermo Collector TM10 sensor) and water boiling temperature, considering the altitude of the city of Resende - RJ.

From the comparison of the results, adjustment curves were extracted for each thermocouple. Then, first-degree correction equations were used to minimize the error of the thermocouples. The temperature of the water stored in the storage tanks was also monitored by means of a calorimeter, thus allowing the accounting of the energy production in the form of heat. Daily samples of similar amounts of water were extracted from the collectors at pre-established times. Knowing the temperatures involved in the process, which were read by the thermocouples and obtained by the calorimeter, and using the energy conservation equation to calculate sensible heat, it was possible to obtain the value of the energy gain in the form of heat over the analyzed period. It is important to note that before each collection, 3 liters of water were always discarded, thus ensuring that the water analyzed always came from inside the storage tank and not from the piping, despite the fact that a very short section of duct was used in the water extraction position. The experimental uncertainties regarding the results of the energy gain in the form of heat were calculated, and the values found were insignificant.

## ANALYSES OF RESULTS

The aim was to measure the water temperature at the manifold outlet and also at the point of consumption, thus quantifying the energy accumulated in a defined mass of water. Three models of solar collectors were tested simultaneously: collector 1 from the ASUS brand, which is made up of double evacuated glass tubes and two-phase thermosyphons with fins; collector 2 from the ASUS brand, made up of double evacuated glass tubes and without two-phase thermosyphons; and collector 3 from the ASUS brand, made up of double evacuated glass tubes and two-phase thermosyphons built at the Center for Renewable Energy Sources of UERJ – FAT. All collectors had 10 glass tubes making up the same external area. It is worth noting that in the double evacuated tube collector, the water penetrates the interior of the glass tube, while in the collector that uses the thermosyphon, the interior region does not have contact with the water. Therefore, there are construction differences in the manifold in the set situations and also between collectors 1 and 3, although less pronounced. This will cause changes in the water flow pattern inside the manifold, imposing changes in the flow rate and pressure drop, thus not allowing a complete similarity between the models tested.

The tests were carried out over a period of eight months and, as there was qualitative reproducibility of the results. Two specific periods were chosen for presentation. The graphs that were presented in the sequence were constructed using a 24 hour period, starting at 12:00h on one day and ending at 12:00h on the next day. For convenience during the construction of the figures, the x axis uses a range from 12 to 36 configuring a 24 h period. At the thirty-sixth hour, the temperature readings at the inlet and outlet of the collector 1, 2, 3, of the water coming from the supply network and of the water collected at the outlet of the storage tank by a calorimeter were recorded for analysis purposes.

With the experimental values in hand, the calculation of the heat stored in each calorimeter collection over a 24 hour period could be obtained, and served for the purpose of comparing the collectors. With the appropriate assumptions and assuming that there was no phase change, the energy conservation equation can be written in the form:

$Q = m\ c_p\ \Delta T$ (1)

where: Q= represents the heat stored in the fluid contained inside the calorimeter, [kJ] m= mass of water contained in the calorimeter, [kg]

$c_p$= the specific heat of water at constant pressure, [kJ/kgK]

$\Delta T$= temperature difference between the water collected by the calorimeter and the water coming from the supply network, [K]

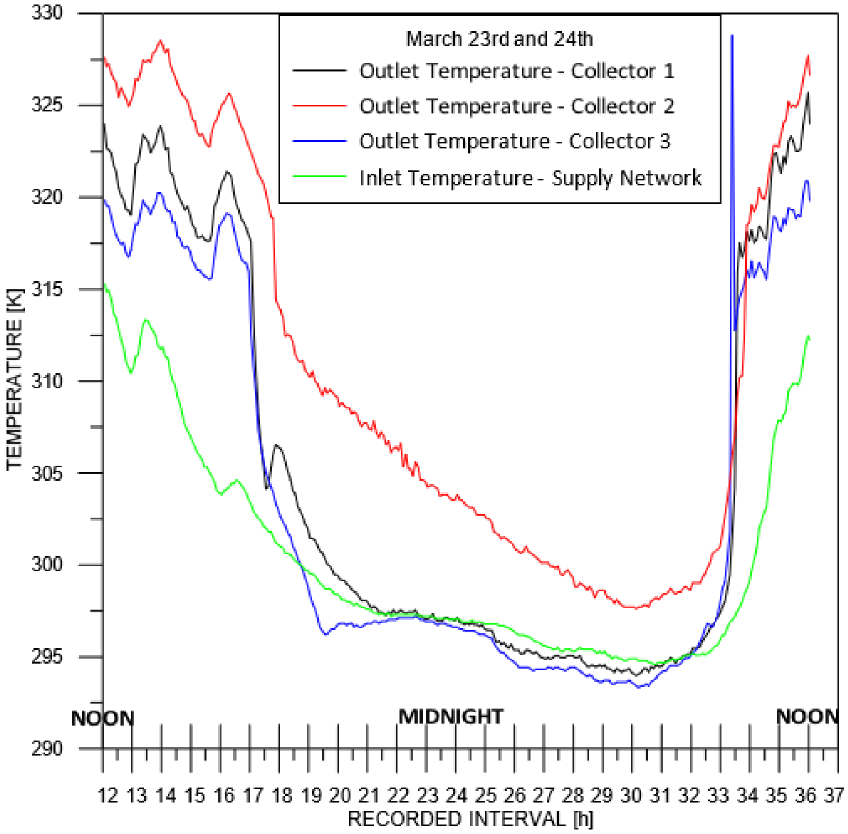
## TEMPERATURE BEHAVIOR STUDY

Fig. (6) shows the temperature value as a function of time at the collector outlet and also at the water supply network that feeds them. Collector 2 presents higher temperatures than the others in the afternoon period – 12:00 A.M to 18:00 P.M – but is practically the same as collector 1 in the morning period – 35 h to 36 h. Collector 3 shows a temperature pattern that is always lower than the others in the period mentioned. The same pattern was found in Fig. (10), which was a cloudy day with lower feed water temperatures. The difference is that in this case collector 1 surpassed the others and collector 3 continued to supply the lowest temperatures. The set of graphs shown in Fig. (7), Fig. (8) and Fig. (9) presents the temperature difference between the manifold inlet and outlet region for all collector models in the period between March 23 and March 24. The largest temperature difference considering 12h as a reference was found in collector 2, while collectors 1 and 3 with lower differences obtained practically the same value. Larger temperature differences in the manifold are certainly an indication of obtaining a higher value in the buoyancy force, which is responsible for the proper functioning of passive systems. It is important to point out that the mass flow rates for the collectors were different. In the collectors with thermosyphons the head loss is smaller since the fluid flows directly across the manifold while in the other collector the flow must go through the entire heating tube. As the mass flow rate is smaller, for the same collected heat, the achieved temperatures were higher. For the cloudy day, the values of the temperature difference between the inlet and outlet region of the manifolds were shown in the set of graphs represented by Fig. (11), Fig. (12) and Fig. (13). It is noted that the values of the temperature difference of collectors 1 and 2 are similar and higher than collector 3, taking 12h as a reference time.

A temperature inversion phenomenon between the inlet and outlet region was captured in collectors 1 and 3 that use two-phase thermosyphon technology. This inversion that occurs approximately between 18 h and 34 h should be caused by the drop in ambient air temperature. The two-phase thermosyphon will not work, but the copper structure can act as a fin. This is shown in Fig. (7), Fig. (9), Fig. (11) and Fig.

(13). This temperature inversion phenomenon does not occur in collector 2, as corroborated by Fig. (8) and Fig. (12).

Figure 6. Temperature between 12 A.M. of one day until 12 A.M. of the next day.



Source: From author.

Figure 7. Temperature between 12 A.M. of one day until 12 A.M. of the next day.

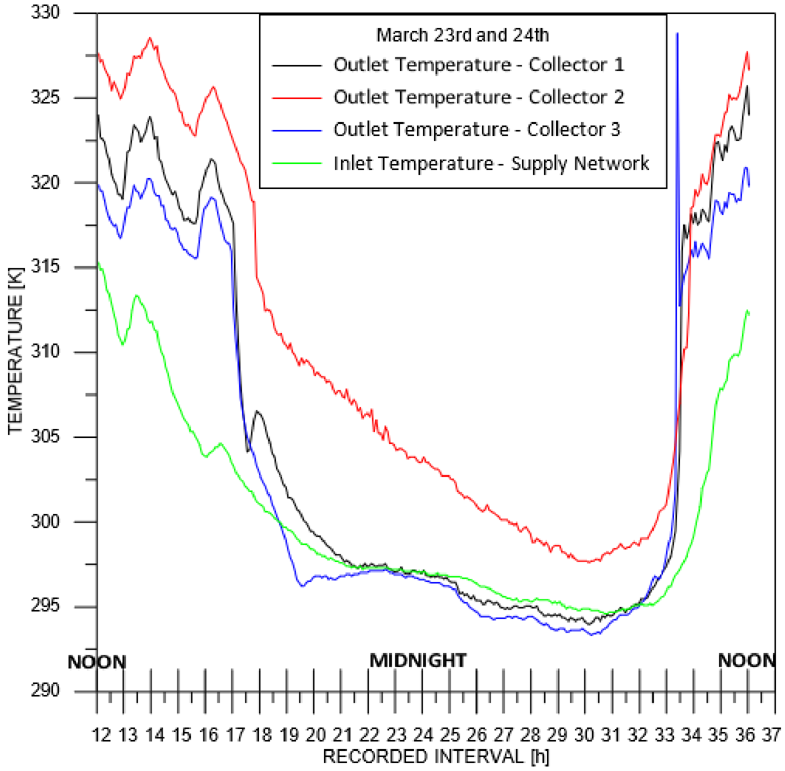


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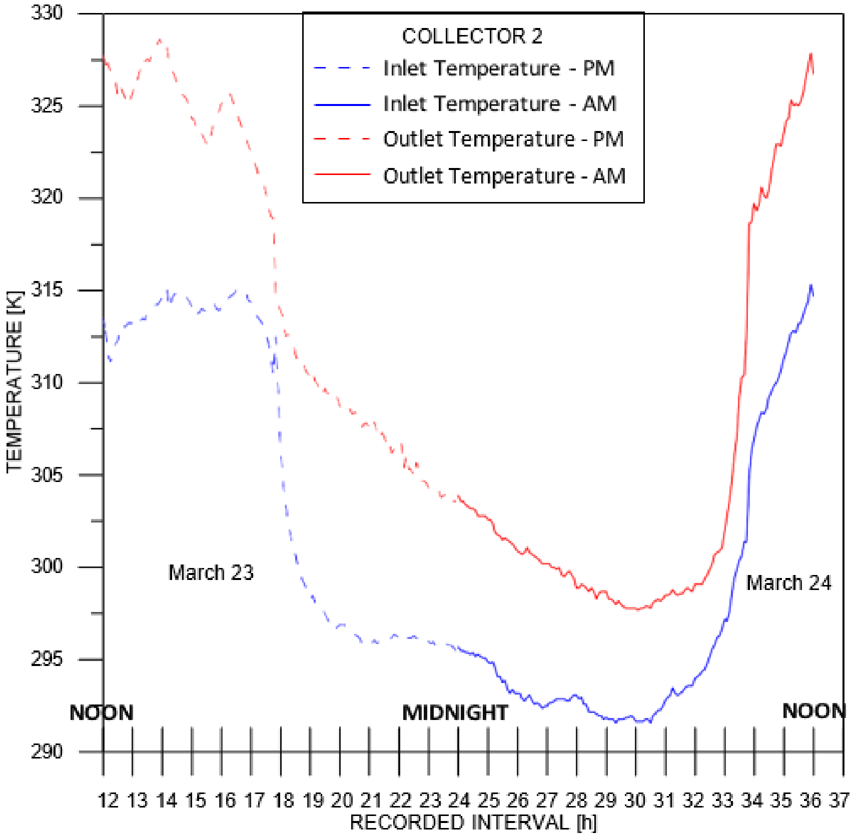
Figure 8. Temperature between 12 A.M. of one day until 12 A.M. of the next day.



Source: From author.

Figure 9. Temperature between 12 A.M. of one day until 12 A.M. of the next day.

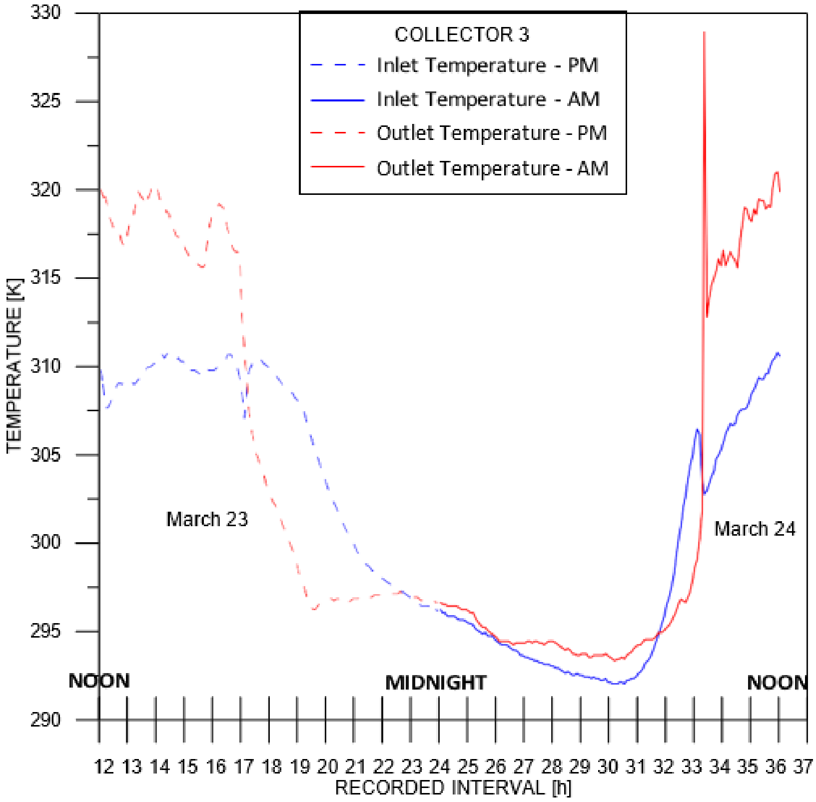


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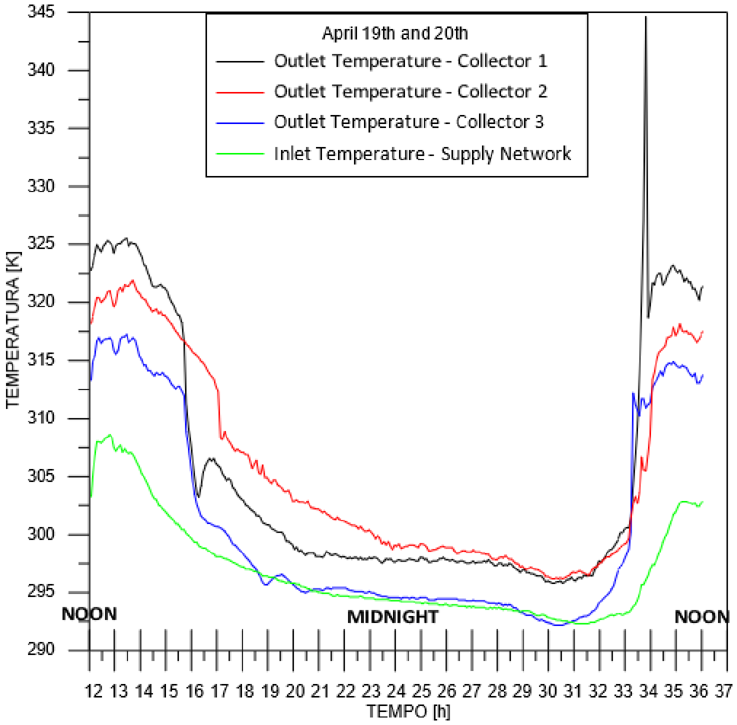
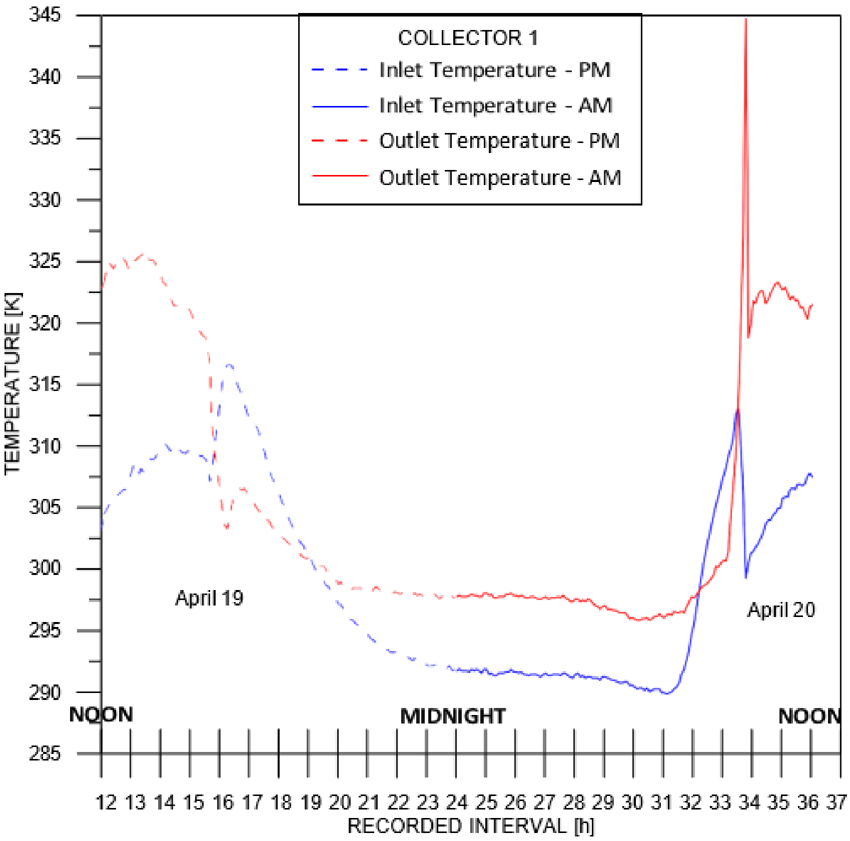
Figure 10. Temperature between 12 A.M. of one day until 12 A.M. of the next day.



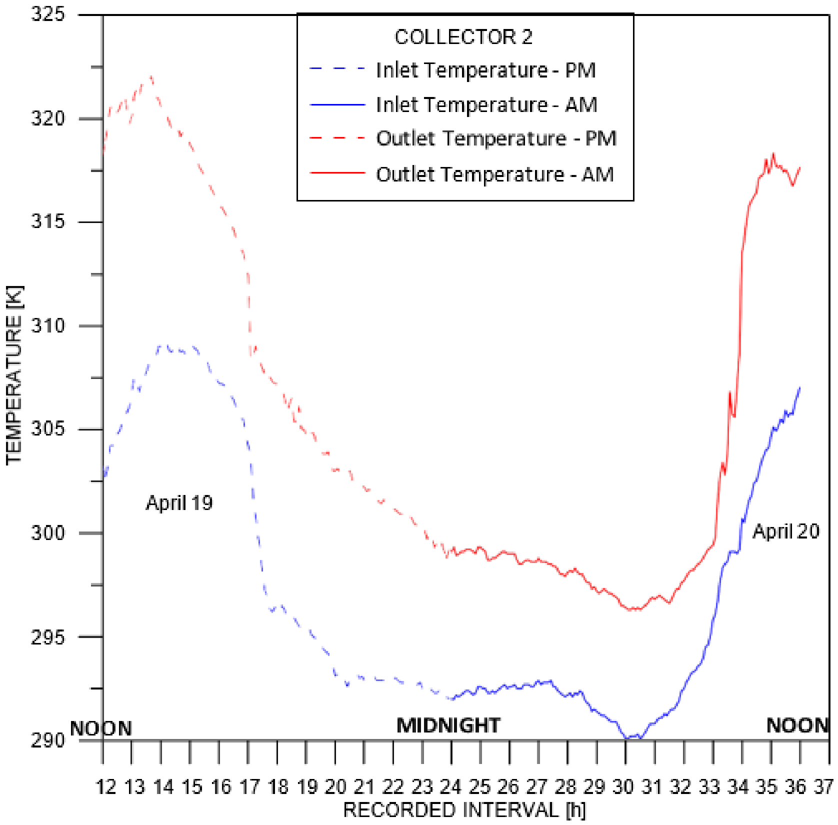
Source: From author.

Figure 11. Temperature between 12 A.M. of one day until 12 A.M. of the next day.



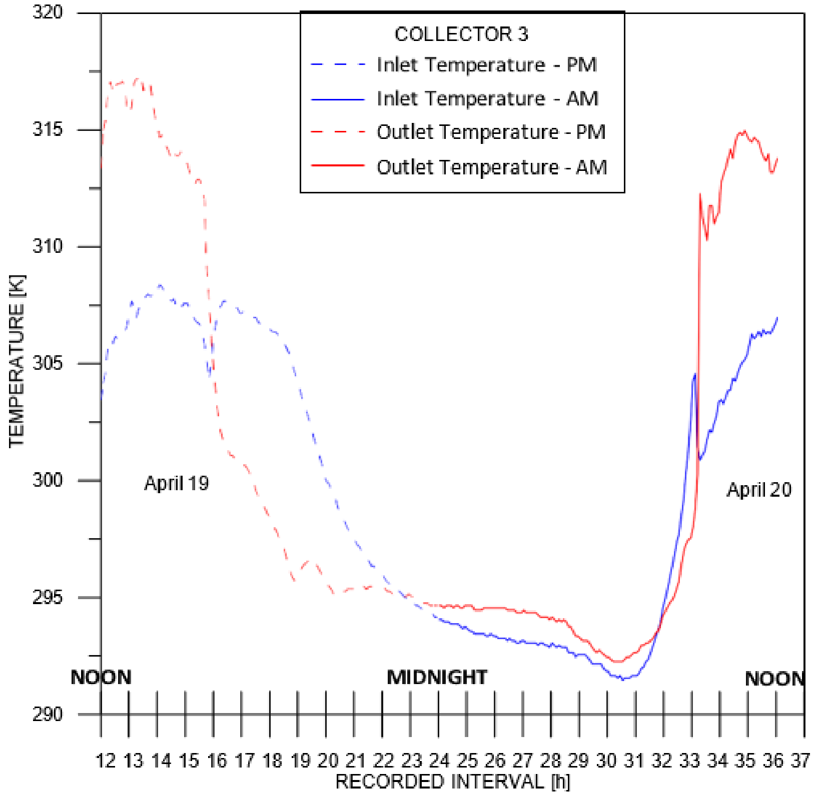
Source: From author.

Figure 12. Temperature between 12 A.M. of one day until 12 A.M. of the next day.



Source: From author.

Figure 13. Temperature between 12 A.M. of one day until 12 A.M. of the next day.



Source: From author.

## ENERGY ACCUMULATION

The energy accumulated in the mass of water contained in the calorimeter was measured over a period of 20 days, covering the months of March, April and May. This period was chosen because it presents more pronounced climate variations, such as variations in ambient temperature, cloudy days and rainy days in the region where the test was carried out, when compared with the period of eight months. Table (1) shows the results obtained from the use of Eq. (1) to find the accumulated energy and its respective percentage deviations between each collector, in situations where the temperature taken into consideration was that of the storage tank and also that of the manifold outlet.

Table 1. Sum of the accumulated energy for each collector over the twenty-day period.

| **Solar Collector** | **Storage tank [kJ]** | **Deviation [%]** | **Manifold output [kJ]** | **Deviation [%]** |
|---|---|---|---|---|
| **1** | 125.7 | $D_{12}=22.9\%$ | 338.6 kJ | $D_{12}=20.0\%$ |
| **2** | 154.5 | $D_{23}=10.5\%$ | 282.2 kJ | $D_{23}=57.5\%$ |
| **3** | 139.8 | $D_{31}=11.2\%$ | 179.2 kJ | $D_{31}=89.0\%$ |

Source: From author.

It is important to clarify that the energy stored inside the tank was the value for the period of time considered and the energy at the manifold energy is an average value at noon. The results point out that the collector without thermosyphons provided more energy accumulated inside the storage tank for a long period, while the collector with the thermosyphon collects more energy in the short period close to noon. This can be explained when the heating process is analyzed. The energy is more efficiently transferred to the fluid by the thermosyphon but during the period without solar radiation the thermosyphon acts as a thermal diode. This fact can be confirmed by the temperature curves, that shows that the outlet temperature of the manifold reaches the ambient temperature. All the energy stored in the manifold is lost. In the tubular collector, there is a large amount of water inside the tubes that also stores energy. Even during the absence of solar radiation, part of the energy collected during the day will remain in the water mass and will be transferred to the tank.

The results of the accumulated energy from the temperature that represents the storage tank show the superiority of collector 2, which does not use the two-phase thermosyphon technology, followed by collector 3, which was the prototype built, and finally collector 1, which is sold on the market, both with the two-phase thermosyphon installed. The largest percentage deviation (D) found was between models 1 and 2. Now, when the temperature at the manifold outlet is taken into account, collector 1 stands out, occupying first place, followed by collectors 2 and 3. In terms of percentage deviation, all collector types start to move away from each other, especially models 1 and 3, with a value of 89%.

The results suggest that the two-phase thermosyphon technology, when used properly, can achieve the highest temperatures at the manifold outlet; however, this does not mean that the consumer will enjoy these temperature levels in a long-term period. Since all the collectors used in this work were of the same brand, were installed in a strictly identical way and occupied the same external area for solar energy collection, it seems that the thermal and fluid dynamic processes within the storage tank are strongly affected by the way in which solar energy is captured. It was also possible to note that in relation to the temperatures taken at the manifold outlet, the prototype was compromised by the non-use of a fin as was done in collector 1.

## FINAL STATEMENTS

This study concludes that:

- Double evacuated tube solar collectors with thermosyphon operating in a passive system present higher water temperature levels at the manifold outlet.
- Thermal and fluid dynamic processes in storage tanks can be influenced by the collector model used to capture solar energy, resulting in a drop in the temperature of the water that reaches the consumer.
- Active systems – the use of pumps – can benefit solar collectors that use two-

phase thermosyphon technology by improving the internal film coefficient inside the manifold and also perhaps reducing the stratification that occurs inside the reservoirs.

- Removing the fin covering the two-phase thermosyphon can only be performed if there is an adequate design of the thermosyphon, to compensate for the loss of solar energy capture area.
- The solar collector without the two-phase thermosyphon is cheaper and seems to serve domestic consumers well, but the solar collector with two-phase thermosyphon technology has great potential for industrial use.

## ACKNOWLEDGMENTS

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