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COMPARATIVE STUDY FOR UNGLAZED SOLAR FLAT PLATE COLLECTORS USED AS SWIMMING POOL HEATERS

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Abstract. Solar energy systems can be used either for production of domestic hot water as on pools heating. Water heating of swimming pools, whether for therapeutic or for comfort, has many advantages such as: energy savings and higher efficiency than other sources. One of the major problems for expansion of these systems is their high initial cost. An attempt to reduce this cost is replacing traditional solar collectors by a material of lower cost and good efficiency. Considering this fact, this paper aims to analyze the efficiency of a solar collector model for pool made by polyethylene pipes forming a spiral geometry and compare it with a commercial one. Some analyses show that using this simple model of solar collector for swimming pool can bring economic benefits. It is observed that there are companies currently focused for collectors developed this type of polyethylene, providing solutions at a lower cost to local customers. To achieve this purpose of evaluating thermal efficiency of the collector it was mounted an experiment according to Brazilian standards and a theoretical model, based on bibliography expressions. Using these tools, it was developed a comparative analysis between the spiral collector and a commercial one. Observing the results it was noted a very similar thermal behavior for two devices.

Keywords: *Swimming pool heaters, Unglazed Solar Collector, Solar energy, Solar Collector Tests.*

1. INTRODUCTION

The socio-economic evolution of humanity has always been associated with increasing energy availability. With this availability, it was increased food production and distribution and a lot of other facilities for daily life and, even, new technologies to prevent and treat health problems. However, some problems have been observed on the most used power source nowadays: fossil fuels. The main problem is the increasing free carbon in the atmosphere, resulting from using large fossil fuels reservoirs may be causing an increase in Earth's temperature surface, the called "Greenhouse Effect". In this context, nuclear power would be an important alternative energy, but it has encountered problems too, and some catastrophic accidents were reported on a recent past. Thus, the greatest expectations for the future of energy sources have been deposited on renewable energy and, especially, solar energy.

The solar energy uses have verified significant growth in recent decades and, despite the different utilization forms developed, its most common use is yet the domestic hot water systems. These systems can be used for both: water bath and pool heating, respecting some constraints. The main difference is related to water temperature, since the pool should be maintained at a constant temperature for a long time period. However, this temperature is typically much lower than that required for bath water. These differences imply that the devices used for each of these purposes are different from another one.

Based on these different objectives, studies developed for domestic hot water systems contributed to increase the utilization of solar collectors for heating swimming pools. Although previous studies had already been developed with respect to geometry suitable for collectors pools, researchs from Govaer & Zarmi (1981), Govaer (1984), Dang (1986) and Rakopoulos & Vazeos (1987) organized the methodology and established the basic principles for designing these systems. This model was further developed by Almanza & Lara (1994), who applied techniques used in the design of solar ponds to improve it. At same time, Hahne & Kübler (1994) developed an analytical model using TRNSYS and highlighted the important influence of local wind regime on the pool energy loss. A similar work-up using some different expressions in the evaluation of the thermal load has been further developed by Ruiz & Martinez (2010). In this work, the model data were compared with experimental results.

The solar collector is the main system component and also been analyzed in several studies, trying to identify the most suitable design. Molineaux et al (1994) evaluated different collectors in different Switzerland regions to determine the adequate operating conditions for each case. Smith et al (1994) also developed a similar study in the United States. More recent papers as Medved et al (2003) e Juanicó (2008) proposed the inclusion of collectors for heating swimming pools attached to houses roof.

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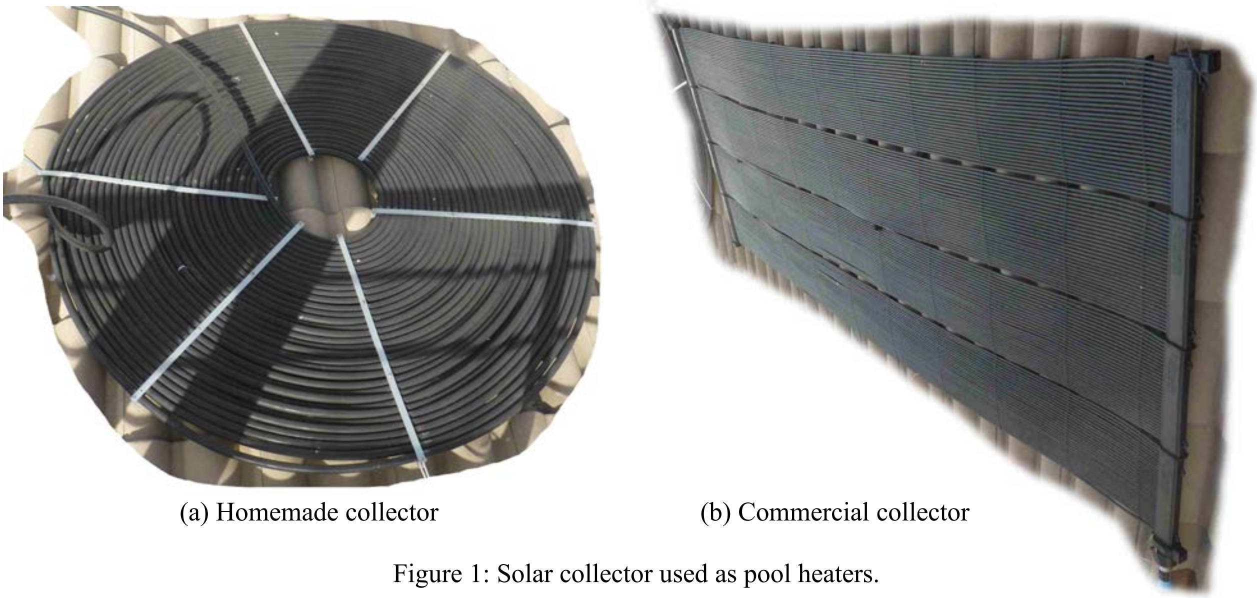

(a) Homemade collector (b) Commercial collector

Figure 1: Solar collector used as pool heaters.

Another important study line for these systems is related to energy optimization and economical operation, since in addition to solar energy, electricity must be used at least for operation of the circulation pump water. Croy & Peuser (1994) studied coupling solar and conventional heating systems for pools, previously used to demonstrate the technical and economic feasibility of the device. Stefanelli et al. (2010) and Cunio & Sproul (2012) associate the pump operating parameters, such as time of operation and mass flow, with the energy efficiency of the system. Finally, a new line of developments of these systems proposes the integration of solar collectors with heat pump systems as a way to improve system performance and attend greater demands. Studies aiming this issue were published by Tagliafico et al. (2012) and Chow et al. (2012).

This study presents a comparative test the performance for solar collectors made from polyethylene, commercial and homemade, which has been used as alternative system for heating pools in recent years. Figure 1 shows a photo from collectors tested. The assembly from experimental apparatus is based on the principles established in ABNT:1084 (1998), ASHRAE:93 (2003) and EN:12975-2 (2000) standards. These standards had some of its operating parameters changed and others not considered, since the comparative analysis is the goal and performed tests intend to replicate the operational conditions. Results for efficiency of each collector in the the test period will be presented and discussed.

2. EXPERIMENTAL TEST

The experimental apparatus and the procedure for measurements were based on the previous principles established by the standards. The system components are mounted according to the suggestions of these same standards. A representative scheme of the experimental setup can be seen in figure 2.

The constant flow rate in the collectors during the all the time of experiment is a fundamental principle for these tests. Hence, a usual scheme using a overflow rate to suply the main reservoir is used. The overage water flow is captured by an external tank that sends it back to the lower reservoir. Thus, no change in water level or pressure head is verified. However, it is recommended to check fluid flow sometimes during the experiment time once small changes could be verified due to instabilities and changes in the flow characteristics. The assembly scheme with two attached tanks used in these cases can be seen in figure 3.

The experimental design was done by exploiting the infrastructure of a constructed pool. The upper reservoir with two tanks was placed on an elevated area to allow large pressure head that could attend the flow requirements for tests. It was used the pool as the lower reservoir. The pool pumping system was used for perform water circulation. The constant level reservoir fed the two collectors allowing simultaneous analysis for heating behavior under the same environmental conditions.

The fluid flow measurements were performed using a reservoir accumulation with defined volume. The mass was subsequently measured by using a weighting-machine. Volume of water was measured in different time interval by test, but always allowing the subsequent mass flow rate calculation for each of the collectors independently. As collectors pools must operate at lower temperatures, the flow rate was adjusted to rates close to 4 liters/min. The pump flow rate conditions needs to attended the experiment requirements once the upper inner tank was operating on continuous overflow.

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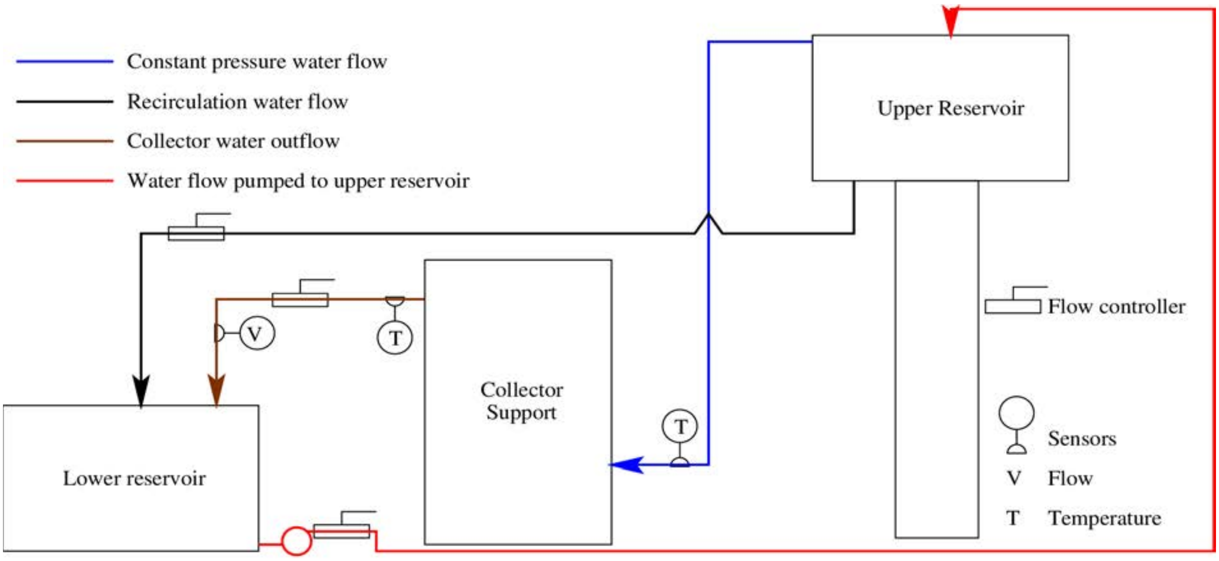

Figure 2: Experimental apparatus scheme.

The inlet and outlet temperatures of water flow in collector were measured by RTD PT100 type. Values for ambient temperature, pool temperature and surface temperatures on collector were measured using T type thermocouples.

The temperature values were stored by a computer through a data acquisition system at rate of 1 sample per minute. The data acquisition system was positioned near the collectors and transmits the information to the computer via wireless network. The data acquisition system is a modular system manufactured by National Instruments (NI-DAQ) with the modules focused to measure RTDs and thermocouples. It was used a RJ-45 acquisition system connected to a wireless router that transmitted the information over the wireless network to the computer.

During the tests time period, the intensity of solar radiation and wind speed were also measured. As a reference, solar meter is a TES-1333 digital solarimeter and the measuring device for wind speed (anemometer) was the LCA6000 AirFlow model. The wind speed was made based on measurements in both directions, N-S and E-W. The incident radiation (G_r) is achieved by sloping the radiometer at the same angle of flat plate solar collector and obtain the projected radiation. Thus, the values presented are the ones that effectively focus on the collector and does not need any correction concerning to the angle.

Based on collected data it is possible to estimate the useful heat flux that was absorbed (Q_u) for each collector using the increasing in the water internal energy, as:

$$Q_u = \dot{m} \cdot c \cdot (T_{ms} - T_{me}) \tag{1}$$

where $\dot{m}$ is the mass flow on the colletor, c is the specific heat for the fluid, T_{me} is the bulk temperature on the

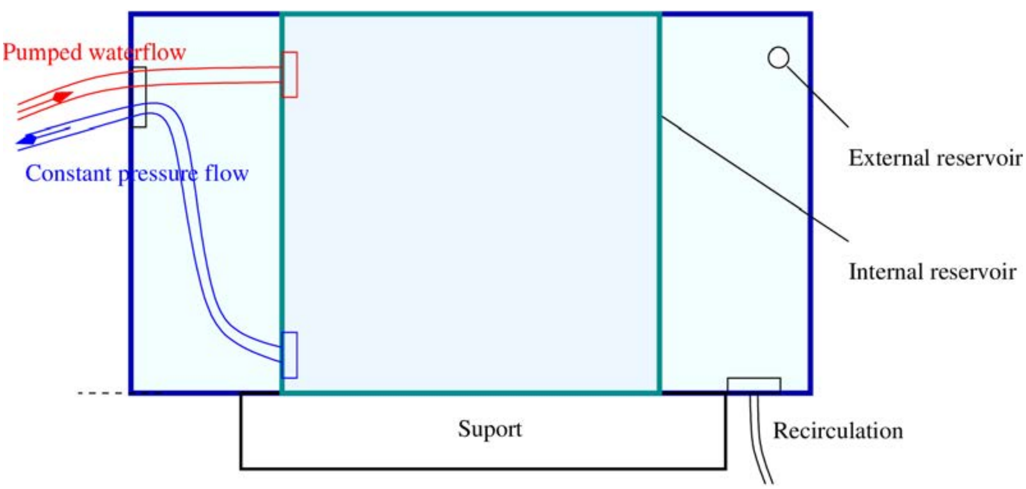

Figure 3: Upper water reservoir scheme.

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collector inlet and is the T_{ms} bulk temperature on the collector output.

The global efficiency η could be determined by the relationship of the collector usefull heat flux by the incident solar radiation:

$$\eta=\frac{Q_u}{(Gr\cdot A_{sc})} \tag{2}$$

where G_r represents the total radiation directed to the solar collector and A_{sc} is the absorbing surface for the collector.

The collector global efficiency η can be formulated analytically and the result can be expressed by different ways. Although some newer standards such as EN:12975-2 (2000), present a quadratic function for efficiency related to the ratio of temperatures difference and incident radiation $(\Delta T/G_r)$, the Brazilian standard ABNT:1084 (1998) still uses a linear relationship, which can be expressed by:

$$\eta=F_R\cdot(\tau\cdot\alpha)_n-F_R\cdot U_P\cdot\left(\frac{T_{me}-T_a}{G_r}\right) \tag{3}$$

where F_R is the heat removal factor, $(\tau\cdot\alpha)_n$ transmitance-absortance product for normal radiation and U_P is the global heat transfer coefficient of losses. Further details on how this relationship is obtained can be found on basic references such as Kalogirou (2009) and Duffie & Beckman (2006).

The parameters used for the calculations were based on the average of measurements on each test considered. The uncertainty of the measurements were taken on the basis of statistical procedures. It was considered that a very large number of measurements were taken(Gauss distribution). Considering a confidence level of 90% for all cases, the magnitude of the uncertainty is given by:

$$\delta\varphi=1.65\cdot\mathrm{STD}(\varphi_i) \tag{4}$$

where φ_i represents any measurements on test such as temperatures, solar radiation, fluid flow, etc. Certain parameters fluctuated during the tests and induced a large uncertainties range for these cases. Moreover, the number of temperature measurements were large enough, but estimations of the parameters like solar radiation, wind velocity and fluid flow were taken in smaller number of times. This indicates that confidence level based on a Student distribution could be more suitable for these magnitudes.

The uncertainties for values directly measured were defined by this previously description and it could be used to estimate the collector efficiency uncertainties. For this purpose, it was used Q_u definition shown in Equation (1) and after it, this result is applied on Equation (2).

Thus, the uncertainty value associated with these experimental data can also be calculated using the RMS sum of the components by the expression:

$$\delta\eta=\sqrt{\left(\frac{\delta Q_u}{A_{sc}\cdot G_r}\right)^2+\left(\frac{Q_u}{A_{sc}\cdot Gr^2}\delta G_r\right)^2} \tag{5}$$

The uncertainty of useful heat flow transferred to water can also be obtained from Equation (1), represented by:

$$\delta Q_u=\sqrt{\left(c_{ag}\cdot(T_{bo}-T_{me})\cdot\delta\dot{m}\right)^2+\left(\dot{m}\cdot c_w\cdot\delta T_{me}\right)^2+\left(\dot{m}\cdot c_w\cdot\delta T_{ms}\right)^2} \tag{6}$$

Furthermore, as has been shown previously, one of the most common ways to express the performance is as a linear function using parameter $(\Delta T/G_r)$. In this case the incident radiation and temperatures were experimentally determined and uncertainty of this component can be calculated as:

$$\delta\left(\frac{\Delta T}{Gr}\right)=\sqrt{\left(\frac{\delta T_{me}}{Gr}\right)^2+\left(\frac{\delta T_a}{Gr}\right)^2+\left(\frac{T_{me}-T_a}{Gr^2}\delta G_r\right)^2} \tag{7}$$

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Thus, for anyone could have a clear sense of how fluctuations measures may affect the results obtained from the experimental data, these data will be presented on graph plots with its uncertainties. These results can be used to obtain the parameters of the linear equation using a linear regression of the data. The absolute results, without considering the uncertainties, will be used in determining the coefficients of the linear regression.

I. Numerical model

For estimating the behavior of these collectors, an energy balance in steady state will be used. Collectors will be considered as flat surfaces and the balance of heat fluxes results in:

$$Q_i - Q_u - Q_P = 0 \tag{8}$$

where:

$$Q_i = S_{col} \cdot A_{sc} = \alpha_{col} \cdot G_r \cdot A_{sc} \tag{9}$$

$$Q_u = \dot{m}_{ag} \cdot c_{ag} \cdot (T_{ms} - T_{me}) \tag{10}$$

$$Q_P = U_P \cdot A_{sc} \cdot (T_{sc} - T_{amb}) \tag{11}$$

Using this energy balance it is possible the estimation of temperatures. It is necessary to use a correlation for surface temperature and water outlet temperature on collector such as:

$$T_{ms} = T_{sc} - \exp\left(-\frac{\pi \cdot D_i \cdot L \cdot U_i}{\dot{m}_{ag} \cdot c_{ag}}\right) \cdot (T_{sc} - T_{me}) \tag{12}$$

The collectors were modeled using the fluid flow inside tube and by estimating radiation and heat loss fluxes by expressions available on bibliography. For the spiral flow collector (homemade) the half of the total fluid flow is used and, for commercial ones, the fluid flow was divided equally distributed by total number of tubes that composed it.

The total length of polyethylene tubes used for mounting the spiral collector was unknown and could be estimated based on an expression obtained from problem geometry. Knowing the outer and inner spiral diameter, number of laps one can shown that:

$$L = \sum_{i=1}^{n} A_i = \sum_{i=1}^{n} 2 \cdot \pi \cdot \left[R_i + \left(i - \frac{1}{2} \right) \cdot d_{et} \right] \tag{13}$$

Most of parameters of these equations are operating and environmental conditions for solar collector. However, both heat transfer global coefficients: internal (U_i) and loss (U_p), depend large calculation procedure using geometrical parameters and environmental conditions. This procedure can be easily found in the literature and, for this casef it was used the methodology proposed by Duffie & Beckman (2006). These equations were implemented in a numerical model using GNU-Octave and solved by an iterative procedure until convergent results for the outlet temperature and for the water in the collector was verified.

3. RESULTS AND DISCUSSIONS

Based on the procedure, the solar collectors were tested in parallel on three different days. The efficiency observed in each day, theoretical and experimental, depends on some informations about collector geometry and test conditions that can be seen in table 1. Both, water and the collector, physical properties were considered constant for all experiments.

For the spiral collector case, two devices were used in way that its area would similar to commercial collector. Spiral collectors were placed in parallel and the fluid flow was considered the same in both ones. In the case of commercial collector, the fluid flow was also considered equally divided among all small diameter pipes. These assumptions were used in the numerical model for efficiency estimation of each collector.

Three experimental tests for spiral collector were performed in parallel with operating temperatures recorded during the experiment in one minute intervals. The fluid flow, solar radiation and wind speed measurements were done manually, sometimes during the experiment. Figure 4a shows the behavior for various temperatures in one test for commercial collector. Temperatures profiles for collector surface, inlet and outlet, for swimming pool and environment

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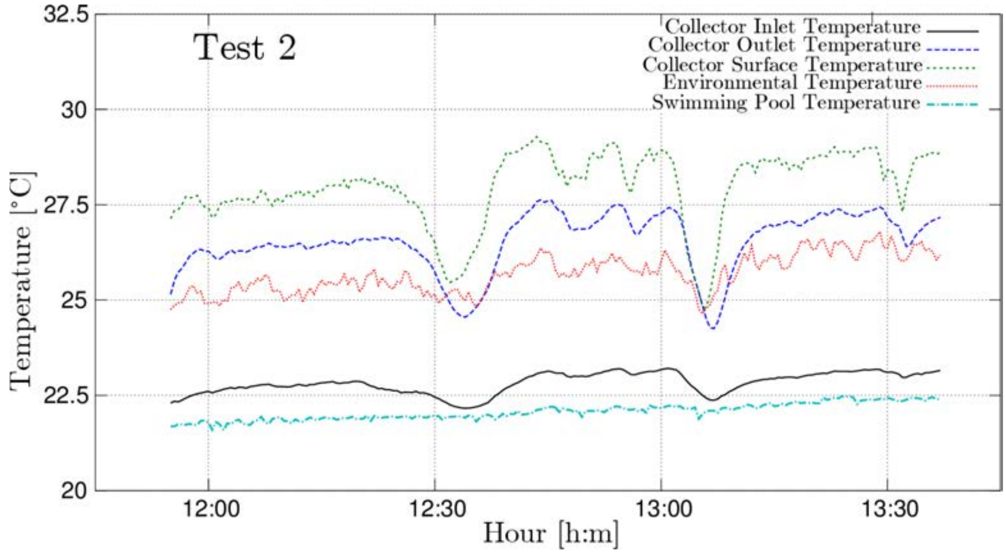
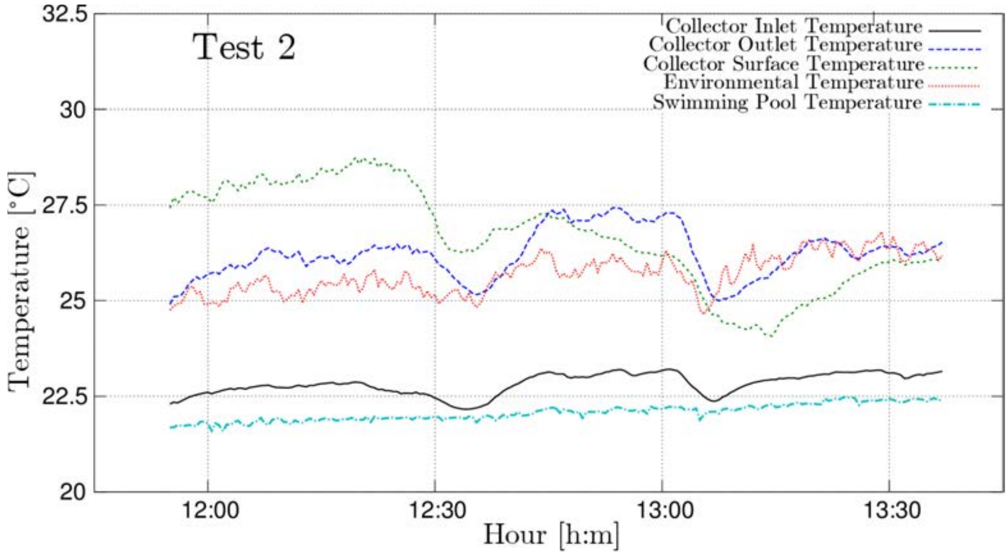
Table 1: Physical and geometric data for numerical simulation and tests.

Water	**Homemade Solar Collector**	**Commercial Solar Collector**
c_{ag}=4200 J/kg K	n_{div}=2 (massflow subdivisions)	n_{div}=116 (massflow subdivisions)
ρ_{ag}=990 kg/m³	D_{tc}=0.014 m	L=2.854 m
k_{ag}=0.66 W/m K	e_{tc}=0.0025 m	W=1.2 m
μ_{ag}=375 x 10^{-6} N/s m	L=94 m (calculated)	D_{tc}=5.3 mm
Poliethylene	$D_{i,esp}$=2 x 0.14 m	e_{tc}=1.5 mm
c_{pe}==1000 J/kg K	n_{esp}=33	A_{sc}=L x W
ρ_{pe}=1380 kg/m³	$D_{e,esp}$=2 x 0.77 m	P_{sc}=2 x (L+W)
k_{pe}=0.19 W/m K	A_{sc}=n_{div} xπ x($D_{e,esp}^2$-$D_{i,esp}^2$)/4	**Collector Positioning**
ε_{pe} = 0.92	P_{sc}=n_{div} xπ x($D_{e,esp}$+$D_{i,esp}$)	β=17°
		A_N=-185°

during testing times are shown too. The same temperatures of the homemade collector for this test shows may be seen in figure 4b.



(a) Commercial solar collector test



(b) Homemade solar collector test

Figure 4: Experimental data for a test of commercial and homemade solar collectors.

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Table 2: Experimental data for discrete measurements

Test	T_{amb}[°C]	G_r[W/m^2]	V_w[m/s]
1	27.7 ± 0.6	384.1 ± 137.2	2.8 ± 0.5
2	25.7 ± 0.8	338.1 ± 195.5	1.9 ± 0.8
3	25.7 ± 1.1	482.9 ± 231.1	2.2 ± 0.9

The results show temperature fluctuations during the testing period occasioned by changes in solar radiation, wind speed and ambient temperature. The temperatures measurements on inlet and outlet of each collector were done with PT100 type RTDs and other measurements are taken using T type thermocouples. Changes in pool temperature were not significant due to the small relationship of collection area and pool surface. Although the ideal situation would be also an acquisition of values for solar radiation, wind speed and flow, the device for this purpose were not available. Therefore, these measurements were manually done, at different times, and the mean values and statistical deviations were used as a representative for each of tests. The obtained values for each of the tests can be seen in table 2 and 3.

Table 3 also shows the temperature measurements on fluid flow input and output and, also, for the collector surface with their respective deviations. Results are presented for both types of collectors: commercial and homemade. One also can see on the table 3, for various presented conditions, estimations obtained by numerical model developed. For numerical simulations, data was included using only the reference values and the uncertainties are discarded. The numerical model performs estimations for the collector output temperature of fluid flow and average surface temperature. Although the test has been performed in parallel, the table shows the results separately for each one of the collectors. Taking into account the fluctuations in ambient conditions during the experiment, a good approximation for estimating temperature was verified.

Table 4 shows the results calculated using the input data like $\left(\Delta T/G_r\right)$ relation, Q_u and η values and uncertainties for each of these quantities. Considering the experimental data, it was calculated the value for these same parameters using the numerical simulation. The table columns described as Numerical and Experimental show these results, respectively. Since the values are based on estimations of the table 3, similar deviations between the numerical and experimental results are observed.

Analyzing these results, it was verified that the test numbered as 1 shows deviations higher than expected for theoretical and experimental values for both collectors. In this case, it is noted that the results are out of 90% confidence interval. This unexpected deviation may be due to the adopted methodology, where confidence interval for all the parameters are based on normal distribution and not the Student distribution, more suitable for smaller number of measurements. The results of tests 2 and 3 show a level adequate agreement with the experimental results.

Table 3: Fluid flow, numerical results and measured temperatures on tests.

Test	Flow [l/min]	T_{me} [°C]	Numerical		Experimental	
			T_{ms}[°C]	T_{sc}[°C]	T_{ms} [°C]	T_{sc}[°C]
Commercial Collector						
1	4.0 ± 0.15	22.0 ± 1.0	26.7	26.8	24.5 ± 0.5	28.1 ± 1.6
2	3.9 ± 0.20	22.8 ± 1.0	26.5	26.4	26.5 ± 1.3	28.0 ± 1.6
3	4.6 ± 0.30	23.2 ± 0.6	27.5	27.4	26.6 ± 1.3	28.4 ± 2.0
Homemade collector						
1	3.8 ± 0.15	22.0 ± 1.0	27.0	27.4	25.0 ± 0.7	26.5 ± 1.6
2	4.4 ± 0.10	22.8 ± 0.5	26.2	26.5	26.2 ± 1.0	26.7 ± 2.2
3	4.7 ± 0.50	23.2 ± 0.6	27.4	27.9	26.8 ± 1.1	28.1 ± 2.2

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Table 4: Parameters for efficiency analysis on tests.

Test	$\Delta T/G_r$ [°C m²/kW]	Numerical		Experimental	
		Q_{ut} [W]	η [%]	Q_{ut} [W]	η [%]
Commercial Collector					
1	-14.8 ± 6.1	1309.6	99.6	704.2±309.2	53.5 ± 30.3
2	-8.7 ± 6.4	918.9	85.9	1000.8±367.5	87.5 ± 60.5
3	-5.2 ± 3.6	1348.0	81.5	1079.7±471.4	65.3 ± 42.3
Homemade collector					
1	-14.8 ± 6.1	1307.5	94.5	800.5±317.4	57.9 ± 30.9
2	-8.7 ± 6.4	1019.7	84.8	1034.5±345.1	86.1 ± 58.0
3	-5.2 ± 3.6	1341.8	77.1	1135.6±425.8	65.3 ± 39.7

Considering these results, it is important present the linear correlation representing the behavior of the solar collector as a function of environmental conditions. This graph is used by many standards and contributes for evaluation of thermal losses behavior as function of temperature and incident radiation. This representation is taken from the equation (3) and represented in a diagram $(\Delta T/G_r)\times\eta$. Figure 5 shows this behavior for the commercial collector used on tests. Based on obtained results by numerical model, a linear regression was performed to obtain the parameters of collector behavior. The value of the constants obtained indicating that the correlation suitable for this collector is given by:

$$\eta = 0.703 - 0.019 \cdot \left(\frac{T_{me} - T_a}{G_r} \right) \tag{14}$$

In studies referring to solar heating systems for pools it is important to note that the operating temperature is very close, and in most cases, lower than ambient temperature. This fact implies that operation range will be in the negative region of graph where the heat transfer coefficient of losses for environment becomes a "gains" one. Factors associated

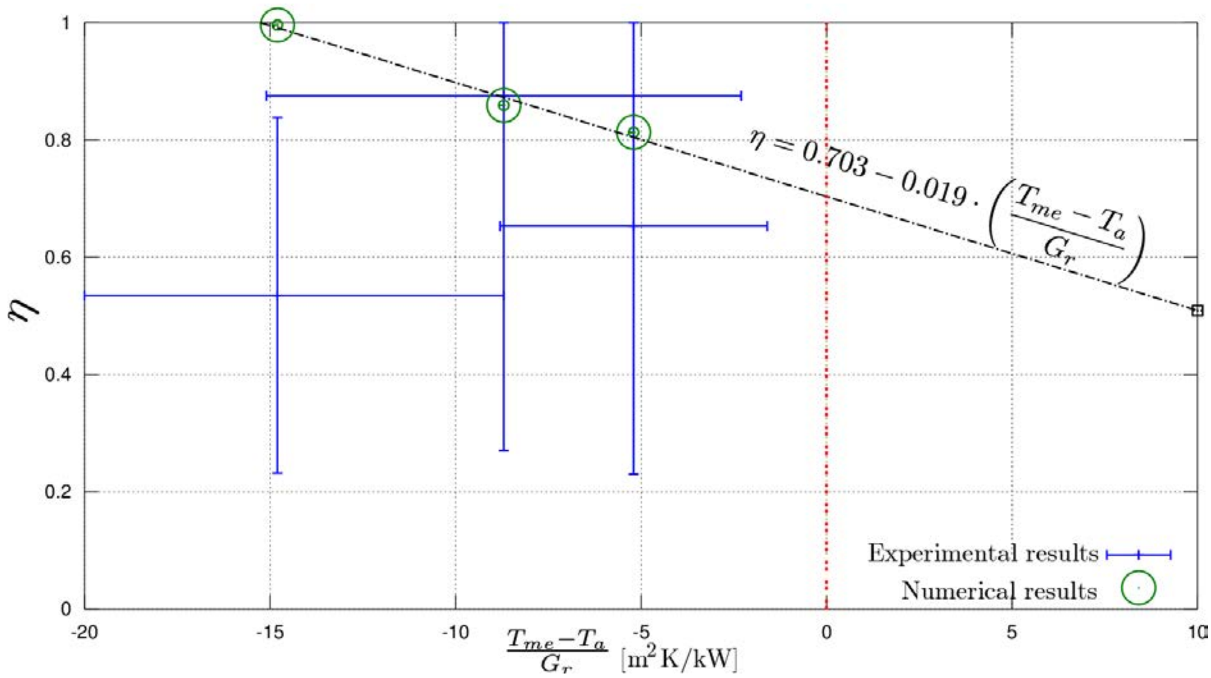

Figure 5: Efficiency behavior for commercial collector on tests.

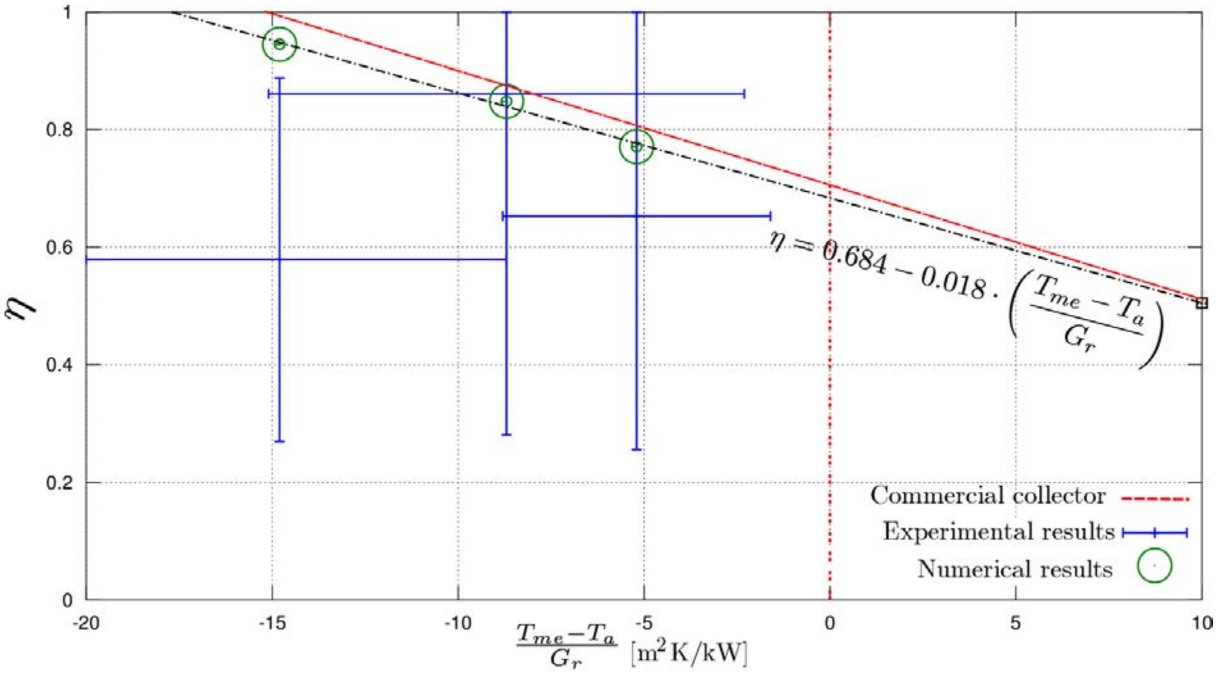

Figure 6: Efficiency behavior for homemade collector on tests.

with the pool thermal losses, mainly evaporation losses, make this fact quite common. In the studied case, all performed tests are in the negative range.

Figure 6 shows the behavior of homemade collector efficiency used in the tests. The procedure adopted is quite similar to presented for commercial collector. Using the results from numerical model, shown in table 4, a linear regression was performed to obtain the equation coefficients. The equation obtained in this case was:

$$\eta = 0.684 - 0.018 \cdot \left(\frac{T_{me} - T_a}{G_r}\right) \tag{15}$$

which is quite similar to equation for commercial collector presented on equation (14). For comparison aspects the behavior of the commercial one is showed. One can note small differences on equations and lines, as can be seen on Figure 6. Comparing linear regression coefficients, a lower base efficiency was verified but the changes in inclination representing lightly smaller heat losses coefficient.

4. CONCLUSIONS

Results show the efficiencies and their behavior are very similar for commercial and homemade collectors. The commercial collector has some advantages in overall system efficiency for situation which there is no heat transfer to the environment. However, the loss global heat transfer coefficient, which is associated with the slope of linear approximation, is slightly lower for homemade collector. This fact, although it is advantageous in the positive regions of graph, it is a disadvantage in the negative range. Anyway, the performance differences obtained are minor and other issues related to installation cost and visually pleasing roof tend to be the most relevant in decision making about which is more appropriated.

Referring to experiment, parameters taken manually could be acquired with higher sampling frequency on shorter tests, reducing the uncertainty of values and leading to results with a higher reliability rate. Future tests considering dynamic models in transient state can contribute to this analysis, too.

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