Conference Proceedings

Solar World Congress 2015
Daegu, Korea, 08 – 12 November 2015

Experimental evaluation of the influence of infiltration on the efficiency of solar flat plate collectors

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Abstract

PBE (Brazilian Labeling Program) is a national program in Brazil that aims to establish standard criteria to compare the energetic efficiency and quality of several devices, such as refrigerators, vehicles, and flat plate solar collectors. The vast majority of solar collectors tested by PBE fail in the topic of infiltration of water condensation. Arguably, the presence of water inside the collector decreases its efficiency, since part of the solar radiation is lost to heat the infiltrated water. However, the determination of the heat losses due to infiltration has not yet been proven in actual flat plate solar collectors, since it has not yet been properly measured. The aim of this study was to evaluate the influence of water infiltration in the efficiency of flat plate solar collectors, evaluating devices from three classes of energetic efficiency: A, B, and C. For the samples evaluated, it was observed that the influence of the amount of water infiltrated on the efficiency is not significant. Therefore, this criterion should not be used to promote the rejection of the collector.

Keywords: *Efficiency, Solar collector, Infiltration.*

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1. Introduction

A significant part of the energy consumption in residential segment is attributed to water heating (Prado and Gonçalves, 1998). According to Ghisi et al. (2007), it is estimated that refrigerators, freezer, air conditioners and electric showers account for nearly 60% to 70% of the Brazilian´s residential energy consumption. Also, except for the northeast of Brazil (the hottest region of the country), 81-92% of the Brazilian population use electric showers. Since electric showers consist of an electric-resistance water heater, they require very high electrical power (Oliveira and Rebelatoo, 2015). Flat plate solar collectors use the incident solar radiation to heat the water. Since Brazil has high levels of solar radiation and the solar collectors are able to operate with direct and diffuse components of solar radiation, these devices can successfully replacing electric showers. The basic parameter to consider in an analysis of a solar collector is its thermal efficiency, which depends on the collector parameters and thermal losses.

The efficiency of a solar collector depends upon how much a working fluid carries away the heat from the collector. Techniques are used to enhance the performance of solar collectors, mainly divided in increasing the heat transfer coefficient between the absorber plate/tube and the working fluid, using special type of coatings on the absorber (i.e, solar selective coatings), and increasing the thermal conductivity of the working fluid using nanoparticles (Suman, Khan and Pathak, 2015). Nanofluids are a mixture of liquid (base fluid) and nano sized particles (1-100 nm) suspended (Ferrouillat et al., 2013) that can be used instead of conventional heat transfer fluids (Al-Shamani et al., 2014).

Different countries have different standards to characterize and evaluate the efficiency of solar collectors. The most important standard for collector testing in Europe establishes a steady-state method and allows the application of a quasi-dynamic method performed outdoors. Osório and Carvalho evaluated and compared

doi:10.18086/swc.2015.10.15 Available at http://proceedings.ises.org

both the steady-state and the quasi-dynamic methods, showing similar results. The advantage of the quasi-dynamic tests was in terms of the time required to perform the analysis. Cruz-Peragon et al. (2012) proposed a 2D finite difference method to validate a characterization of a solar collector. Steady and transient states were analyzed under different operating conditions and results depicted the robustness of the method.

Sözen, Menlik and Ünvar (2008) developed a new formula based on artificial neural network to determine the efficiency of flat-plate solar collectors, for different conditions of ambient temperature, date, time, solar radiation, declination and azimuth angles.

In Brazil, there is a national program to evaluate and classify the solar collectors based on their energetic efficiency, named PBE – Programa Brasileiro de Etiquetagem (Brazilian Labeling Program). The efficiency is evaluated through a series of standard tests performed in laboratories, taking account several parameters, such as hydrostatic pressure, sealing, and water infiltration. According to the results, the collectors receive a grade from A to E, depending on the specific monthly energy production - PEME, according to the values shown in Table 1. One of the tests performed is the thermal shock, in which the device is exposed to water, and the maximum amount of infiltrated water is 5 g/m^2 of area. If the amount of infiltrated water exceeds this value, the solar collector is rejected.

It is well known that the infiltrated water reduces the efficiency of a solar collector, but the influence of the amount of water on the thermal efficiency has not been properly measured. The objective of this paper is to evaluate the thermal efficiency of solar collectors subjected to different levels of water infiltration. The tests were performed in devices evaluated as A, B, and C according to PBE Brazilian Program.

Tab. 1: Classification of the solar collector according to the energy production

Grade	Range of PEME (kWh/month-m^2)
A	PEME > 77
B	71 < PEME < 77
C	61 < PEME < 71
D	51 < PEME < 61
E	41< PEME < 51

2. Experimental setup

Experimental tests for the determination of the thermal efficiency of flat-plate solar collectors were performed in a closed location, using a Solar Simulator. This device consists of a eight special lamp system, with total power of 40kW, and the radiation spectrum similar to the sun. The artificial sky is composed of two tempered glass plates; between them, cool air flows, in order to simulate the radiation heat losses between the solar collector, sky and the wind generator system (Fig. 1).

Figure 1 – Solar simulator, front view

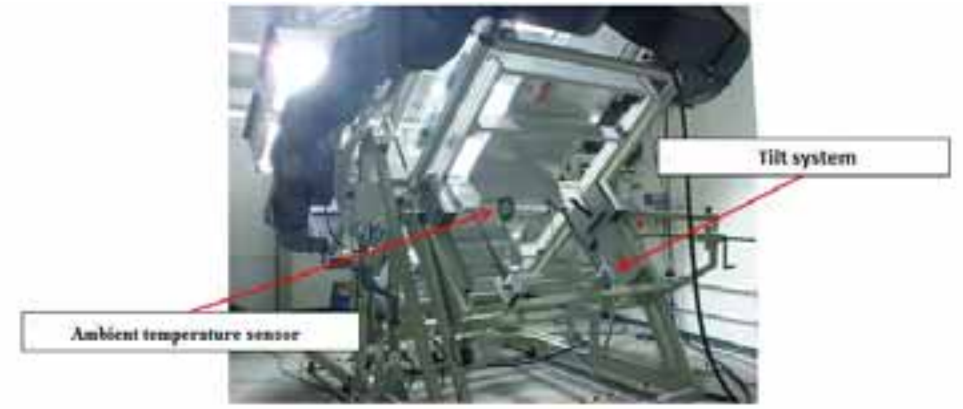

Figure 2 – Solar simulator, rear view

Figure 3 – Solar simulator and pyranometer

The tests followed Brazilian Standards NBR 15747-1 and NBR 15747-2. NBR 15747-1 specifies the reliability and durability requirements, safety and thermal performance of solar collectors for heating liquids. NBR 15747-2 specifies test methods for validating the durability requirements, reliability, safety and thermal performance of solar collectors for heating liquids presented in the previous standard.

In order to determine the efficiency, measurements of incident radiation on the solar collector plane, inlet and outlet water temperatures, volume flow rate and ambient temperature were performed, with the sensors indicated in Figures 2 and 3. A Precision Spectral Pyranometer (PSP) is used to determine the solar radiation, as indicated in Fig. 3. Platine resistance thermometer (PT100) are used to determine the inlet and outlet water temperatures and the ambient temperature (Fig. 2). The volume flow rate is measured with a volume flow meter. The wind velocity is controlled to be within the range specified by the Standards.

Based on the Quality Technical Regulations for Solar Water Heating Systems and Equipment, elaborated by the Brazilian National Institute of Metrology, Quality and Technology (INMETRO), the proof of non-compliance of the solar collector due to the infiltration and condensation must be performed through the thermal shock and rain penetration tests. The amount of infiltrated water is measured by the comparison of the weight of the solar collector before and after the exposure of the device to water for a pre-determined time interval. In order to be approved on the certification test of water penetration, the maximum acceptable amount of infiltrated water is 5 g/m^2. The ambient temperature inside the Solar Simulator was kept between 15°C and 30°C.

A, B and C collectors were tested, in order to evaluate how the class influenced the results.

Water was inserted into the collectors, in pre-established quantities, using a syringe. The range of leakage was determined from the maximum allowed quantity of 5g/m^2. The standard states that the solar collectors when subjected to rain penetration test must present a maximum infiltration of 5 g / m^2. The infiltrated water withdraw collector heat to warm itself, which could reduce its efficiency. It is not defined in the standard reason for the threshold value of 5 g / m^2 have been adopted. For each collector, four tests were performed, in quantities equal to 10 g/m^2, 20 g/m^2, and 30 g/m^2, named, respectively, Test 1, Test 2, Test 3 and Test 4. The dimensions and quantities of infiltrated water are presented in Table 2.

Tab. 2: Dimensions and amount of infiltrated water

Collector	Area (m^2)	Amount of water (g)			
		Test 1	Test 2	Test 3	Test 4
A	1.7068	0	17	34	51
B	1.0060	0	10.06	20.1	30.2
C	1.0171	0	10.17	20.35	30.5

3. Analysis

The collector efficiency is defined as the ratio of the useful gain over some specified time period to the incident solar energy over the same time period (Duffie and Beckman, 2006)

$$\eta = \frac{\int Q_u dt}{A_C \times \int G dt} \qquad \text{(eq.1)}$$

In eq. 1, G is the instantaneous solar radiation on the collector plane (W/m^2), A_c is the collector area (m^2) and Q_u is the useful energy gain.

The solar radiation is measured on the collector plane, as indicated in Fig. 3. The collector area is determined by the product of the width and length. The useful energy gain is determined by a energy balance between the outlet and inlet fluid.

$$Q_u = \dot{m}(h_o - h_i) \qquad \text{(eq.2)}$$

Where $\dot{m}$ represents the mass flow rate of the water inside the collector, h represents the specific enthalpy and the subscripts *o* and *i* refer to the outlet and inlet. The enthalpy change is determined by:

$$h_o - h_i = c_p(T_o - T_i) \qquad \text{(eq.3)}$$

The mass flow rate and the outlet and inlet temperatures are measured during the tests.

4. Results and discussion

In order to evaluate the influence of the infiltrated water in several kinds of solar collectors, type A, B, and C collectors were chosen. Table 3 shows the PEME and the uncertainties of the collectors, based on the tests performed without infiltration of water. It is important to mention that the PEME did not considerably change with the infiltrated water, with maximum variation of 4.3%, relative to type A collector.

Tab. 3: PEME and uncertainties collectors us without water infiltration tests

Collector	PEME (kWh/month-m^2)	Uncertainty (kWh/month-m^2)
A	84.87	0.32
B	83.90	0.34
C	75.66	0.37

The classification follows the range of values specified in Table 1.

Solar collector efficiency is expressed in the form of either a linear or a quadratic equation (Duffie and Beckman, 2006). The equations can be used to estimate the energy performance of a solar heating system. Based on the measurements the efficiency expressions were found for the collectors, for the tests performed. The expressions are given in Table 4. The average efficiency is defined as the efficiency for an abscissa of 0.02, which corresponds to the average value for a bath. The uncertainty is shown in the last column.

Tab. 4: Efficiencies of the solar collectors

	Expression	Efficiency with 0.02	Uncertainty
Collector A – Test 1	$\eta = 70.22 - 466.32\left(\frac{T_m - T_a}{G}\right)$	60.89%	0.32%
Collector A – Test 2	$\eta = 70.81 - 496.84\left(\frac{T_m - T_a}{G}\right)$	60.87%	0.33%
Collector A – Test 3	$\eta = 71.19 - 618.26\left(\frac{T_m - T_a}{G}\right)$	58.83%	0.41%
Collector A – Test 4	$\eta = 70.93 - 526.00\left(\frac{T_m - T_a}{G}\right)$	60.41%	0.37%
Collector B – Test 1	$\eta = 63.68 - 452.72\left(\frac{T_m - T_a}{G}\right)$	54.62%	0.34%
Collector B – Test 2	$\eta = 66.05 - 556.52\left(\frac{T_m - T_a}{G}\right)$	54.92%	0.38%
Collector B – Test 3	$\eta = 66.30 - 587.38\left(\frac{T_m - T_a}{G}\right)$	54.55%	0.40%
Collector B – Test 4	$\eta = 66.48 - 582.33\left(\frac{T_m - T_a}{G}\right)$	54.84%	0.41%
Collector C – Test 1	$\eta = 62.16 - 541.53\left(\frac{T_m - T_a}{G}\right)$	51.33%	0.37%
Collector C – Test 2	$\eta = 62.53 - 494.04\left(\frac{T_m - T_a}{G}\right)$	52.65%	0.34%
Collector C – Test 3	$\eta = 62.48 - 511.62\left(\frac{T_m - T_a}{G}\right)$	52.25%	0.36%
Collector C – Test 4	$\eta = 62.58 - 578.14\left(\frac{T_m - T_a}{G}\right)$	51.02%	0.41%

Figures 4 to 6 show the efficiency curves for collectors A, B, and C, respectively.

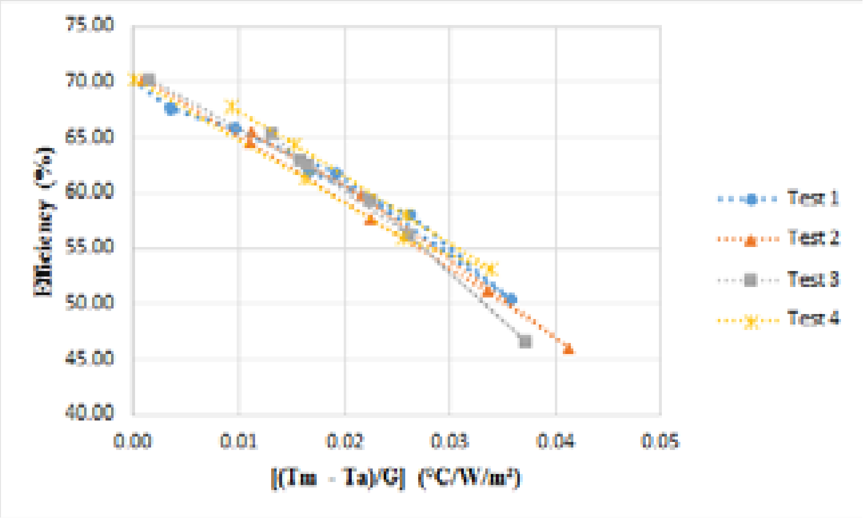

Figure 4 – Experimental collector efficiency for type A collector

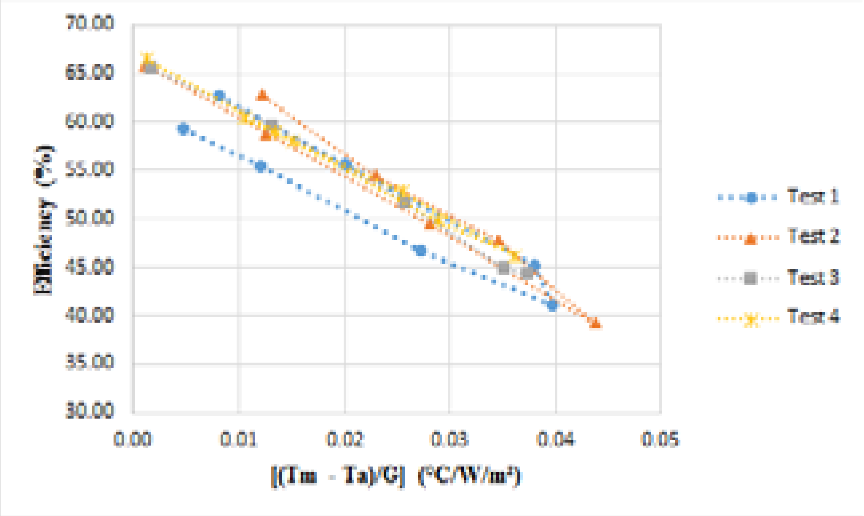

Figure 5 – Experimental collector efficiency for type B collector

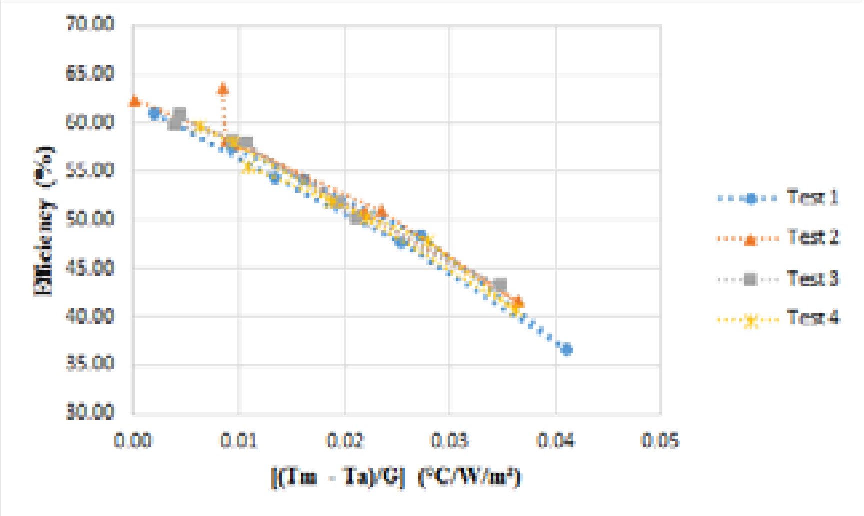

Figure 6 – Experimental collector efficiency for type C collector

It can be seen that the infiltration of water did not provide significant variations on the collector efficiency. The maximum variations of the average efficiency were 2.06%, 0.37% and 1.63%, for collectors A, B, and C, respectively. It is worth noting that, for type B collector, the efficiencies were within the uncertainty range, meaning that, for this collector, the water did not cause any effect on the average efficiency. It was not possible to determine a relationship between the amount of infiltrated water and the efficiency.

The Brazilian Standard specifies that, when the amount of infiltrated water in a solar collector exceeds 5 g/m^2 of area in the thermal shock test, it is rejected. The analysis performed showed that it was not possible to determine a decrease of the efficiency when values of 10, 20 and 30 g/m^2 of water are infiltrated. Therefore, the amount of 5 g/m^2 should not be considered to reject the new solar collector.

5. Conclusions

In this paper, it was evaluated the influence of water infiltration in a solar collector. There is not relationship between the infiltration and the classification of the collector A, B or C. Solar collectors of different specific monthly energy production were chosen to the analysis. The efficiency curve was obtained for the collectors without water and, subsequently, 10, 20 and 30 g/m^2 of water were infiltrated in the collector and the test was repeated.

The analysis showed that no significant variations of the efficiency or specific monthly energy production were observed with the infiltrated water for any type of collector, and that it could not be identified a relationship between the amount of water and the efficiency. Therefore, it can be concluded that the acceptable limits of the Brazilian Standard are too strict and should be rectified. The Standard is now in a revision process, in which the new limit is 30 g/m^2 to a higher period of sun exposure. Nevertheless, the analysis showed that, even this value is too strict.

Acknowledgments

The authors are thankful to PUC Minas, FAPEMIG and CNPq.

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