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THERMAL ANALYSIS OF A TUBELESS FLAT-PLATE SOLAR COLLECTOR

Felipe Boragina da Silva[1]
Guilherme Magalhães Viana[1]
Julia Maria Massareli Costa[1]
Vinicius Bizache Cruz[1]
Ana Beatriz Valentin[1]
Paulo Cesar Mioralli[1]
Elson Avallone[1]
[1] Instituto Federal de São Paulo – IFSP Câmpus Catanduva, Departamento de Indústria, Av. Pastor José Dutra de Moraes, 239, Distrito Industrial Antônio Zácaro, Catanduva-SP, 15808-305, Brazil
felipeboragina@gmail.com; guilhermemagalhaes2009@gmail.com; juliamassareli@hotmail.com; vinibizache@hotmail.com; anahh_beatriz@hotmail.com; mioralli@ifsp.edu.br; elson.avallone@ifsp.edu.br

Abstract. The tubeless flat-plate solar collector constitutes of two-parallel plates made of steel and welded to each other. The equipment configuration is simple, inexpensive and enables high thermal efficiency values in the water heating domestic process. Given these features, the feasibility study of the use of this collector in popular collective dwellings becomes interesting. The goal of this study is the construction and the thermal analysis of a tubeless flat-plate solar collector to be used in popular residences built from governmental programs for low-income families. The thermal analysis encompasses the measurement of the physical variables of the system and the evaluation of the useful energy gain and the thermal efficiency of the solar collector. An electronic system was developed using the Arduino® MEGA board for data acquisition and storage. Test results indicate that the tubeless flat-plate solar collector is efficient and a suitable alternative for heating water in popular houses.

1. INTRODUCTION

The energy demand on the planet has increased significantly in the last decades. Nowadays, a major focus has been given to the use of renewable energy due to the numerous environmental problems arising from the use of fossil fuels. Whenever possible, the association between low cost and preservation of the environment must be present in the framework of any project focused of energy supply, regardless of the intended energy modality and its purpose of use.

In the case of thermal energy conditioning for the heating of water in homes, the sun is an inexhaustible energy source that enables a good compromise between the two parameters of the aforementioned association. For this reason, researchers are investing in studies aimed at the development and improvement of different types of solar collectors.

In Brazil, the widely used solar heater is the flat-plate collector type, which is generally constructed of tubes and plates of conductive material, in order to optimize the thermal changes between the absorber and the water. However, the cost of this equipment may still be significant for some people, depending on the materials used in its manufacture, as well as the dimensions of the flat-plate and the tank. An alternative that aims to reduce the cost of this equipment is the use of hollow flat-plate collectors, without cover and with absence of tubes for water circulation. This type of collector is commonly called tubeless solar collector.

Some studies about tubeless solar collector are found in the literature. One of the pioneers investigating this equipment was Tamimi (1985) that analyzed a tubeless thermosiphon solar collector consisting of two parallel plates, where the treated water flowed in the space between them in a closed loop thermosiphon cycle. Steady-state performance of this system showed high efficiency values. Tamimi (1986) studied a tubeless solar collector of two-parallel plates made of galvanized steel and welded to each other. This type of collector proved to be more efficient and economic than conventional flat-plate solar collectors. Similar results to those obtained in this research were published by Tamimi (1987). An extended-surface flat-plate solar collector was investigated and tested by Tamini and Rawajfeh (1990). Comparative test results with an identical tubeless, flat-plate solar collector without surface extension, indicated that the surface extension by indentation improved the collector efficiency almost in the same proportion as the absorber area was increased by extension for the same heat flux. Another study similar to this was performed by Tamini and Rawajfeh (1992) two years later. A tubeless solar collector charged with Refrigerant-113 was installed and tested by Tamini and Rawajfeh (1991). High efficiency values were obtained from steady-state performance of this system due to phase-change heat transfer characteristics of a boiling process that is accompanied by low plate temperature as well as low thermal

resistance to heat flow from the absorber plate to the fluid. Al-Nimr (1995) compared the performance of a particulate tubeless collector with that of a conventional type. Two mathematical models which describe the steady state behaviour of these collectors were presented. It was verified that the efficiency of the particulate collector is higher than that of the tubeless conventional type, especially for high Biot and low Peclet numbers. Three years later, Al-Nimr and Alkam (1998) improved the thermal performance of a conventional tubeless collector by inserting porous substrates at the inner side of the collector absorber plate. The porous substrate improved the heat exchange between the absorber plate and the fluid. After the year 2000, studies about tubeless solar collector were less found in the literature. Abu-Qudais *et al.* (2002) experimentally studied a tubeless convex type solar collector and the results were compared with those obtained by the use of a tubeless flat-plate collector. The efficiency and the useful energy were considerably greater for the convex type collector than for the flat-plate collector under the same environmental and insolation conditions. In a more recent study, Abdulhadi and Ghorayeb (2006) investigated the thermal performance of a tubeless hemispherical solar collector for use in heating and cooling purposes. From the experimental-analytical investigation, the hemispherical collector was found to be much more efficient than a tubeless flat-plate collector.

The purpose of the present work is the manufacture and the thermal analysis of a tubeless flat-plate solar collector, in order to be an alternative of use in popular residences built from governmental programs for low-income families. This type of collector is a viable option for small collective dwellings because, besides adding low cost and sustainability, it presents advantages such as simplicity, ease of manufacture and great social impact. The thermal analysis of the tubeless collector is performed from the measurement of physical parameters such as inlet and outlet temperatures of the water inside the solar collector, the ambient temperature, the surface temperature of the flat-plate of collector, the mass flow rate of the circulating water and the local incident solar irradiation. The amount of absorbed heat by the collector and the thermal efficiency of the equipment are evaluated. An experimental apparatus was developed for solar collector accommodation and an electronic system using the Arduino® MEGA board was built for data acquisition and storage.

2. EXPERIMENTAL SETUP AND PROCEDURE

The tubeless flat-plate solar collector constitutes of two parallel concentric plates made of steel. The plates are welded to each other on the sides and spaced 9 mm apart. The dimensions in mm of the plates are 1000 x 600 x 0.6. A piping network connects the tubeless collector to the storage and supply tank. A set of valves are used to assist the operation of the system. The working fluid is water, which circulates through the system by thermosiphon mode. Figure 1 depicts the configuration of the system.
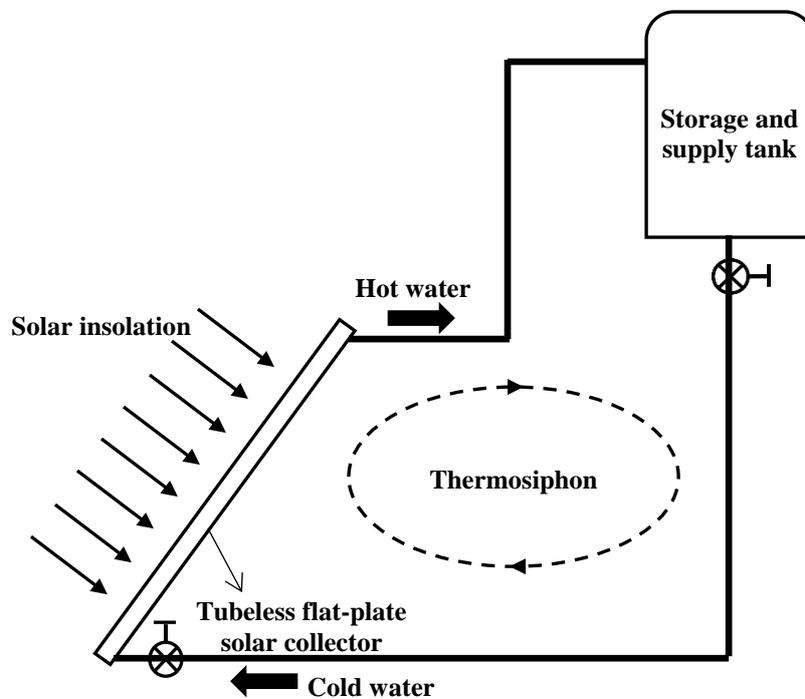

Figure 1. Configuration of the solar system with tubeless flat-plate solar collector.

A mechanical steel structure was manufactured for tubeless solar collector accommodation. The frame can be tilted at an angle of 0° to 90° from the horizontal plane, allowing the collector to be mounted in any region. The collector was installed with a slope angle corresponding to local latitude plus 10°. Moreover, the equipment was positioned with its

surface facing geographical north with a maximum deviation of up to 30° east or west (ABNT, 2008). The collector also received a layer of black paint in order to improve its thermal energy absorption capacity. The storage and supply tank was insulated with a thermal blanket to minimize the heat loss to the environment.

Dallas sensors DS18B20 were used to measure the inlet and outlet water temperatures as well as the collector surface temperature and the ambient temperature. The incident solar irradiation was measured from the pyranometer developed by Avallone *et al.* (2016, 2018). The water flow rate was measured from the Sea sensor model YF-S401 positioned near the water inlet of the collector. All measured variables were monitored and recorded at time intervals of 20 minutes from electronic system using Arduino® MEGA board. Tests were carried out during days under local typical weather conditions. The tests were performed in the period between 7:00 and 19:00 hours of the day.

Kalogirou (2009), Duffie and Beckman (2013) and Struckmann (2008) present the basic method for the thermal analysis of solar collectors. The accrued thermal performance of the tubeless flat-plate solar collector is determined from its exposure to solar radiation at steady state conditions with the variables of interest measured instantaneously at several intervals of time. So, the instantaneous useful energy gain of collector is given by

$$\dot{Q}_u = \dot{m} c_p \left(T_h - T_c\right) \tag{1}$$

where $\dot{Q}_u$ is the absorbed useful energy by the water inside the collector (W), $\dot{m}$ is water mass flow rate (kg/s), c_p is the water specific heat at constant pressure (J/kgK), T_h and T_c are, respectively, the water outlet temperature and the water inlet temperature in the collector, both in (K).

The total instantaneous energy received by the collector is given by

$$\dot{Q}_{tot} = A_c G_t \tag{2}$$

where $\dot{Q}_{tot}$ is the total incident solar energy (W), A_c is the useful area of the collector (m^2) and G_t is the global solar insolation on the collector (W/m^2) measured by the pyranometer.

The instantaneous thermal efficiency of the solar collector is defined as follow

$$\eta = \frac{\dot{Q}_u}{\dot{Q}_{tot}} \tag{3}$$

where η is the thermal efficiency of the solar collector, which is determined over a finite time period.

The saturated water thermophysical properties required for the thermal analysis of the tubeless solar collector were determined using the polynomial equations developed by Charters and Sadafi (1987).

3. RESULTS

Results were obtained including: temperature profiles, solar irradiation data, incident and absorbed energies and collector efficiency. All tests were performed from 7:00 to 19:00 hours in a day on Brazilian summer time. Figure 2 shows the water inlet and outlet temperature profiles inside the collector. Note that there was a significant increase in the water temperature at the collector outlet during a large period of the day.
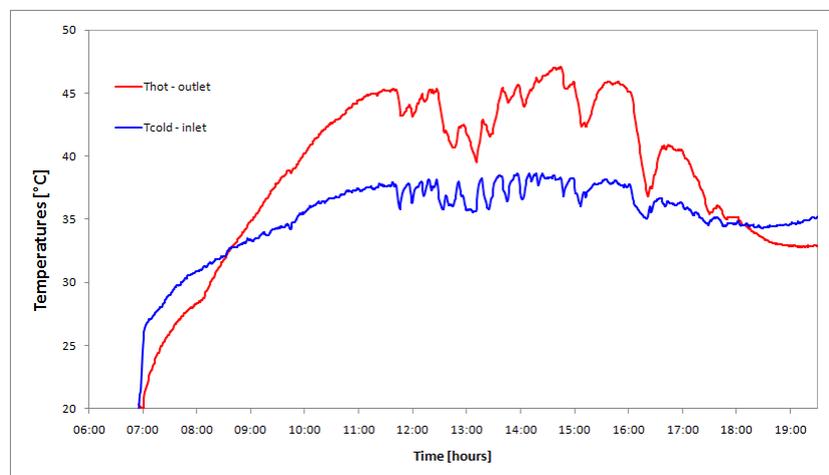

Figure 2. Water inlet and outlet temperature profiles.

The presence of clouds during the experiment is responsible for decreasing the outlet temperature values in the period from 12:30 to 13:30 hours. The mean increase in the outlet temperature when compared to the inlet temperature was around 19% over the test period observed in Figure 2.

Figure 3 shows the global solar insolation on the collector measured by the pyranometer. It is observed that the highest values of solar irradiation occur in the period from 11:00 to 15:00 hours. The instability of the solar intensity occurred in this period is due to the appearance of clouds during the experiment.
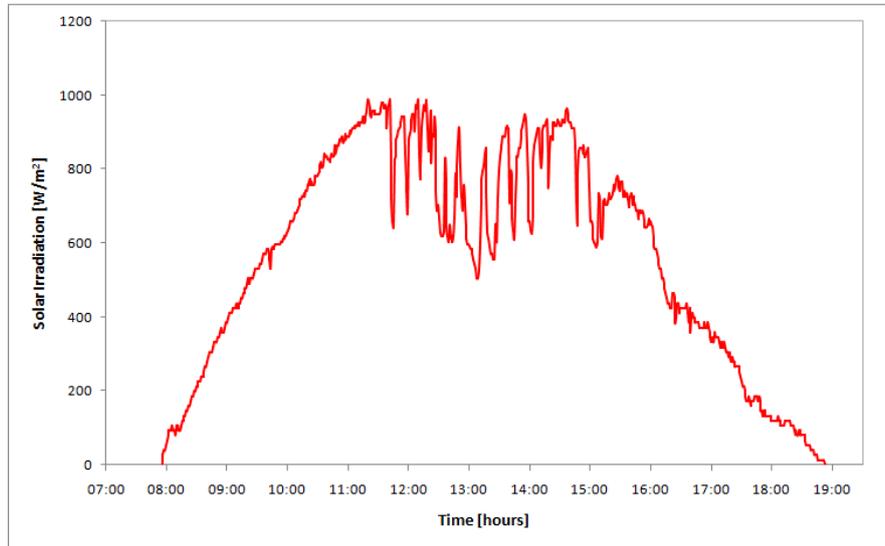

Figure 3. Global solar insolation on the collector.

The total incident and the absorbed useful energies are show in Fig. 4. The region between the two graph curves represents the energy loss of the system. The energy loss is more significant in the period from 11:00 to 15:00 hours, when there are high values of solar incidence and low energy absorption by the collector. In general, the absorbed useful energy by the collector is less than half the total incident energy.
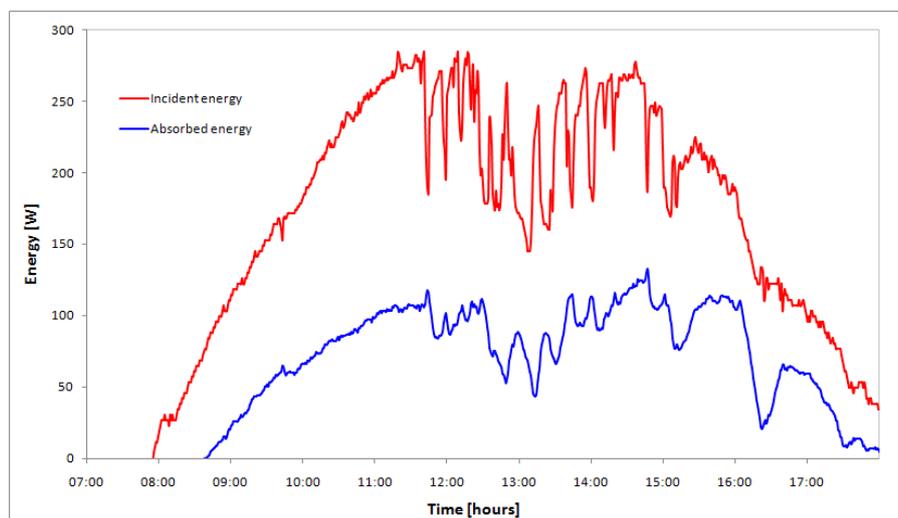

Figure 4. Total incident and absorbed useful energies.

Figure 5 shows the instantaneous thermal efficiency of the solar collector. Note that the efficiency increases considerably up to about 09:30 hours and decreases significantly from 17:00 hours. The average daily efficiency is around 40%.
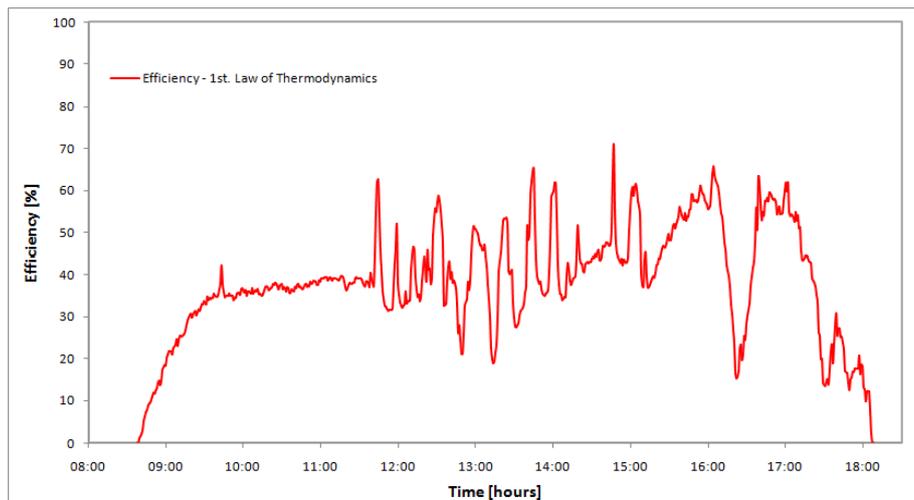
Figure 5. Instantaneous thermal efficiency of the solar collector.

4. CONCLUSIONS

In the present work, the manufacture and the thermal analysis of a tubeless s flate-plate solar collector were realized. The thermal analysis of the tubeless collector was performed from the measurement of physical parameters and the inlet and outlet temperature profiles, as well as the total incident energy, the absorbed useful energy and the instantaneous thermal efficiency of the solar collector were presented.

The testing results show that the tubeless flat-plate solar collector has potential to be used in domestic water heating systems for low-income families. The results obtained for this solar collector will also serve as a basis of comparison for a later study with a similar collector of the same material, dimensions and projected area, but with the presence of tubes inside.

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