



Analysis of absorbed energy and efficiency of a solar flat plate collector

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ABSTRACT. The highest percentage in home electricity demands in Brazil lies with the water heating systems, where the electric shower has a great contribution in consumption. The use of solar thermal panels is an alternative to minimize the strain on the electrical system by heating water. Current study evaluates a water heating system built with materials commonly used in home constructions. The tested collector is a 1 m² flat plate. Experiments were conducted at the State University of Western Paraná (UNIOESTE), campus Cascavel, Paraná State, Brazil. Temperature data were collected by PT100 sensors and solar radiation was measured with a pyranometer, coupled to a CR-1000 datalogger, with readings and collection every 5 minutes for 1 year. Data collection and analysis showed that the system presented monthly efficiency ranging between 33.7 and 53.54%, and energy absorbed between 30.79 and 75.29 kWh m⁻².month. Results show the system is a good option for use in residential or rural water heating due to decrease in the electric bill.

Keywords: flat plate collector, electricity demand, water heating system, solar radiation, pyranometer.

Análise da energia absorvida e eficiência de um coletor solar de placa plana

RESUMO. A maior parcela da demanda de energia elétrica no setor residencial no Brasil é consumida por sistemas de aquecimento de água, e o chuveiro elétrico tem grande contribuição no consumo. Visando minimizar a pressão sobre o sistema elétrico por parte do aquecimento de água, uma alternativa é o uso dos painéis termossolares. O objetivo deste trabalho foi avaliar um sistema de aquecimento termossolar construído com materiais comumente encontrados em construção civil, sendo o coletor ensaiado do tipo placa plana com 1 m² de dimensão. Os experimentos foram conduzidos na Unioeste (Universidade Estadual do Oeste do Paraná), no campus de Cascavel-PR, sendo que a coleta dos dados de temperatura foi feita com sensores PT100, a radiação solar com um Piranômetro, todos acoplados a um datalogger CR-1000, que realizou leituras e coleta a cada 5 min durante um ano. Após a coleta e análise dos dados, verificou-se que o sistema apresentou eficiências mensais variando de 33,7 a 53,54%, e a energia absorvida mensal variou de 30,79 a 75,29 kWh m⁻² mês. Assim, este sistema representa uma boa opção para ser utilizado em aquecimento de água residencial ou rural, reduzindo a conta de energia elétrica.

Palavras-chave: coletor placa plana, demanda de energia elétrica, sistema de aquecimento de água, radiação solar, piranômetro.

Introduction

Home electricity consumption in Brazil corresponded to approximately 24% of total energy consumption in 2013 (Oliveira, Ferreira, Almeida, Lobato, & Medeiros, 2008), whereas the electric shower has a major slice in total energy consumption of households in Brazil, consuming approximately 26% of household electricity and totaling 6% of national consumption (Oliveira et al., 2008). Most electricity for heating is consumed during peak hours, from 18 to 21h (Basso, Souza, Siqueira, Nogueira, & Santos, 2010), the time of day characterized by end of business, activation of street

lights, intensive use of household appliances, all imposing enormous pressure on the national interconnected system.

According to data by Pottmaier et al. (2013), about 65.6% of electric energy generated in Brazil in 2012 came from hydroelectric plants, with their electricity generation potential directly affected by changes in rain cycles or climatic variations due to the use in power generation rainwater stored in reservoirs. Since Brazil's energy matrix is extremely vulnerable to climate variations, possible multi-annual climate variability such as droughts may affect the capacity of power plants in the supply of

electricity demand (Bessa & Prado, 2015). The above situation compels the activation of natural gas thermoelectric plants, which currently corresponds to 10.6% of the energy generated in Brazil (Pottmaier et al., 2013), without taking into consideration 1.6% nuclear energy, 1.5% coal and 5.7% of petroleum products. In addition to being non-renewables, the latter two cause air and environment pollution (Souza, Schulz, Fischer, Wagner, & Sellin, 2012).

The use of alternative sources and energy rationing should be expanded to reduce the need of thermoelectric plants and lessen the vulnerability of the electricity system to climatic variations. One of the most promising sources is the use of solar thermal energy for water heating proposed by Wong, Mui, & Guan (2010) and Altoé, Oliveira Filho and Carlo (2012).

One of the basic systems for heating water by thermal energy is the flat plate collector (FPC) coupled to a thermally insulated water tank (Purohit & Michaelowa, 2008). Water circulation may occur in two ways: forced by pump or by natural convection thermosiphon, where the water is at the collector to be heated by solar radiation (Kalogirou, 2014). It decreases water density and tends to rise to the highest part of the system. As the warmer water rises, water at lower temperature moves down. This occurs until there is a thermal equilibrium temperature of the lower point towards the highest system (Pillai & Banerjee, 2007).

A well-sized solar water heating system, adapted to the geographic region and consumption conditions, may replace the electric heating of the water system (Chandrasekar & Kandpal, 2004). The collector may be used in various locations such as residential units, shopping malls, needy family's homes and on farms, where they may be used in heating water for cleaning milking equipment (Altoé & Oliveira Filho, 2010). The need of electricity for heating water decreases, especially in the case of showers, and electricity costs lowered (Oliveira et al., 2008).

Among the various ways to make use of solar energy, the solar water heating system is one of the most efficient ways to take advantage of this feature (Yu et al., 2014).

Studies in the northern hemisphere, at latitudes between 40 and 60°, have evaluated the performance of solar flat plate collectors (FPC) and efficiency averaging between 35 and 40% was recorded (Ayompe & Duffy, 2013a). Another study in Brazil (Naspolini & Rüther, 2012) registered that the consumption of electricity in an electric and thermo

hybrid system decreased by 38% mean annual consumption average and 42% at peak periods. According to Ayompe & Duffy (2013b), in Dublin, Ireland (53°20'N; 6°15' W), the evaluation of a thermosolar system with 4 m² collector plates, within one year, indicated a 39 - 55% efficiency.

On a global level analysis, the installed capacity of solar water heating system evolved from 160 GWth in early 2010 to 185 GWth in early 2011 (Allouhi et al., 2015), with more than 80% of panels manufactured in China during the period (Huang, Feng, & Zhang, 2014).

Brazil may be highlighted as one the countries with the greatest potential for the use of solar energy since most of its vast territory lies between the Equator and the Tropic of Capricorn, a region with more hours of solar radiation per day than any other (Jong, Sánchez, Esquerre, Kalid, & Torres, 2013). One of the limiting factors for the expansion of solar heating technology in Brazil is its high initial costs (Martins & Pereira, 2011). In order to minimize this difficulty, a solar heating system built with alternative inexpensive materials, commonly found in building constructions, was evaluated.

Current paper presents results of the thermal performance of a SWHS, with 1 m² FPC, and evaluates the system over a period of 12 months, to verify the amount of heating energy absorbed in this period and thus the system's efficiency. The assay sizes water heating systems and provides cost cuts in hybrid systems featuring solar energy and electricity.

Material and methods

Flat plate collector

The solar collector was assembled and data were collected for analysis at UNIOESTE, campus Cascavel, Cascavel, Paraná State, Brazil (24 56 '26 "S; 53 33' 32" W).

The mounted flat solar collector is basically composed of five main elements: a transparent cover (3 mm transparent glass); 32" PVC pipes (painted in matte black ink); aluminum plate-shaped omega, which lateral inclination of 45 degrees every 2.5 cm; thermal insulation (expanded polyurethane foam TYTAN PRO 30) and galvanized steel structure. Figure 1 gives a sketch of the collector. The model and the disposition of the system's parts of the panel were based on model described by Deng et al. (2013).

The transparent cover is tasked to reduce losses by convection and ensure the tightness of the collector to water and air, connected to carcass and joins. The greenhouse effect by the cover causes a part of the radiation that passes through the coverage

to be retained within the collector and defines its characteristics: high transmittance of solar radiation; low coefficient of transmission into long waves; low thermal conductivity; high reflection coefficient for the long wavelength of the radiation emitted by the collector plate. The heat absorbed by the glossy black painted aluminum plate and retained in the flat plate collector (FPC) is transferred to the water through PVC pipes, also painted matte black. Albeit simple, the solar heating system has certain fundamental details in its manufacture and installation for its smooth operation.

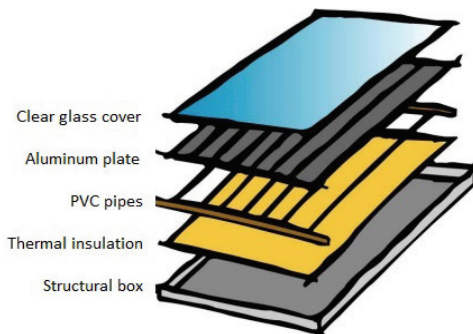


Figure 1. Flat plate collector (FPC).

The aluminum box, made of light and resistant metal below the PVC pipes, is protected in its lower part by a heat insulating blade to avoid heat losses. The main feature is insulation resisting high temperatures without deterioration. The material comprised expanded polyurethane foam, density between 30 and 80 kg m⁻³; compression strength of 200 N mm⁻²; thermal conductivity around 0.023 W mK⁻¹; friction coefficient of 0.0135; operating temperature between -40 and 115°C; high tensile strength, flexing and impact, lightweight; no electrical current conduction; ample flexibility in design for molding wrapped pieces to the collector. FPC housing (flat plate collector) consisted of a recycled aluminum structure (collecting, pressing, casting and rolling).

Data collection

Data from solar radiation comprised temperature of the water tank and ambient temperature. A pyranometer Kipp & Zonen, CMP3 model, with a sensitivity of 15.30 microvolts / watt / m², collected solar radiation data. It was installed near the collector as shown in Figure 2. Five J thermocouples connected at characteristic points of the system measure temperature at the collector inlet (T_{ec}), collector output (T_{sc}), reservoir outlet (T_{sr}), reservoir (T_r) and ambient temperature (T_a). Reading and data acquisition was made by a CR-

1000 datalogger, Campbell Scientific, to which all sensors were locked, with collections at 5-minute intervals for a period of 12 months, from July 11, 2014 to July 11, 2015.

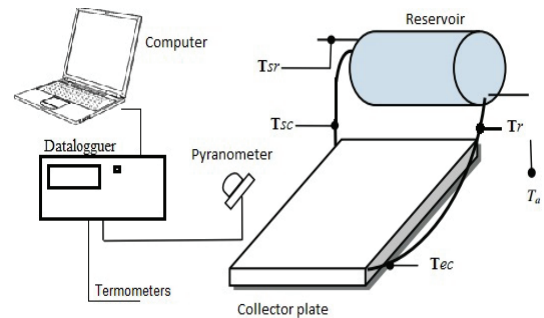


Figure 2. Scheme of data collection.

Analysis of performance

Efficiency was the parameter for the analysis of the system's performance. Rates were calculated by the amount of thermal energy absorbed by the system, following (Ling, Liu, Mo, Li, & Wang, 2015) and (Kalogirou, 2009), by Equation 1.

$$Q_d = \frac{m C_p (T_{rM} - T_{rm})}{860} \quad (1)$$

where:

Q_d - Absorbed daily energy (Wh day⁻¹).

m - water mass (g).

C_p - Specific heat of water (cal g⁻¹°C).

T_{rM} - Highest temperature recorded in the reservoir (°C).

T_{rm} - Lowest temperature recorded in the reservoir (°C).

By means of daily incident solar irradiation in Wh m⁻².day (measure obtained by collecting the pyranometer data) and absorbed energy, the efficiency may be calculated by Equation 2.

$$\eta_s = \frac{Q_d}{A_c * I_d} * 100 \quad (2)$$

where:

η_s = system efficiency (%).

Q_D = daily absorbed energy (Wh day⁻¹).

I_d = total day irradiation (Wh m⁻².day).

A_c = collector area (m²).

Results and discussion

The mean global solar irradiation on the day with the greatest incidence (December 4, 2014) was 328.02 Wh m⁻² throughout the day. Figure 3 shows irradiation variation on this day, which was not constant and varied according to cloudiness, with

peak 1296 Wh m^{-2} at 14:55. Total registered solar irradiation on this day was $7872.47 \text{ Wh m}^{-2}$ day. Variation on 4/12/2014 was similar to data variation reported by Michels et al. (2009).

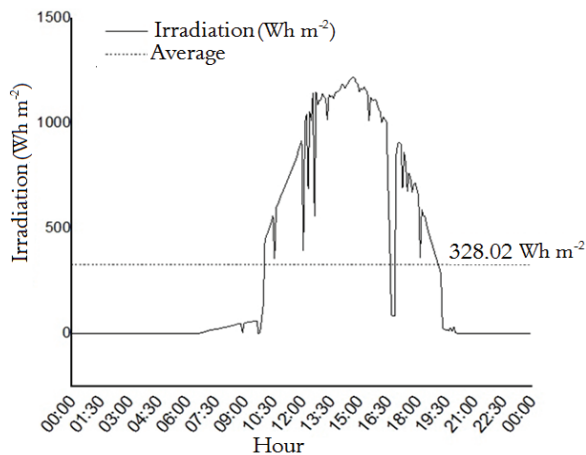


Figure 3. Solar irradiation throughout the day December 4, 2014.

Figure 4 shows data of solar energy and total solar irradiation on each month of the period analyzed. August 2014 had the highest rate in incident radiation when compared to that of the other months, at $164,637.28 \text{ Wh m}^{-2}$ month, whereas July 2014 had the lowest rate, at $65,570.06 \text{ Wh m}^{-2}$ month. It must be highlighted that measurements started on 11th July; adding the irradiation of the first 10 days of July, 2015, July still had the lowest total solar irradiance, with $88,657 \text{ Wh m}^{-2}$ month.

The month featuring the greatest energy absorption was August, with $75,291.95 \text{ Wh m}^{-2}$ month, absorbed by the system, while July, with $30,792 \text{ Wh m}^{-2}$ month, had the lowest absorption rate. When the entire period was taken into consideration, the absorption of a medium day radiation reached 1905 Wh m^{-2} day. The average solar irradiation for the city of Cascavel, Paraná

State, Brazil, for the given period and conditions of the experiment, was 4074 Wh m^{-2} day. The common rates for Cascavel, Paraná State are compared to the date obtained by Basso et al. (2010).

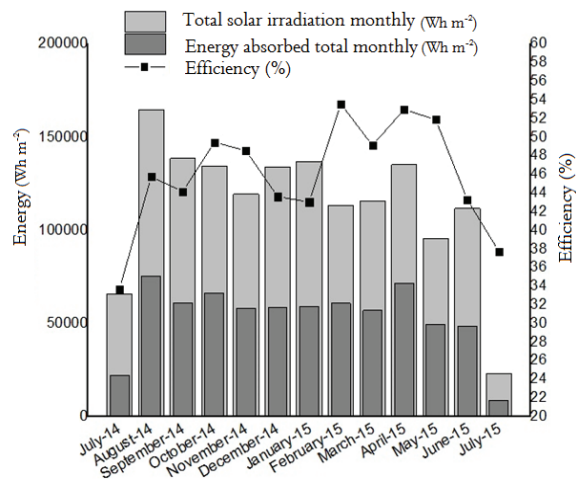


Figure 4. Monthly and absorbed solar energy and system efficiency.

August had the highest total solar irradiation due to the occurrence of a great number of days with low cloud cover. It was observed that since September total incident irradiation decreased due to a great number of days with increased cloud cover reducing the radiation that reached the plate, and therefore absorbed energy.

Throughout a one-year collection period, the system absorbed by a 1 m^2 flat collector plate was $695,394 \text{ Wh}$ thermal energy.

Verifying the efficiency variation over the whole period illustrated in Figure 5 and described in Table 1, the highest efficiency occurred on February 2015, with 53.54% at an average temperature 20.65°C . The month with the lowest efficiency was July 2014, with 33.7% at an average temperature of 17.42°C .

Table 1. System performance data.

	Total monthly solar irradiation (Wh m^{-2} month)	Total monthly energy absorbed (Wh m^{-2} month)	Efficiency (%)	Average temperature ($^\circ\text{C}$)
July 2014	65,570.06	22,090.45	33.69	17.42
August 2014	164,637.28	75,291.95	45.73	20.65
September 2014	138,395.06	61,086.18	44.14	23.04
October 2014	134,244.31	66,349.26	49.42	24.86
November 2014	119,332.58	57,915.79	48.53	22.81
December 2014	133,778.78	58,315.21	43.59	23.47
January 2015	136,880.94	58,885.54	43.02	24.32
February 2015	113,240.89	60,624.91	53.54	22.53
March 2015	115,713.13	56,802.86	49.09	24.70
April 2015	135,015.01	71,496.53	52.95	22.99
May 2015	95,561.69	49,550.61	51.85	18.43
June 2015	111,600.08	48,282.02	43.26	19.10
July 2015	23,087.25	8,702.23	37.69	15.63

The system's average efficiency reached 45.9% over one year, with average temperature 21.54°C during the period. The coldest month was July 2014, with 15.63°C, whereas the hottest was October/2014, with 24.86°C.

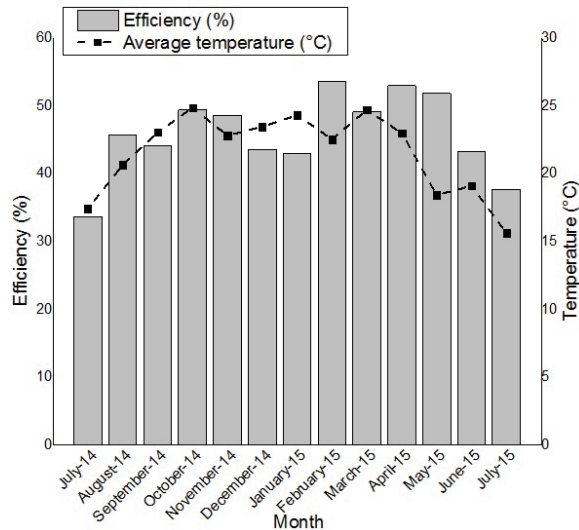


Figure 5. Efficiency and temperature during the studied period.

Efficiency rates lie within the variation range reported by Ayompe & Duffy (2013b), with efficiency ranging between 39 and 55% and by Ayompe & Duffy (2013a) between 35 and 40% of variation efficiency.

When average rates of monthly efficiency and air temperature are analyzed, one may not conclude that there is a direct relationship between efficiency and temperature. However, efficiency and temperature increased together in the first four months. Further, a relationship between the variations of the two measurements occurred during the last two months, with no relationship between efficiency and average temperature during the other months.

The variation of daily solar energy absorbed by the system in September 2014 (Figure 6) revealed that during that month the temperature variation directly affected the variation of the system's efficiency. In two days, namely on the 14th and on the 26th, a 15°C drop occurred in the temperature, with a drastic decrease of 30% in the system's efficiency, down from a 44.14% monthly average. This decrease would be caused by thermal losses in some parts of the system. Although wind speed was not measured on the day temperatures dropped, wind gusts associated to the passage of cold fronts, characteristic of the period, enhanced heat dissipation.

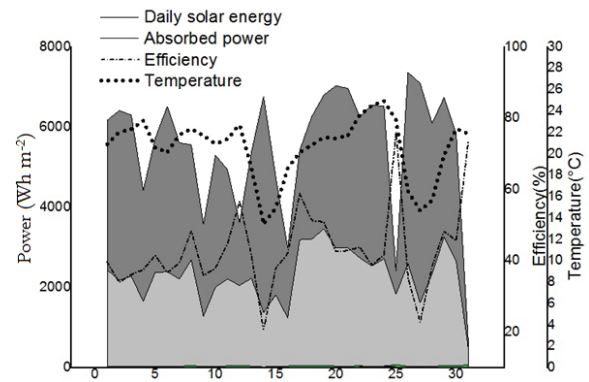


Figure 6. Daily and absorbed solar energy, efficiency and temperature on September 2014.

Conclusion

It may be observed that, as a rule, the system presented a satisfactory average efficiency of 45.9%, consistent with that found by other investigators who evaluated systems manufactured with standard materials. The above shows that the system made with common building materials may be used in residential water heating systems. Taking the effect of temperature on the system performance into account, it may be noted that no major influence has been observed in the performance when the monthly average values are observed. However, the variation of temperature and efficiency on September 2014 revealed a negative influence of low temperatures on the efficiency of the system and enhanced the need in the improvement of the insulation system.

The system absorbed 695,394 Wh of thermal energy throughout the period studied, at an average of 1905 Wh m².day. This amount of energy may replace electric showers in water heating, or may minimize electricity consumption in hybrid systems with heating solar electric water. Solar Water Heating System may reduce dependence on fossil fuels and increase the sustainability of residential.

Performance data measure solar thermal collectors of water, based on the demand to be met, or rather, the number of square meters required to supply all or part of the demand for hot water. In fact, the system is a method to convert solar energy into useful energy with high efficiency.

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