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Evaluation of a tracking flat-plate solar collector in Brazil

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HIGHLIGHTS

- A model was developed for solar radiation based on experimental data for K_T.
- Useful energy gain and efficiency of a flat-plate solar collector were evaluated for a one-year period.
- Several sun tracking systems were compared to fixed devices.
- Tilt angle for a fixed device does not significantly affect the useful energy gain.

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ABSTRACT

The continuing research for an alternative power source due to the perceived scarcity of fuel fossils has, in recent years, given solar energy a remarkable edge. Nevertheless, the Earth's daily and seasonal movement affects the intensity of the incident solar radiation. Devices can track the sun in order to ensure optimum positions with regard to incident solar radiation, maximizing the absorbed solar energy, and the useful energy gain. In this paper, a mathematical model is developed to estimate the solar radiation absorbed, the useful energy gain, and the efficiency of a flat-plate solar collector in Brazil. The results for a sun tracking flat-plate solar collector were compared to fixed devices. The full tracking system with rotation about two axes presented higher absorbed energy, when compared to the rotation about a single axe and to a fixed collector. Also, it was shown that the tilt angle for a fixed solar collector does not cause significant variations in the useful energy gain or in the absorbed solar radiation, for the same azimuth angle.

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1. Introduction

Energy is essential for the economic growth and social development of any country. The quality of life is closely related to energy consumption, which has continuously increased over the last few decades in developing countries. The result is that energy demand is increasing and cannot be satisfied by traditional energy technology. Besides, there is a connection between energy consumption and environmental impacts. The world's total primary energy supply is essentially based on fossil sources, as shown by IEA [9]. In 1973, renewable sources were responsible for 12.5% of the total primary energy supply, and in 2009, for 13.3%. Therefore, finding clean sources of energy to satisfy the world's growing demand is one of the society's foremost challenges for the next half-century.

Solar energy is a clean, renewable, abundant and cheap source of energy. Solar heating technologies use solar energy to provide heat. Collectors can be designed to provide heated water on a household scale, but the technology is also being increasingly employed on larger scales to provide hot water for commercial and industrial operations or linked to district heating installations [10]. A flat-plate collector is the simplest device available for solar energy utilization. Flat-plate collectors can be designed for applications requiring energy delivery at moderate temperatures, up to 100 °C above ambient temperature [4]. The solar thermal collector capacity in operation worldwide at the end of 2009 was equivalent to 172.4 GW_{th}. Between 2004 and 2009, the annually installed glazed water collector area worldwide had almost tripled, and the worldwide average annual growth rate between 2000 and 2009 was 20.8% [9]. According to ABRAVA (Brazilian Association of HVAC) data, in 2010 the Brazilian production of solar collectors increased 21.1% above that of 2008, achieving 6.2×10^6 m^2.

The amount of energy absorbed by a solar collector plays an important role in the sizing and optimizing of solar systems. The

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performance of a flat-plate solar collector is highly influenced by its orientation and tilt with the horizontal. It is important to know the optimum tilt and azimuth angles at which to mount a fixed collector on a flat roof or on the ground such that it receives maximum irradiation [14]. The diurnal and seasonal movement of the Earth affects the radiation intensity on solar systems. Sun trackers move the solar systems to compensate for these movements, keeping the best orientation relative to the sun [15].

Ref. [15] described different types of sun-tracking systems and discussed their pros and cons. Solar tracking can be implemented by using one-axis, and for higher accuracy, two-axes. For a two-axes sun-tracking system, two types are known: polar (equatorial) tracking and azimuth/elevation (altitude–azimuth) tracking. Sun-tracking systems are usually classified into two categories: passive (mechanical) and active (electrical) trackers. Ref. [1] presented a general form of sun-tracking formula that embraces all the possible on-axis tracking methods. The application of the general formula is to improve sun-tracking accuracy. According to the authors, the expression can be used in immediate solar receivers or reflectors that direct sunlight to a target.

Although the use of sun-tracking systems can be applied to both flat-plate solar collectors and photovoltaic cells, it is more common to find literature related to photovoltaic systems [5,7,14,18,20]. During the last few years, photovoltaic solar systems have become one of the most popular renewable energy sources. Nevertheless, the high cost of these installations in relation to the generated electricity constitutes one of the main barriers of this technology. In this sense, one-axis and two-axes solar-tracking systems seem to be an attractive alternative compared to the fixed systems since they make it possible to maximize the capture of solar energy [3].

Ref. [6] studied the theoretical aspects of choosing a tilt angle for the solar flat-plate collectors used in Egypt and made recommendations on how the collected energy can be increased by varying the tilt angle. In order to perform this analysis, the authors compared three anisotropic models for solar radiation with experimental data for vertical surfaces facing south and determined the most accurate model. Then, this model was used to determine the optimum collector slope based on the maximum solar energy availability. The results showed that the optimum tilt angles with respect to the maximum daily incident insolation amounts on the collector surface exhibit a strong seasonal trend. The maximum yearly solar radiation can be achieved using a tilt angle approximately equal to a site's latitude. Ref. [11] developed a computer program to simulate the collected energy by a solar flat-plate collector for a varying tilt angle, with the surface facing toward the Equator. Ten different locations in the world were simulated. It was shown that nearly optimal energy can be collected if the angle of tilt is varied seasonally, four times a year. The annual optimum tilt angle was found to be approximately equal to the latitude of the location. The authors concluded that a yearly average fixed tilt could be used in many general applications (e.g. domestic water heating) in order to keep the manufacturing and installation costs of collectors low. When higher efficiency is required, solar tracking systems can be used. Ref. [12] predicted the optimum slope and surface azimuth angles to determine the maximum solar energy gain for solar flat-plate collectors in Iran. The results showed that the energy gain of the collector when it is adjusted to the daily optimum slope angle is almost the same compared with the case of the monthly optimum slope angle. With the results for the monthly optimum slope angle, a map was outlined for a fixed collector used for the entire year.

In this paper, a mathematical model is used to predict the absorbed energy, the useful energy gain and the thermal efficiency of a flat-plate solar collector. A comparative study of several tracking systems is presented. For a fixed slope, the parameters were determined for several slopes. The influence of the inlet temperature of the water, the number of covers, and the plate emittance was also studied.

2. Mathematical model

The equation set presented in the mathematical model was developed according to Ref. [4]. In order to study the influence of the tilt angle, the performance of a flat-plate collector was determined, based on an energy balance that indicates the distribution of incident solar energy into useful energy gain, and thermal and optical losses. A steady state condition was assumed.

The collection efficiency of a flat-plate solar collector is defined as the ratio of the useful gain over some specified time period to the incident solar energy over the same time period. In this paper, the time period considered was 1 day:

$$\eta = \frac{\int Q_u \mathrm{d}t}{A_c \int G_T \mathrm{d}t} \tag{1}$$

where G_T is the incident solar radiation. Q_u represents the useful energy output of a collector of area A_c, given by:

$$Q_u = A_c\left[S - U_L\left(T_{pm} - T_a\right)\right] \tag{2}$$

where S is the solar radiation absorbed by the collector, U_L is the collector overall loss coefficient and T_{pm} and T_a represent the mean absorber plate temperature and the ambient temperature, respectively. The collector overall loss coefficient is the sum of the top, bottom and edge loss coefficients,

$$U_L = U_t + U_b + U_e \tag{3}$$

The top loss coefficient U_t takes into account convection and radiation thermal losses to the surroundings through the top of the collector. The bottom loss coefficient U_b represents convection and radiation losses to the environment through the back, and the edge loss coefficient represents the losses from the edge of the collector. The modeling of these loss coefficients is the same as that presented in Ref. [4] and it was suppressed.

The mean absorber plate temperature is solved in an iterative procedure involving the collector overall loss coefficient, as suggested by Duffie [4]. The ambient temperature is fixed for the problem.

The absorbed solar radiation was determined on an hourly basis, assuming an isotropic sky model. Radiation was considered to include three components: beam radiation, isotropic diffuse radiation, and solar radiation diffusely reflected from the ground:

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \left(\frac{1+\cos\beta}{2}\right) + \rho_g (I_b + I_d)(\tau\alpha)_g \left(\frac{1-\cos\beta}{2}\right) \tag{4}$$

where I_b and I_d represent the beam and diffuse components of the incident solar radiation, respectively. R_b is the geometric factor, defined as the ratio of beam radiation on the tilted surface to that on a horizontal surface at any time. β is the slope of the collector, ρ_g is the ground reflectance, and $(\tau\alpha)_b$, $(\tau\alpha)_d$ and $(\tau\alpha)_g$ represent the transmittance–absorptance products for the beam, diffuse and ground-reflected radiation, respectively.

The transmittance–absorptance product is a property of the system. It is well known that, of the radiation passing through the cover system and incident on the plate, some is reflected back to the cover system. However, all this radiation is not lost since some of it is, in turn, reflected back to the plate. There are multiple reflections of the radiation between the cover and the absorber plate, in such a way that

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