INFLUENCE OF FLOW RATE AND TEMPERATURES ON THE THERMAL EFFICIENCY OF FLAT PLATE SOLAR COLLECTORS

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Abstract. *Thermal efficiency is often used as one of the most important parameters for the comparison of flat solar collectors. It depends on the physical and geometrical parameters of the collector and of the heat losses to the environment. The efficiency is determined in the thermal performance test, in which solar radiation, the water flow rate, ambient temperature, and inlet and outlet water temperatures are measured. In this work, we intend to evaluate the influence of flow rate, ambient temperature and inlet temperature on the average annual efficiency of a solar collector. A mathematical model to determine the solar radiation absorbed by the collector and the outlet temperature of the water to the city of Belo Horizonte was developed. With these parameters, it was possible to determine the instantaneous collector efficiency. Efficiency was evaluated for the 24 hours of the day, for 365 days of the year. It was observed that the efficiency increases with the flow rate and ambient temperature and decreases with temperature water inlet.*

Keywords*: Efficiency, Flat solar collectors*

1. INTRODUCTION

The solar radiation that reaches the Earth's surface is the most abundant source of energy available to all human activities (Binotti, Manzolini and Zhu, 2014). Among the solutions to the global energy problem, the use of solar energy is one of the most encouraging ecological alternatives. Solar energy is renewable, non-polluting and inexhaustible, and it seems promising to offer sustainable solutions for environmental protection and conservation of conventional energy sources (Buker and Riffat, 2015) Solar thermal systems have been recognized as able to partially or totally replace fossil fuels for heating, cooling and domestic hot water supply in the next 50 years (Visa et al., 2015).

The main component of any solar system is the collector. Solar collectors are devices that absorb and convert incident solar radiation into heat, which is transferred to a fluid (usually air, water or oil). The collected solar energy is transferred directly to the hot water or for space conditioning equipment, or even to a storage tank to be used when there is no sunlight (Kalogirou, 2015).

Brazil receives higher average levels of solar radiation than those in most European countries, with low seasonal variability, since it is located in the tropical zone (Martins and Pereira, 2011). The use of solar energy in Brazil can benefit from a social, economic and environmental point of view. The solar water heating is the most consolidated application for solar collectors in Brazil and worldwide. Although there is no power generation in its broadest sense, the reduction in the share of electric showers in the demand from electric utilities can be interpreted as a virtual power generation.

The thermal efficiency of a solar collector is used as one of the most important parameters to introduce and compare thermal systems, including flat solar collectors (Jafarkazemi and Ahmadifard, 2013). An efficient collector must be able to perform this process of capture and conversion of solar energy with minimal losses to the environment. The efficiency depends on the collector physical parameters and operating parameters such as mass flow, ambient and input temperatures and solar radiation. For a collector installed in a particular location, the incident solar radiation is fixed. The objective of this study is to evaluate the influence of other operating parameters on the efficiency of a flat solar collector.

2. MATHEMATICAL MODEL

The mathematical model was developed according to Duffie and Beckman (2006). The efficiency is determined from an energy balance, which indicates the distribution of the incident solar radiation into useful energy gain, thermal and optical losses. Efficiency is defined as the ratio of the useful energy gain over a specified period of time and the incident solar energy over the same period. In Equation (1), G represents the total solar irradiance in the collector plane, A_c is the area of the collector and Q_u represents the useful energy gain.

The useful energy gain is determined by Equation (2). S is the solar radiation absorbed by the collector, U_L is the global coefficient of heat losses from the collector and T_{pm} and T_a represent, respectively, the instantaneous average temperature of the absorbing plate and ambient temperature. The overall coefficient of heat transfer is the sum of the top (U_t), bottom (U_b) and edges of the collector (U_e) coefficients, according to Equation (3).

$$\eta = \frac{\int Q_u dt}{A_c \int G dt} \tag{1}$$

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

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

The above heat loss coefficients consider losses by convection and radiation to the environment. The lateral losses were discarded, as suggested by Duffie and Beckman (2006). The determination of the average temperature of the absorbing plate is performed by an iterative procedure, and the ambient temperature was considered constant during analysis.

The solar radiation absorbed by the plate was determined on an hourly basis, assuming an isotropic sky model. The radiation was divided into three portions: direct (I_b), diffuse (I_d) and the diffusely reflected portion of the ground. R_b is the geometric factor defined as the ratio between the direct radiation on an inclined surface and the direct radiation on a horizontal surface instantly. β is the collector tilt, ρ_g is ground reflectance and $(\tau\alpha)_b$, $(\tau\alpha)_d$ and $(\tau\alpha)_g$ represent the transmittance-absorptance product for the components of direct radiation, diffuse and reflected by the ground, respectively.

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

$$(\tau\alpha) = \frac{\tau\alpha}{1-(1-\alpha)\rho_d} \tag{5}$$

The product $(\tau\alpha)$ is given by Equation (5), where τ is transmittance of the collector at a given angle, α is the absorptance of the plate and ρ_d is system collector for the diffuse reflectance of the incident radiation. The optical losses can be estimated for a given angle of incidence, as suggested by Duffie and Beckman (2006). The incidence angle for direct radiation is given in terms of collector slope and the time and the angles of incidence for diffuse and reflected plots the ground are given respectively by Equation (6) and Equation (7).

$$\theta_d = 59.7^\circ - 0.1388\beta + 0.001497\beta^2 \tag{6}$$

$$\theta_g = 90^\circ - 0.5788\beta + 0.002693\beta^2 \tag{7}$$

Rb is given by Equation (8), θ represents the incidence angle of direct radiation, given by Eq. (9) and θ_z is the zenith angle given by equation (10). In Eq. (9), it was considered that the solar collector has a fixed tilt and is facing north. ϕ is the latitude, δ is the declination and ω is the hour angle.

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{8}$$

$$\cos\theta = \cos(\phi+\beta)\cos\delta\cos\omega + sen(\phi+\beta) sen\delta \tag{9}$$

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + sen\phi\ sen\delta \tag{10}$$

The collector efficiency and the absorbed solar radiation were determined for a period of one day, on an hourly basis and the hourly radiation was estimated from daily data. The procedure was repeated for 365 days of the year. The solarimetric data used refer to the monthly average solar radiation to the city of Belo Horizonte, Brazil (latitude and longitude of 19°55'S and 43°56'W, respectively). The clearness index K_T is the ratio of solar radiation (H) and extraterrestrial radiation for the same day (H_o), Equation (11).

$$K_T = \frac{H}{H_o} \tag{11}$$

The extraterrestrial radiation is determined by Equation (12), where G_{sc} is the solar constant, equal to 1367 W/m², n is the nth day of the year and ω_s is the hour angle of the sunset.

$$H_o = \frac{24 \cdot 3600 G_{sc}}{\pi}\left[1 + 0.033 \cos\left(\frac{360^\circ n}{365}\right)\right]\left(\cos\phi \cos\delta \, sen\,\omega_s + \frac{\pi\omega_s}{180^\circ} sen\,\phi \, sen\,\delta\right) \tag{12}$$

The estimate of hourly solar radiation from the daily data was based on the methodology proposed by Collares-Pereira and Rabl (1979). The ratio between the hourly and daily radiation is given by:

$$r_t = \frac{I}{H} \tag{13}$$

Where

$$r_t = \frac{\pi}{24}(a + b\cos\omega)\frac{\cos\omega - \cos\omega_s}{sen\,\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s} \tag{14}$$

$$a = 0.409 + 0.5016\, sen(\omega_s - 60)$$
$$b = 0.6609 - 0.4767\, sen(\omega_s - 60)$$

The ratio of the diffuse radiation and the total time is given by Equation (15). r_d is estimated by Equation (16).

$$r_d = \frac{I_d}{H_d} \tag{15}$$

$$r_d = \frac{\pi}{24}\frac{\cos\omega - \cos\omega_s}{sen\,\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s} \tag{16}$$

The distribution of daily radiation, monthly average in its direct and diffuse components is obtained from the correlation Collares-Pereira and Rabl (1979), Equation (17).

$$\frac{H_d}{H} = \begin{cases} 0.99 & se\ K_T \le 0.17 \\ 1.188 - 2.272K_T + 9.473K_T^2 - 21.865K_T^3 + 14.648K_T^4 & se\ 0.17 < K_T \le 0.75 \\ -0.54K_T + 0.632 & se\ 0.75 < K_T < 0.8 \\ 0.2 & se\ K_T \ge 0.8 \end{cases} \tag{17}$$

3. RESULTS AND DISCUSSIONS

A mathematical model was developed for the thermal efficiency of a typical collector (dimensions and properties described in Table 1) using the EES® software (Engineering Equation Solver). The program was used to determine the solar radiation and the useful gain of the collector, on an hourly basis. The absorbed solar radiation is integrated over a day and the average collector efficiency was determined to this day. The procedure was repeated for each day of the year, allowing the determination of global parameters throughout the year, as well as the annual average efficiency.

The developed computational routine was run for the city of Belo Horizonte, Brazil. It was considered that the solar collector had a slope equal to latitude, to increase the radiation in the winter period. For comparison purposes, it has established a reference mass flow condition of 0.028 kg/s, ambient temperature of 20°C and water inlet temperature of 30°C. Subsequently, each of the variables was changed and it observed its influence on the annual average efficiency.

Table 1. Collector parameters.

Property	
Collector area	1.4 m²
Length	1.4 m
Width	1.0 m
Number of covers	1
Glass thickness of cover	0.004 m
Extinction coefficient of coverage	20
Collector of the refractive index	1.526
Spacing between the pipes	0.1 m
Internal diameter of the tubes	0.008 m
Emittance coverage	0.88
Plate absorbance (normal incidence)	0.90
Thermal conductivity of insulation	0.040 W/m²K

Figure 1 shows the estimated solar radiation on collector plane, the absorbed solar radiation and the useful energy (collector unit area). It can be seen that, as expected, the incident radiation is higher than the absorbed radiation, which is higher than the useful energy.

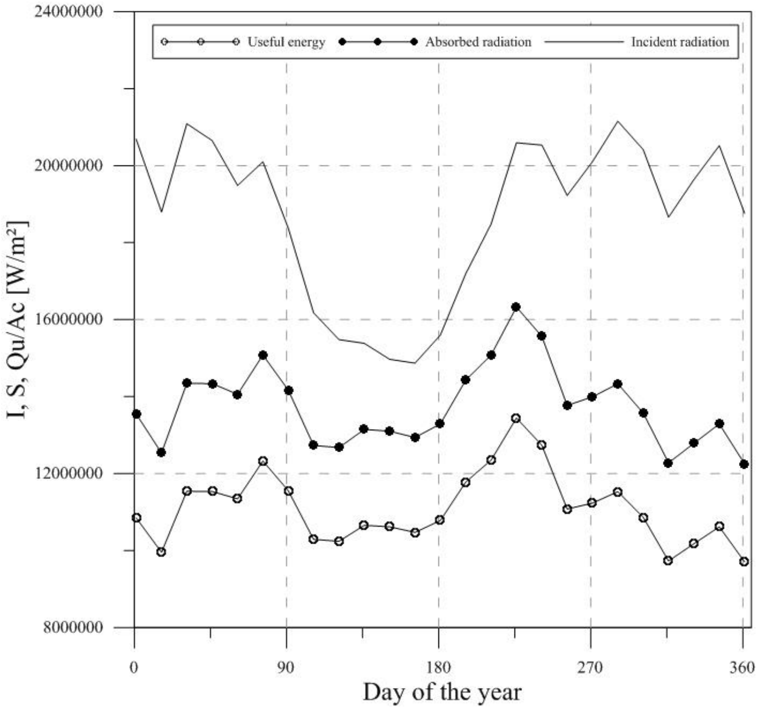

Figure 1. Radiation incident, absorbed and useful energy

The incident solar radiation on the collector plan follows the expected trend, higher in the summer months and lower in the winter months. The absorbed solar radiation and the useful energy are higher in the winter months, because it was adopted a slope for the collector equal to the latitude of the location, increasing the solar radiation absorbed in the winter months. Furthermore, it was adopted a fixed value for ambient temperature throughout the year. It is known that in the winter months, the ambient temperature is lower. The adoption of a higher value for the ambient temperature reduces thermal losses to the environment, increasing the absorbed solar radiation and useful energy, which is also reflected in the increase of the daily average efficiency (Fig. 3).

Figure 2 presents the daily average efficiency. Since the efficiency is the ratio between useful heat and incident radiation, the efficiency in the winter months is quite superior to the efficiency in the summer months.

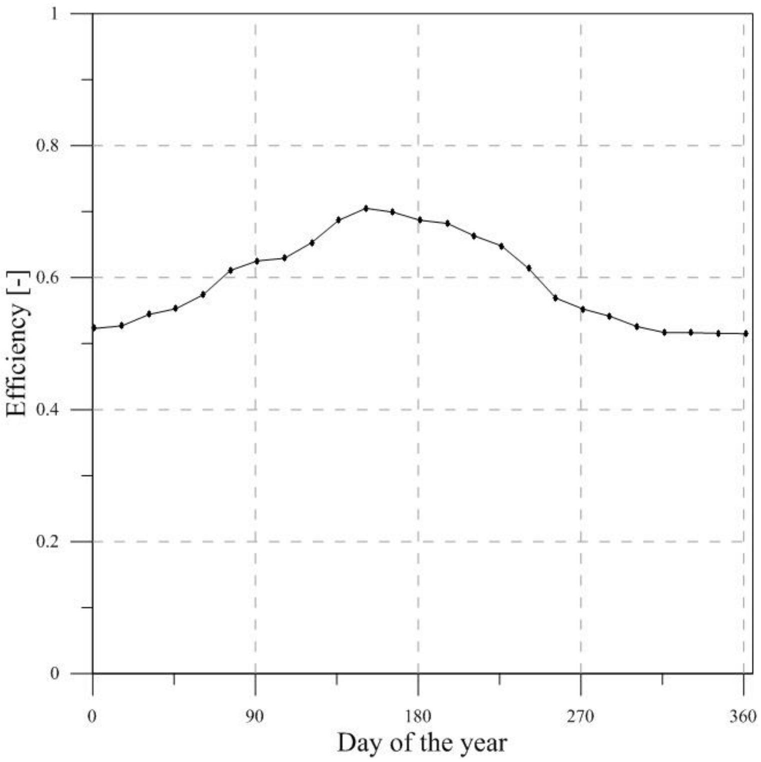

Figure 2. Radiation incident, absorbed and useful energy

Once known the behavior of the efficiency throughout the year for fixed values of mass flow rate, inlet temperature and ambient temperature the influence of these parameters on performance efficiency can be evaluated. Figure 3 shows the daily average efficiency throughout the year for different values of ambient temperature. It is observed that the efficiency increases with the temperature. This behavior can be attributed to the reduction of the thermal losses to the environment.

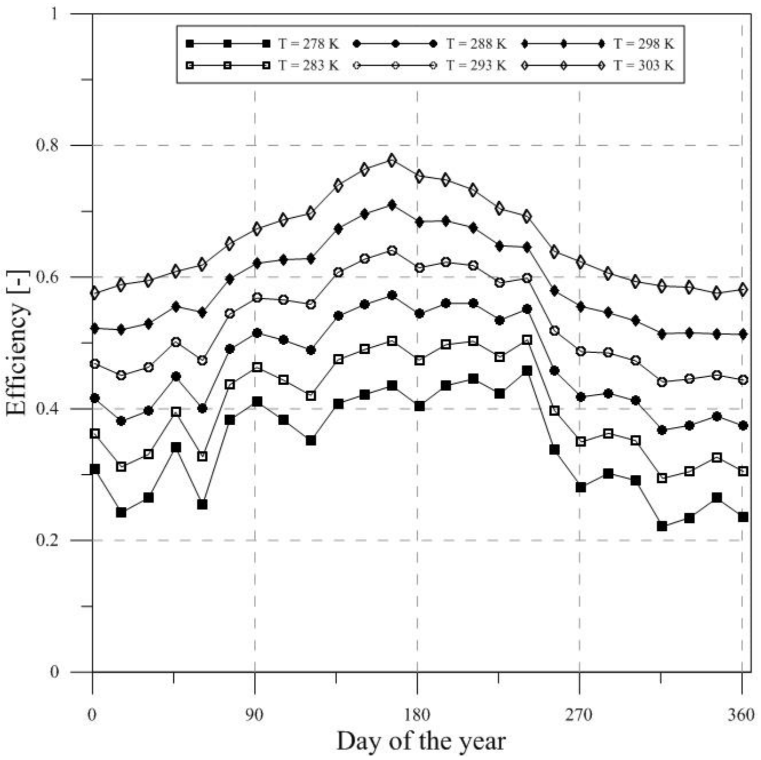

Figure 3. Daily average efficiency as a function of ambient temperature

Figures 4, 5 and 6 show, respectively, the annual average efficiency as a function of mass flow, inlet temperature and ambient temperature.

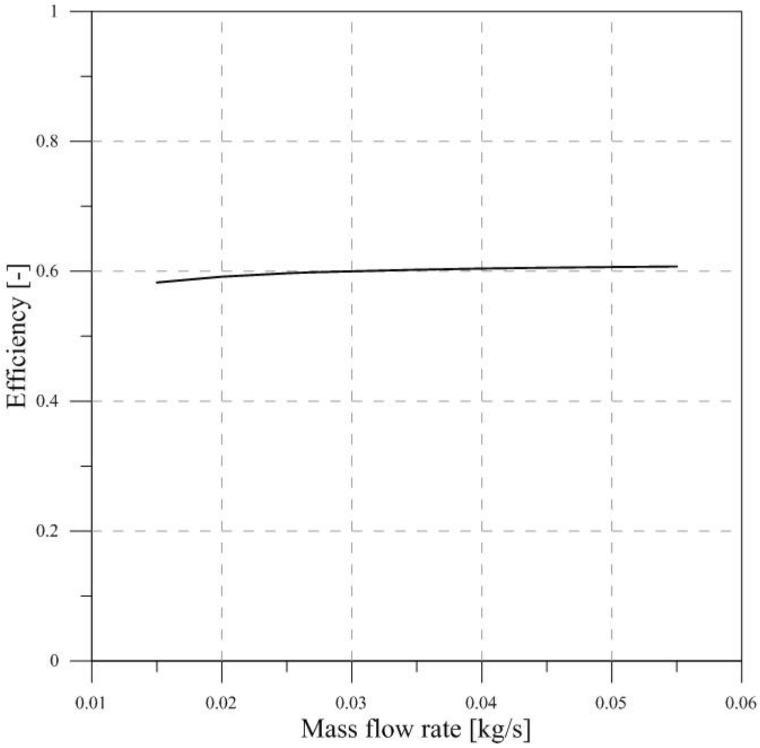

Figure 4. Annual average efficiency in relation to the mass flow

It is observed that the efficiency increases slightly with the mass flow rate. The increased flow rate increases the amount of energy that the working fluid can absorb, increasing its efficiency.

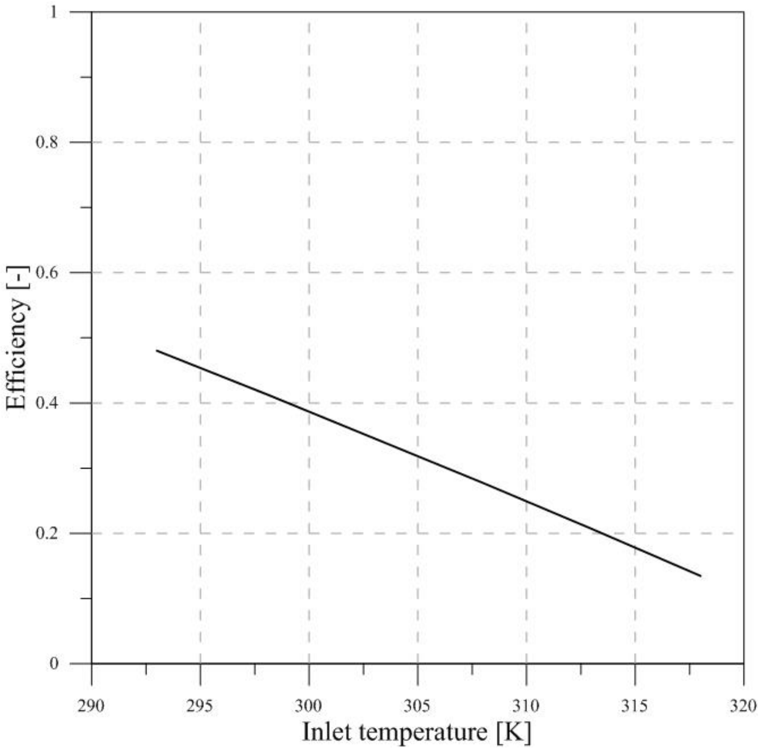

Figure 5. Annual average efficiency as a function of water inlet temperature

The higher the temperature of the inlet water, the lower the amount of energy it is able to absorb, since the temperature difference between the fluid and the plate is smaller. Thus, the lower the efficiency of the solar collector.

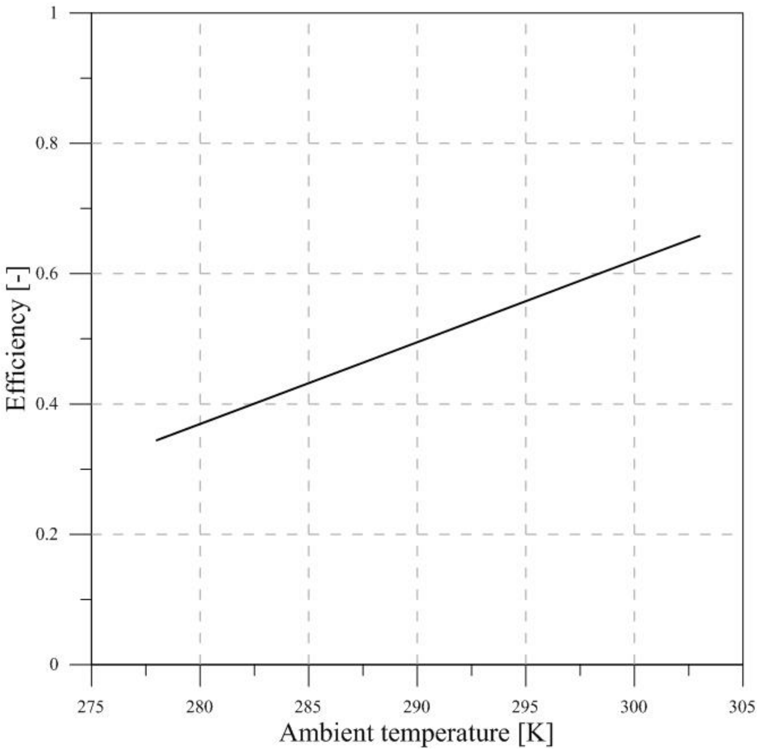

Figure 6. Annual average efficiency as a function of ambient temperature

As already mentioned, an increase on ambient temperature reduces the thermal losses to the environment, increasing the daily average efficiency, as reflected in annual average efficiency, as seen in Fig. 6.

4. CONCLUSIONS

A mathematical model was developed to determine the thermal efficiency of a flat solar collector installed in the city of Belo Horizonte, with slope equal to the latitude. The model was simulated for different mass flow rates, temperature and water inlet temperature, allowing the evaluation of its influence on the average annual efficiency of the collector.

It was observed that as the flat plate solar collector was positioned to promote the increase of radiation absorbed in the winter months, the performance was higher in this period, even though the incident solar radiation is smaller. The higher the energy absorbed by the working fluid for the same incident solar radiation, the greater the collector efficiency. Thus, higher average efficiencies on an annual basis were found for higher flow rates and higher ambient temperatures and for smaller collector inlet temperature values.

5. ACKNOWLEDGEMENTS

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