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FLAT PLATE SOLAR COLLECTOR PERFORMANCE INVESTIGATION BASED ON PLATE EMISSIVITY AND SLOPE ANGLE

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Abstract. *The efficiency of a flat plate solar collector may show significant variations due to its manufacturing and operating mode. The slope and the characteristics of the absorbing plate surface are some of the key factors that might directly affect the collector´s performance. This paper investigates the influence of both variables on the performance of a flat plate solar collector. A mathematical model has been developed through SCILAB, on which the incident beam radiation, absorbed radiation, useful heat and overall efficiency have been analyzed daily throughout the year, using the collector geometry and ambient temperature as input data. Incident beam radiation has been estimated using the isotropic sky model, which considers the clearness index in the typical meteorological year. The model has been applied to the city of Belo Horizonte, Brazil (latitude19.93°S and longitude 43.95°W) but can also be used for any other location by only changing the clearness index and the ambient temperature. The obtained results cover a full year of operation in Belo Horizonte. It was obtained an efficiency increase by utilizing a selective surface and defining an appropriate collector slope angle monthly. The obtained results were compared with recommended values from the literature, in which the optimum collector slope angle must be the location latitude increased by 10° for the summer and decreased by 10° for the winter.*

Keywords: *Flat plate solar collector, slope angle, selective surface, collector´s efficiency.*

1. INTRODUCTION

Considered as the world´s primary energy supply, fossil fuel depletion has become a worldwide concern, since energy is a key factor for the economic growth and social development of any country as shown by IEA. This depletion, as well as the harm caused by the extensive emission of carbon dioxide, has created a demand for new energy sources since energy consumption is directly related to the quality of life.

In the 1990s renewable energy became directly linked to sustainable development, being part of international actions aimed to minimize the effects of climate-changing thus addressing renewables as a possible alternative to fossil fuels. Many countries and international organizations now recognize renewables as an important element to enhance energy security, dynamic growth development, environmental protection, and greenhouse effect reduction efforts (Carley *et al*.,2009), (Johnstone *et al*., 2010).

Solar energy collectors/concentrators can convert solar radiation into heat and transfer it to carry fluids, in other words allowing energy to be restored or transported to the customer side (Langniss *et al*., 2005). Therefore, for decades, the efficiency and recovered heat quality remain as one of the most challenges to overcome in the scientific world.

The typical solar heating system consists of a collector; a heat transfer circuit that includes the fluid and the means to circulate it; and a storage system including a heat exchanger. Flat-plate collectors have been and may remain as one of the most popular types of solar collectors for general and residential purposes since they have a simple design, operate at medium to low temperatures, and have competitive prices. According to Oussama (2018), the performance of a flat-plate solar collector is essentially assessed by its efficiency, which is normally obtained on a steady-state basis thus being difficult to ensure a correct track of the instantaneous performance of the collectors in several case studies.

This matter has been investigated by J. Kern and I. Harris (1975) from other different points of view such as a function of latitude, weather data, and the character of the energy demand which recommend the latitude angle as the most suitable one. Yakup (2001) states that the best way to maximize the energy incidence of a collector is through a sun-tracking system which consists of a mechanism to track the sun's movement around the sky and its efficacy depends most likely on its cost as well as the desired precision. Nevertheless, when the adoption of solar tacker still is not enough for economic purposes, focusing on the most suitable slope angle for a flat plate collector ends up being the most recommended alternative as already observed by (Moghadam *et al.,* 2011), during his study to determine the ideal slope angle for Iran located collectors.

To achieve that, a mathematical model has been developed in Matlab allowing us to also determine the amount of energy received in the specific day. In order to avoid operational limitations for a daily basis angle adjustment, the procedure has been repeated for specific time intervals so that the slope angle for a monthly, seasonal, semiannual, and annual basis could be determined. Other studies have been carried to obtain the ideal angle, such as (Shariah *et al.*, 2002) recommending that the most suitable slope angle should be determined as a fixed value to be carried out throughout the year while others suggest that the most suitable angles be based on the best results for summer and winter thus having the collector slope angle being changed twice as previously stated. The results have shown that the latitude increment has directly impacted the obtained ideal slope angle.

It is evidenced that only two adjustments over the year have positively impacted a gain of 8% in the amount of energy received.

Furthermore, the influence of applying micro-channel heat pipe array for the collector has been studied by (Deng *et al.*, 2014), obtaining an efficiency of 80% and also a better temperature distribution. Therefore, it has been stated that such a method has a high cost and also potential technical issues due to its complexity and also scaling problems.

Some studies about the radiation estimation in slope surfaces have been carried out for the city of Belo Horizonte, but none of them utilizing the hourly data to obtain more precise values.

Thereby, the main objective of this work is to determine the influence of both slope angle and plate emissivity on the performance of a flat plate solar collector in the city of Belo Horizonte, Brazil.

2. METHODOLOGY

The applied methodology consists of the following procedure:

- The first step is to select the location for where the analysis will be carried and to define the input data, such as latitude, clearness index, and azimuth angle.
- Then, a mathematical model is applied to estimate the incident solar radiation and the absorbed energy by the solar collector. The model has been built on an hourly basis under the number of hours of sunlight for each day of the year.
- Next, according to heat transfer rates between the solar collector to the environment, it is possible to determine the available useful heat and efficiency through an iterative process based on the temperature from both cover and absorbing plate.
- The most suitable slope angle is obtained as follows: for each hour of the day and all days of the year, the slope angle of the collector (β) is changed with increments of 1°, from 0° (horizontal) to 90° (vertical), so that the highest values of useful heat and efficiency can be obtained to a determined slope angle (β).
- The optimization procedures continue, with the most suitable slope angle for the year (case 1), for the season (case 2), and the month (case 3), following the total useful heat obtained in the period under evaluation.

2.1 Incident solar radiation

The calculation was developed for a surface located in Belo Horizonte, Brazil, with a latitude (∅) of 19,92° S. The clearness index (K_t) from a standard year of the city of Belo Horizonte provided by INMET has been used. Figure 1 shows the variation of the clearness index K_t along the year. Average values of ambient temperature and wind speed from Windfinder (2021) were used. According to Stanciu (2014), the total radiation H is the sum of the direct and diffuse components H_b and H_d, respectively. The total daily incident solar radiation in a horizontal surface can be calculated by:

$$H = H_b + H_d, \tag{1}$$

To calculate the daily solar radiation, it is necessary to have the extraterrestrial daily radiation integrated for a horizontal surface H_o. This is obtained from the integration of the instant extraterrestrial solar radiation from sunrise to sunset, Eq. (2), in which G_{SC} is the solar constant (1367 *W/m²),* n represents the day of the year, Ø is the latitude of the considered location, ω_s is the sunset angle, and δ is the declination angle that can be calculated as proposed by Spencer (1971).

$$H_o = \frac{24.3600\, G_{SC}}{\pi}\left[1 + 0.033\cos\left(\frac{360°\, n}{365}\right)\right]\left(\cos\emptyset\cos\delta\,\mathrm{sen}\,\omega_s + \frac{\pi\omega_s}{180°}sen\,\emptyset\,sen\,\delta\right), \tag{2}$$

The total daily solar radiation can be calculated through Eq. (3).

$$H = K_t \,.\, H_o, \tag{3}$$

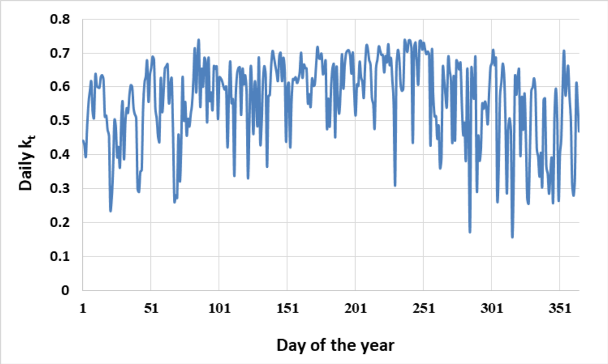

Figure 1. Annual variation of daily clearness index (K_t).

Table 1. Temperature and wind speed (monthly average) for Belo Horizonte.

Month	Average ambient temperature (°C)	Wind speed (m/s)
January	26	3.06
February	26	3.06
March	26	3.06
April	24	3.06
May	22	3.06
June	22	3.06
July	22	3.06
August	23	3.57
September	25	3.57
October	26	3.57
November	25	3.06
December	26	3.06

The diffuse radiation component in a horizontal surface (H_d) can be calculated through Eq. (4), proposed by Erbs et. al. (1982). The influence of the season is indicated by the sunset hour angle (ω_s).

$$\omega_s \leq 81.4° \rightarrow \frac{H_d}{H} = \begin{cases} 1.0 - 0.2727\,K_t + 2.4495\,{K_t}^2 - 11.9514K_t^3 + 9.3879\,K_T^4 & para\ k_T < 0.715 \\ 0{,}143 \quad para\ k_T \geq 0{,}715 \end{cases} \tag{4}$$

$$\omega_s > 81.4° \rightarrow \frac{H_d}{H} = \begin{cases} 1.0 + 0.283\,K_t - 2.5557\,{K_t}^2 + 0.8448K_t^3 & para\ k_T < 0.722 \\ 0.175 \quad para\ k_T \geq 0.722 \end{cases},$$

Once H and H_d are known, it is possible to calculate the daily direct component of the solar radiation in a horizontal surface through Eq. (1).

As presented by Duffie and Beckman (2013), relation, r_t, from the hourly total radiation (I) by the total daily radiation (H), as a function of the length of the day and specific hour, can be calculated through Eq. (5).

$$r_t = \frac{I}{H}, \tag{5}$$

The ratio between the total hour radiation and the daily total radiation can be calculated through Eq. (6), proposed by Collares-Pereira e Rabl (1979), with ω representing the hour angle.

$$r_t = \frac{\pi}{24}\left((0.409 + 0.5016\,sen\,(\omega_s - 60)) + ((0.6609 - 0.4767\,sen\,(\omega_s - 60))(\cos\omega)\right)\frac{\cos\omega - \cos\omega_s}{sen\,\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s}, \tag{6}$$

The calculation of the diffuse parcel of the hour radiation in a horizontal surface (I_d) was performed starting from daily data through Eq. (7).

$$r_d = \frac{I_d}{H_d}, \tag{7}$$

in which r_d is the ratio between the diffuse parcel of the hour radiation and the diffuse parcel of the daily radiation thus being calculated through Eq. (8), proposed by Liu and Jordan (1960).

$$r_d = \frac{\pi}{24} \frac{\cos\omega - \cos\omega_S}{sen\,\omega_S - \frac{\pi\omega_S}{180}\cos\omega_S}, \quad (8)$$

2.1.1 Incident solar radiation in a sloped surface

The hourly solar radiation incident in a sloped surface (I_T) for this study, has been estimated utilizing the isotropic diffuse sky model presented by Liu e Jordan (1963). This model considers the sum of the diffuse (I_d), direct (I_b), and reflected by the sun components to obtain the radiation in a sloped surface, as shown in Eq. (9).

$$I_T = I_b.R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I\rho_g\left(\frac{1+\cos\beta}{2}\right), \quad (9)$$

where R_b represents the ratio between the direct radiation in a sloped surface and the direct radiation in a horizontal surface thus being calculated by Eq. (10). The ground reflectance ρ_g for this study is assumed to be 0.6, and the below cosine ratio represents the sun's position to the earth as already shown by Duffie and Beckman (2013).

$$R_b = \frac{\cos\theta}{\cos\theta_z}, \quad (10)$$

Lastly, the total daily radiation in a sloped surface (H_T) has been calculated through Eq. (11), where $H_{sunrise}$ and H_{sunset} represent the time where the sun rises and sets throughout the considered period.

$$H_T = \sum_{H_{sunrise}}^{H_{sunset}} I_T, \quad (11)$$

2.2 Flat plate solar collector

According to Duffie and Beckman (2013), for plat plate solar collectors (FPC) the most indicated correlation for the slope angle is given through Eq. (12), considering positive signal for winter and negative for summer respectively.

$$\beta = |\emptyset| \pm 15°, \quad (12)$$

The water mass flow of 0,04 kg/s has been assumed for the collector in this study, the inlet water temperature of 22°C has been also assumed. The design, dimensions, and further data of a typical collector have been assumed and represented in Table 2.

Table 2. Collector parameters.

Parameter	Value
Absorber area	1.40 m²
Collector length	1.40 m
Collector width	1.00 m
Number of glass covers	1.00
Cover thickness	0.004 m
Cover extinction coefficient	20.00 m^{-1}
Cover index of refraction	1.526
Tube spacing	0.10 m
Tube inner diameter	0.008 m
Glass cover emittance	0.88
Absorptance of the plate at normal incidence	0.90
Insulation thermal conductivity	0.040 W/m.K

2.3 Absorbed solar radiation

According to Duffie and Beckman (2013), adopting the concept of a diffuse isotropic sky on an hourly basis, Eq. (9), could be modified to estimate the absorbed radiation (S), multiplying each term by the multiplication of the cover transmissivity -plate absorptivity ($\tau\alpha$) related to each of the radiation parcels as below represented in Eq. (13).

$$S = I_b.R_b\,(\tau\alpha)_b + I_d\left(\frac{1+\cos\beta}{2}\right)(\tau\alpha)_d + I\rho_g\left(\frac{1+\cos\beta}{2}\right)\,(\tau\alpha)_g, \tag{13}$$

In this paper, Eq. (14), is applied on an hourly basis to determine the property (τα), as below shown.

$$(\tau\alpha) = \frac{\tau\alpha}{1-(1-\alpha)\rho_d}, \tag{14}$$

where ρ_d is the reflectance of the cover for the incident solar radiation diffuse parcel. The optical properties can be estimated under the material, incidence angle, and the properties from the table. 2, as presented by Duffie and Beckman (2013).

2.4 Useful heat and efficiency

To investigate the influence of the slope angle and the absorber plate emissivity, the useful heat, and efficiency of a flat plate solar collector with an energetic balance that indicates incident solar energy distribution in a gain of useful heat as well as optical and thermal losses. Steady-state has been considered and the useful heat (Q_u) for a solar collector of area (A_c) can be calculated through Eq. (15).

$$Q_u = A_c F_R[S - U_L(T_i - T_a)] \tag{15}$$

The removal factor of the collector is represented by F_R, U_L is the collector thermal losses global coefficient, T_i is the water inlet temperature, T_a represents the ambient temperature (Table 1). The global coefficient of losses for a collector is the sum of the top, back and side losses coefficient as shown in Eq. (16), given by Duffie and Beckman (2013), with U_t, U_b, and U_e representing the top, back, and side losses respectively.

$$U_L = U_t + U_b + U_e\,, \tag{16}$$

The efficiency of a flat plate solar collector (η), represented in Eq. (17), is defined by a relation between the useful gain throughout a specific time interval and the incident solar energy in the same period.

$$\eta = \frac{\int Q_u dt}{A_c \int G_T dt}, \tag{17}$$

where $\int G_T dt$ represents the incident solar radiation and is equivalent to H_T.

3. RESULTS

The set of equations previously presented has been converted into a computational algorithm in the SCILAB software, to predict the incident and absorbed solar radiation, useful heat, and the solar collector efficiency, varying the angle in increments of 1° from 0° to 90°. The estimation of the incident solar radiation in a horizontal surface on Belo Horizonte is presented in Figure 2.

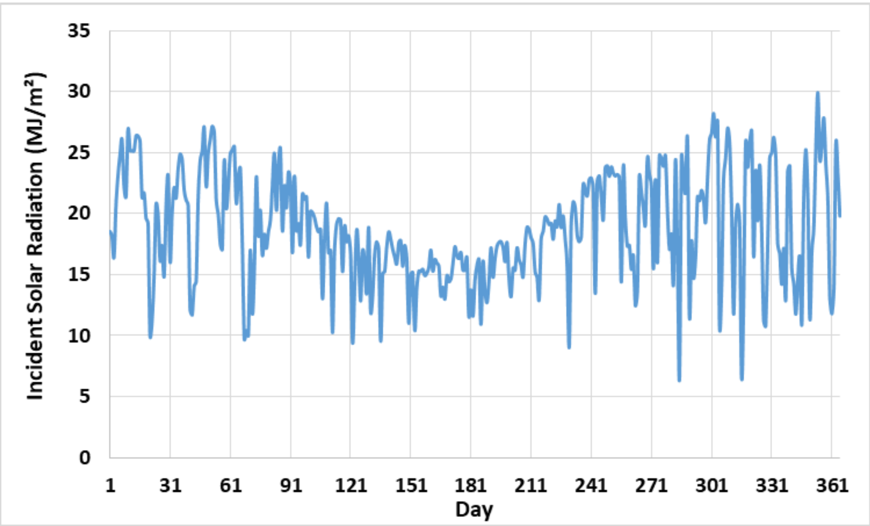

Figure 2. Estimated incident solar radiation in a horizontal surface in Belo Horizonte.

3.1 Case 1

Figure 3 represents the behavior of the total annual useful heat (Q_u), for the three months of winter and summer. It can be stated that the use of a selective surface (ε=0.10) in the absorber plate results in a slight increase in comparison with the results of the standard surface (ε=0.95). Specifically, in summer, the increase of the slope angle results in a loss of performance when utilizing this type of surface. It can also be observed that for small slope values of β (<15° for ε=0.10 and <20° for ε=0.95), the highest levels of useful heat are obtained in the summer months, and when β increases, a profile changing is observed with higher values of useful heat being observed on winter months.

According to Figure 3, it can be stated that the values of the slope angle that maximize the useful heat for the year, summer, and winter in a flat plate solar collector situated in Belo Horizonte are 26° (27° for ε=0.10), 3° and 45°, respectively. These results are per the values recommended by Duffie and Beckman (2013). The annual profile of Q_u and η, for these angles, are presented in Figure 4, with average monthly values for a better comparison.

It has been observed that the efficiency of the collector follows the same profile of the useful heat. Besides that, when prioritizing an adjustment of the slope angle which gives the maximum annual value for the useful heat, it can be observed that the collector shows a baseline of an intermediary useful heat during the seasons of the year. When the adjustment of the slope angle is done to prioritize the summer season, the initial and final months of the year show higher efficiency and useful heat, while the months in the middle of the year show a performance drop. The opposite is observed when the adjustment for winter is prioritized. Table 3 represents the obtained result when the collector is positioned with one annual slope adjustment, considering the hypotheses of maximizing the useful heat throughout the year, winter or summer. Besides that, the recommended slope angle by Duffie and Beckman (2013) considering the same hypothesis has also been used, allowing the maximum useful heat and collector's efficiency for each adjustment to be obtained.

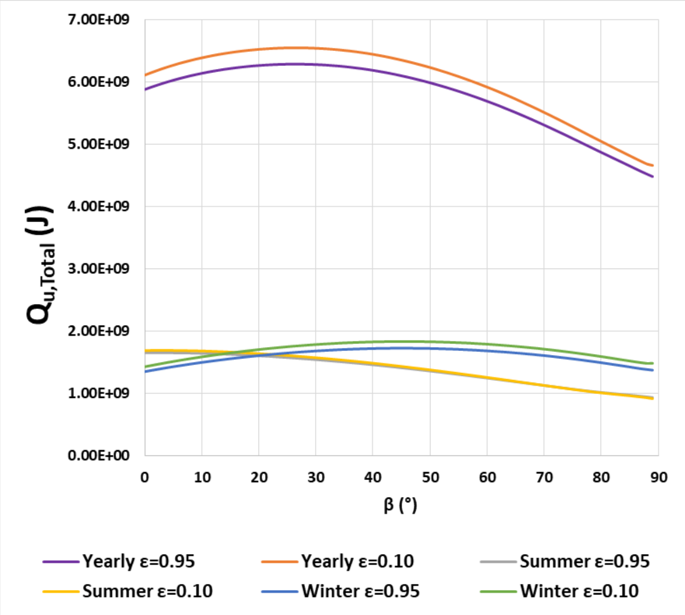

Figure 3. Total annual, winter, and summer useful heat considering a slope angle variation from 0º to 90º.

Table 3. Results Case 1 - Annual adjustment.

Case 1	Normal Surface (ε=0.95)			Selective Surface (ε=0.10)		
Hypothesis	β (°)	$Q_{u,Total}$ annual (J)	$\eta_{average}$ annual (%)	β (°)	$Q_{u,Total}$ annual (J)	$\eta_{average}$ annual (%)
Maximum $Q_{u,Total}$ Annual	26	6.29E+09	62.35	27	6.55E+09	64.93
Maximum $Q_{u,Total}$ Annual (Literature)	20	6.27E+09	62.41	20	6.52E+09	64.99
Maximum $Q_{u,Total}$ Summer	3	5.97E+09	62.10	3	6.21E+09	64.57
Maximum $Q_{u,total}$ Summer (Literature)	5	6.03E+09	62.21	5	6.27E+09	64.70
Maximum $Q_{u,Total}$ Winter	45	6.10E+09	61.89	45	6.35E+09	64.44
Maximum $Q_{u,total}$ Winter (Literature)	35	6.25E+09	62.20	35	6.51E+09	64.79

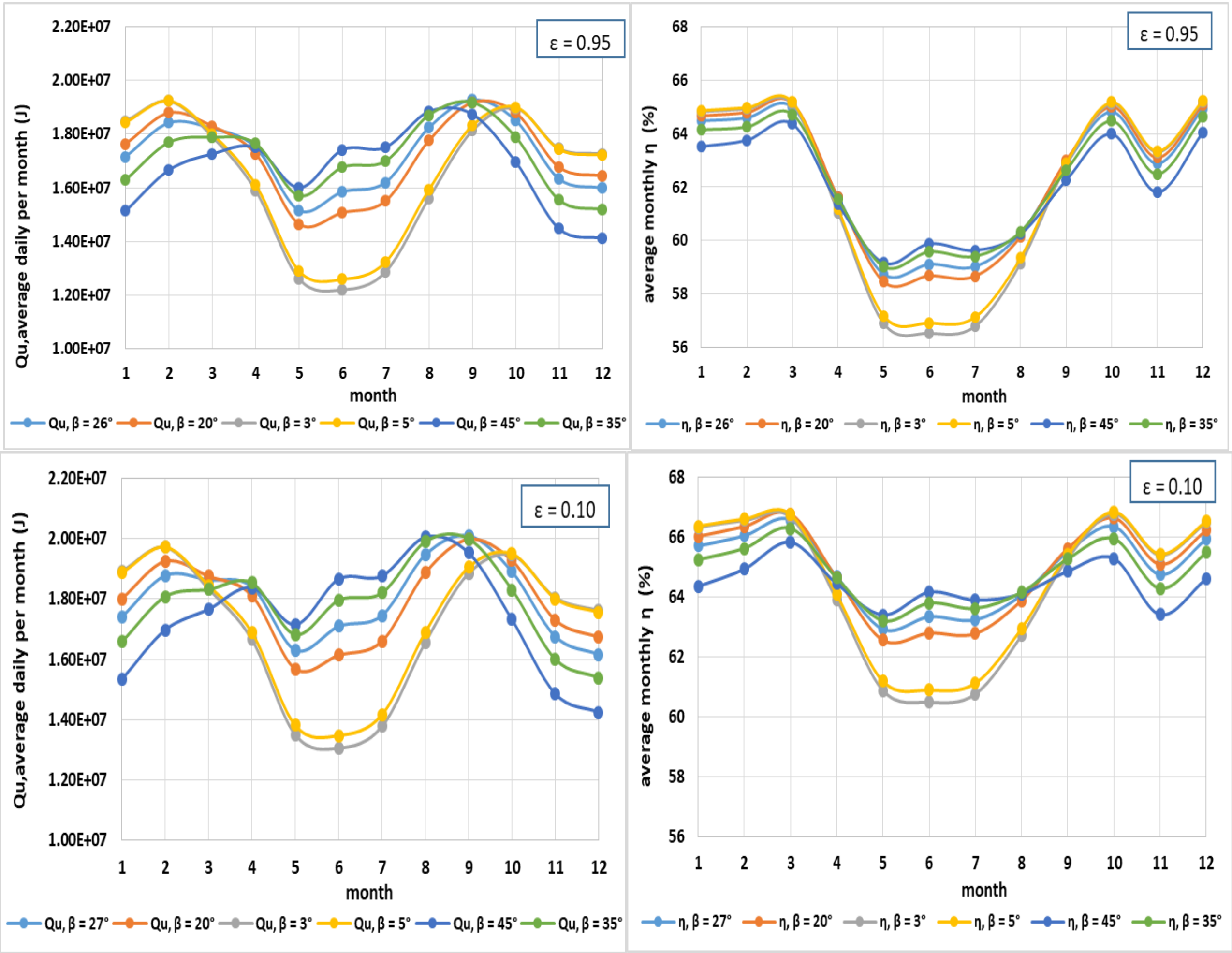

Figure 4. Useful heat and efficiency throughout the year for Case 1, considering the six-hypothesis presented in table 3.

When a selective surface is used, an increase of approximately 4% in both Q_u and η is found. Besides, it could also be seen that slope the angles recommended by the literature show similar results to the ones obtained in this paper, with both useful heat and efficiency varying less than 1% in most of the cases. The highest difference was found for the total annual Q_u when winter was prioritized, with this difference between the obtained angle and the recommended by the literature staying around 10º with an increase of approximately 2% in the total annual useful heat.

Lastly, it could also be stated that the type of surface for the absorber plate does not influence the results of the obtained slope angle to maximize the performance of the collector. The obtained results for both types of surfaces were identical, except for the maximum annual useful heat, which has shown a difference of 1º on the slope angle.

Therefore, the appropriate choice of the slope angle for the collector must be made by the requirements of the user and also with the period in which is desired to maximize its performance.

3.2 Case 2

The left side of Figure 5 presents the behavior of the total useful heat (Q_u) for the four seasons of the year. It could be stated that during the spring, the obtained total useful heat has been slightly smaller than the results obtained for the summer, as well as the ones obtained for the autumn being slightly smaller than the ones obtained for the winter.

The slope angles that maximize the useful heat for the summer, autumn, winter, and spring are 3°, 43°, 45°, and 5°, respectively. The right side of Figure 5 shows the behavior of the average daily Q_u for the month, for the two types of the absorber plate, considering four adjustments of the slope angle β. Table 4 presents some further details about the performance of the flat plate solar collector when this adjustment is made.

It could be concluded that the selective surface shows a minor variation of efficiency throughout the year when compared with the standard surface. The use of a selective surface resulted in a Q_u increasing of 6% for both autumn and winter and the same increase of η for the winter, for the autumn. The efficiency variation was smaller than 1%. For summer and spring, the selective surface resulted in an increase of 2.5% for both Q_u and η.

Table 4. Results Case 2 – Slope adjustment by season.

Case 2	Normal Surface (ε=0.95)			Selective Surface (ε=0.10)		
Season	**β (°)**	**$Q_{u,Total}$ per season (J)**	**$\eta_{average}$ per season (%)**	**β (°)**	**$Q_{u,Total}$ per season (J)**	**$\eta_{average}$ per season (%)**
Summer	3	1.66E+09	65.03	3	1.70E+09	66.54
Autumn	43	1.57E+09	64.09	43	1.67E+09	64.17
Winter	45	1.73E+09	60.52	45	1.84E+09	64.27
Spring	5	1.59E+09	64.44	5	1.63E+09	66.21
Annual	-	6.55E+09	62.56	-	6.84E+09	65.25

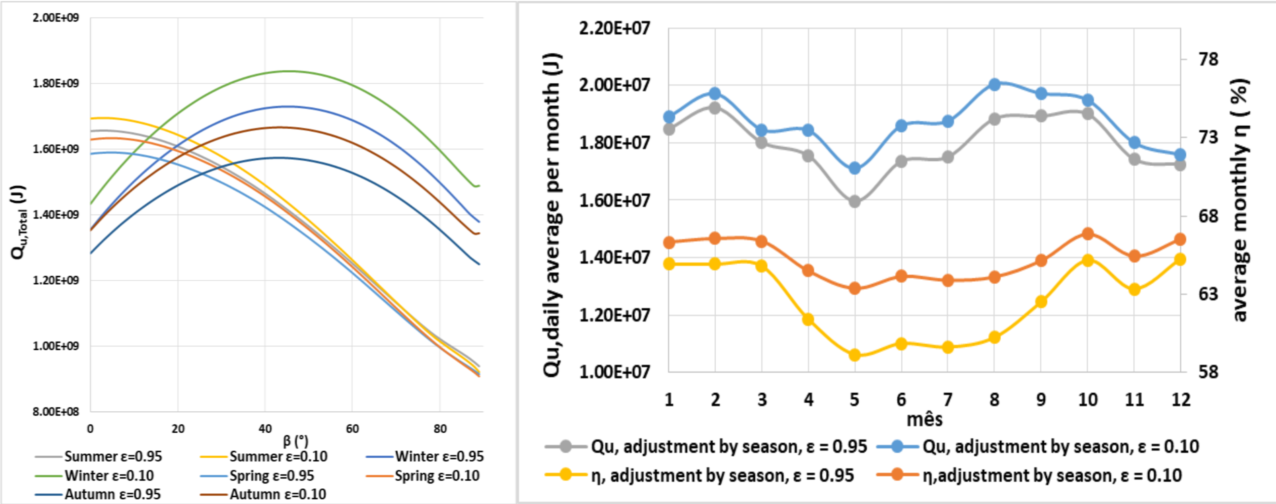

Figure 5. Results were obtained for four annual adjustments in the slope of the collector.

3.3 Case 3

Table 5 shows the most suitable angle for each month. Figure 6 shows the behavior of the average monthly Q_u for the two types of surfaces.

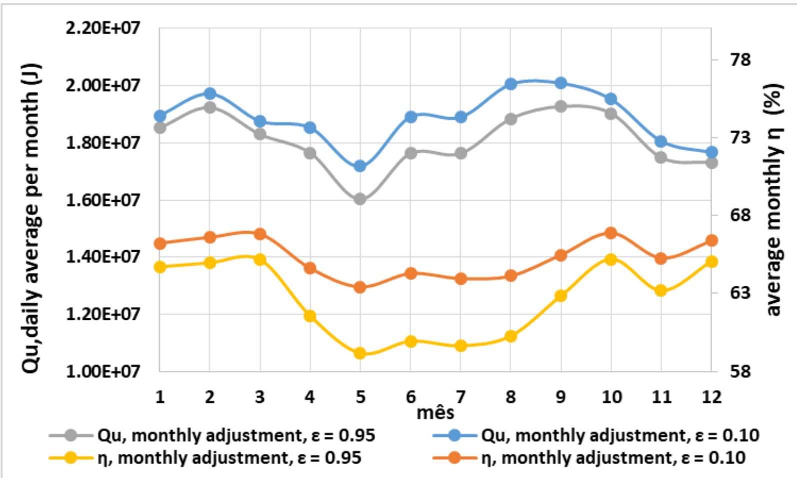

Figure 6. Results were obtained for the monthly adjustment in the inclination of the collector.

As well in case 2, it can be stated that the selective surface shows a smaller variation of the efficiency throughout the year, and also that the months at the end of autumn and winter showed a smaller efficiency when using the standard surface.

The utilization of the selective surface increased both Q_u and η around 7%, in May, June, July, and August and from 3% to 5% for the further months. In general, the annual useful heat and efficiency of the collector have increased when a selective surface has been used. In conclusion, it has been observed that the utilization of a selective surface does not influence the most recommended slope angle for any situation.

Table 5. Results Case 3 – Monthly adjustment for the slope.

Case 3	Normal Surface (ε=0.95)			Selective Surface (ε=0.10)		
Month	β (°)	$Q_{u,Total}$ monthly (J)	$\eta_{average}$ monthly (%)	β (°)	$Q_{u,Total}$ monthly (J)	$\eta_{average}$ monthly (%)
January	0	5.74E+08	64.71	0	5.88E+08	66.23
February	5	5.39E+08	64.97	5	5.52E+08	66.61
March	18	5.67E+08	65.17	18	5.81E+08	66.81
April	35	5.29E+08	61.57	36	5.56E+08	64.62
May	49	4.97E+08	59.17	49	5.33E+08	63.42
June	55	5.29E+08	59.94	56	5.67E+08	64.29
July	53	5.46E+08	59.65	53	5.86E+08	63.96
August	43	5.84E+08	60.28	43	6.21E+08	64.13
September	27	5.78E+08	62.85	28	6.03E+08	65.48
October	9	5.90E+08	65.21	9	6.05E+08	66.88
November	0	5.24E+08	63.19	0	5.42E+08	65.28
December	0	5.37E+08	65.06	0	5.47E+08	66.38
Annual	-	6.59E+09	62.61	-	6.88E+09	65.33

3.4 Comparative

This session is destined to make a comparison among the three presented cases, considering only the regular surface. Figure 7 shows the behavior of the daily average Q_u for the month considering the three studied cases.

Changing the slope angle of a flat plate solar collector is a complex task once a set of tubing would have to be moved every time this alteration is performed thus not being justified by the slight increase in both Q_u and η.

From the data presented in tables 3, 4, and 5, it is possible to quantify the increase in both efficiency and total daily average useful heat throughout the year. If annual adjustment and seasonal adjustment are compared, the results showed an increase of 4.22% in the useful heat and 0.33% in the efficiency of the collector. If annual adjustment and monthly adjustment are compared, increases of 4.89% and 0.42% for useful heat and efficiency are found, respectively.

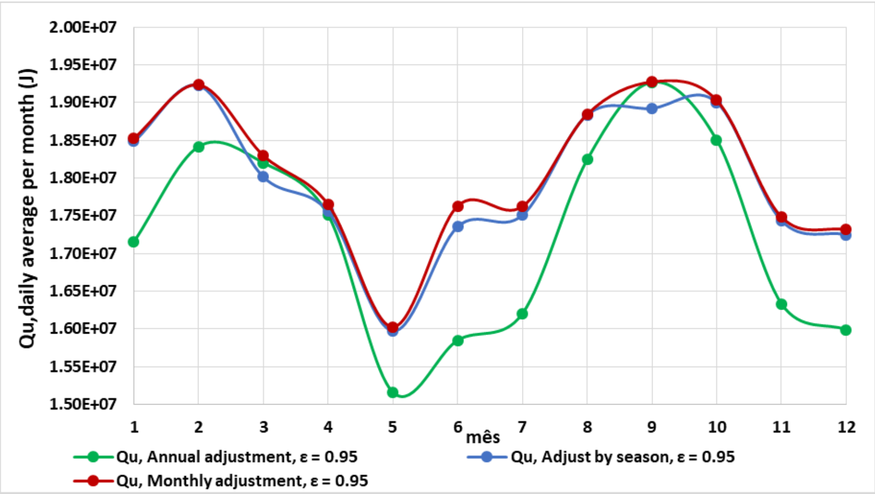

Figure 7. Comparison of the three cases for the same emissivity.

It can be concluded that a slight increase in the performance of the collector is observed by changing the slope angle throughout the year, but it is not recommended since there is a risk of damaging the collector during the adjustments. The investment on a selective surface is also not recommended, therefore, for Belo Horizonte, where the incident solar radiation is abundant, the use of a selective surface and the modification of the slope angle on a monthly or seasonal basis does not result in a significant increase on the performance of the collector.

4. **CONCLUSIONS**

In this paper, an analysis of the performance of a typical flat plate solar collector in Belo Horizonte, Brazil, has been performed under two situations: changing the slope angle throughout the year and using a selective surface in the absorber plate. The obtained results indicated that the use of a selective surface for the absorbing plate increases both efficiency and useful heat by approximately 4%. The variation of the slope angle 4 or 10 times throughout the year increases not higher than 5% when compared to a collector on a fixed slope angle. On the other hand, the efficiency has increased less than 1% under the same circumstances. In conclusion, it could be observed that it is not recommended to change the slope angle on a monthly or seasonal basis or to use a selective surface in the studied location.

5. ACKNOWLEDGEMENTS

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