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Linear Fresnel solar collector prototype: Artisanal system for the production of hot water and/or water vapour

Prototipo de colector solar lineal Fresnel: Sistema artesanal para la producción de agua caliente y/o vapor de agua

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ABSTRACT

The development of a linear Fresnel solar collector prototype is discussed, highlighting the use of direct solar heat radiation for water heating and/or steam production as an alternative to conventional water-heating systems or steam generators, which consume energy from fossil fuels. A solar system was prototyped at the Unidades Tecnológicas de Santander in Bucaramanga, Colombia. We produced mathematical models of sizing, technical specifications and material availability, and assembled and field-tested an ambient collector for model efficiency. The model presented does not have a control system for flow, temperature, pressure or level, and it has no solar tracking of any kind. Its movement was manually managed at each reflex. Finally, the model has neither a hydraulic system nor a preheater at the entry of the concentration point.

RESUMEN

El desarrollo de un prototipo de colector solar lineal Tipo Fresnel tiene como finalidad el aprovechamiento de la radiación solar directa en calor para el calentamiento de agua y/o la producción de vapor, como alternativa para suplir los sistemas de calentamiento de agua o generadores de vapor convencionales, que consumen energía proveniente de combustibles fósiles. Para el desarrollo del sistema, se utiliza la radiación solar de las UTS, ubicada en Bucaramanga, Colombia, se identifican los modelos matemáticos para realizar el dimensionamiento, posteriormente se seleccionan materiales basados en especificaciones técnicas y disponibilidad en Colombia, con el fin de realizar el montaje y realizar pruebas en campo, midiendo la temperatura ambiente y en el colector para determinar la eficiencia del modelo. Cabe resaltar, que el modelo presentado no cuenta con sistema de control de flujo, temperatura, presión y nivel, no tiene seguimiento solar de ningún tipo; el movimiento del mismo se realizó manualmente con cada reflecto. Por último, el modelo no cuenta con sistema hidráulico de tiro forzado, y tiene un precalentador a la entrada del punto de concentración.

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1. Introduction

Accelerated population growth, technological development, industrialization and urbanization have increased the energy demands of developing countries worldwide [1]. Solar energy is a source of clean energy available in most regions, and it is economical and virtually infinite [2]. Additionally, there are several technologies for harnessing solar radiation. The solar concentration technique is one of the most promising forms [3], in which the linear Fresnel [4,5] reflector [6,7] is highlighted [8, 9] as one of best performing solar systems [10,11] that produces useful heat at medium and high temperatures [12]. It is a low-cost technology with sufficient thermal efficiency. Therefore, it is characterized as a worthwhile option [2].

The development of clean energy is essential to combating climate change and reducing the damage associated with the combustion of fossil fuels. In recent decades, we have seen an increase in global temperatures across the planet [13].

In May 2018, the energy production in Colombia was 186.5 GWh/day, of which 85.68 % originated from renewable fuels (84.97 % hydraulic, 0.64 % biomass, 0.05 % wind and 0.02 % solar). The remaining 14.32 % corresponded to nonrenewable fossil fuels, such as coal, oil and natural gas. Although Colombia produces plenty of clean energy, it is at risk, because the greatest production comes from reservoirs whose levels can drop, increasing the national reliance on fossil fuels [14].

It is important to improve and safeguard energy generation with the implementation of new technologies, considering that Colombia has a diverse geography with a variety of climatic conditions monitored by weather stations [15]. Therefore, we should be able to easily implement any type of renewable energy system via solar panels, wind turbines, tidal systems etc.

To effectively take advantage of Colombia's energy potential, the design and construction of a prototype linear Fresnel solar collector was performed. This is a relatively new technology that presents a primary reflector system with a mirror arrangement whose function is to reflect direct solar radiation to a heat-receiving tube located at a given height. When the radiation comes into contact with the surface of the tube, it is transformed into thermal energy via a liquid carrier, which is used to generate electricity.

2. Methodology

Our research uses a descriptive method [16] with a quantitative approach [17, 18]. Our methodological development begins with reviewing the literature to identify mathematical models to determine sizing parameters and to subsequently develop a system using computer- assisted design (CAD) software, producing real plans for subsequent construction at low manufacturing costs so that it remains viable as a source of water heating and steam generation. Finally, field tests are carried out to determine the real functionality of the prototype, and analyze and determine its optical efficiency.

2.1. Sizing of Linear Fresnel Collector

To develop the mathematical models of the collector, the region's geographical information was studied, and field tests were performed with the prototype. The study site at the university has the following geographical coordinates: latitude 7.1, longitude −73.12, elevation 930 m above sea level. See Table 1.

Table 1: Geographic coordinates of the site.

Place	Geographical Coordinates		Elevation
	Latitude	Longitude	
UTS	7.1	-73.12	930 m

Source: own

A search of the geographical area for the implementation was carried out, supported by the Google Maps tool of free access. The tool was used to search and select the data or geographical coordinates of Table 1. The place selected was the Technological Units of Santander (UTS), Bucaramanga, Colombia. Figure 1 shows the infrastructure of UTS, marked in red.

Initial parameters of the prototype are as follows:

- Focal length of the system: 75 cm.
- Mirror area (unit): 10 × 100 cm.
- Up to ten mirrors.
- Time interval 9:00 a.m. - 3:00 p.m.
- Secondary concentration system comprises a U-shaped collector tube or coil having a total length of 2 m and a diameter of 3/8 ft.

Figure 1: Site, [19].

Initially, the parameters defining the position of the reflectors in terms of distance and angle of inclination were calculated. This calculation was made by accounting for the given parameters and the date upon which the system was evaluated (26 February 2019). Thus, Nd = 57, and the solar inclination was calculated using Eq. (1):

$$\delta = 23,45\,\text{sen}\left(360\left(\frac{284+57}{365}\right)\right) = -9{,}41^\circ \tag{1}$$

Subsequently, the hour angle was calculated using the initial working time of the system. Thus, Nh = 9 h, as evidenced in Eq. (2):

$$w = 15(9-12) = -45^\circ \tag{2}$$

Simultaneously, Eq. (4) shows that the approach of calculating the angle of solar incidence accounted for the coordinates cited in Table 1 and the calculation of solar inclination from Eq. (1):

$$\cos(\theta) = \Big[\sin(7,1)*\sin(-9,41)\Big] + \Big[\cos(7,1)*\cos(-45)\cos(-9,41)\Big] \tag{3}$$

Thus, the solar incidence angle equals 47.77°. Consequently, the angle of solar height is calculated using Eq. (4):

$$\gamma = 90 - 47,77^\circ \tag{4}$$

The angle of solar height of 42.33° was thus obtained. After the initial parameters were obtained from the geographic data, the variables defining the position and separation of the reflectors were determined. Thus, in the first instance, to perform the geometric design of the primary reflectors, the first reflector was located just below the test receiver. Then, the next reflector was located on the right side.

There were seven variables immersed in the location of the first reflex, of which six were defined and/or calculated as $L1 = 0$, $\phi = 0$, $\theta = 47{,}77^\circ$, $Y = 42{,}23^\circ$, $W = 10$ cm and $h = 75$ cm.

Subsequently, the angle of inclination of the first reflector raised in Eq. (5) was calculated to produce the seven parameters mentioned above:

$$\beta = \frac{47{,}77^\circ + 0}{2} \tag{5}$$

The angle of inclination of the first reflector was obtained as 23.88°. Then, the separation distance of the second reflector was calculated. Eq. (6) allowed us to calculate the separation distance of the second reflector from the first. Therefore, a separation of 13.6 cm was obtained:

$$L_{2s} = 10\left(\frac{\sin(23{,}88)}{\tan(42{,}23)} + \cos(23{,}88)\right) \tag{6}$$

Subsequently, the angle formed between the vertical axis of the receiver, the reflected solar radiation (10.3) and the angle of inclination of the second reflector was 29°. The same procedure was used to determine the values of the following three reflectors corresponding to the right side of the receiver, in which the inclination angle, ϕ, and the separation distance between reflectors were calculated. These results are shown in Table 2.

Table 2: Data corresponding to the locations of reflectors on the right side of the receiver.

Ei	*Li-1 ---- Li*(cm)	*Li*(cm)	*Φi°*	*βi°*
E1	0	0	0°	23.88°
E2	13.6	13.6	10.3°	34°
E2	14.1	27.7	20.3°	38.55°
E4	14.45	42.15	29.33°	38.55°
E5	14.7	56.85	37.16°	42.46°

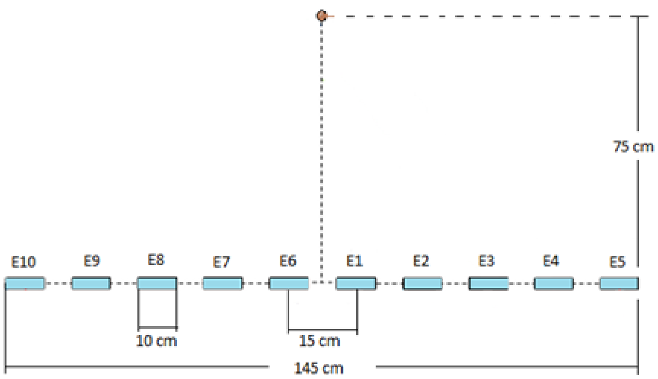
Source: own

Li-1–Li(cm) is the distance between a reflector and the previous one, and Li (cm) is the distance between the vertical axis of the receiver and the corresponding reflector.

Considering the data of Table 2, we identified that the separation having greater extension between a mirror or reflector and the other was given in row E5 of Table 2, having a value of 14.7 cm. Therefore, we took this distance as a reference of separation for the other reflectors. The value of 14.7 cm was closest to 15 cm, and the mathematical models that were obtained to feed Table 2 were raised again.

Noting that the number of reflectors was even (10), an adjustment was made at their location, respecting the symmetry of the geometric plane of the system. Therefore, the first initial reflector was located at an equal distance of 7.5 cm from the vertical axis of the receiver and the reflectors, as evidenced in Figure 2.

Figure 2: Distances between primary reflectors.



Source: own

The values previously calculated in Table 2 were adjusted according to the approximation made to facilitate the assembly of the reflector mirrors, resulting in new model values, as shown in Table 3.

Table 3: Final parameters of the right-area mirrors of the prototype.

Ei	*Li*(cm)	*Φi°*	*βi°*
E1	7.5	5.71°	26.74°
E2	22.5	126.7°	32.23°
E2	37.5	26.56°	37.16°
E4	52.5	35°	41.38°
E5	67.5	42°	44.88°

Source: own

The left-side reflector parameters per system symmetry were kept at angle ϕ, and the distances of each reflector, regarding the changes in the angles of inclination of each element with respect to the receiver, were applied to obtain Tables 2 and 3, providing the values reflected in Table 4.

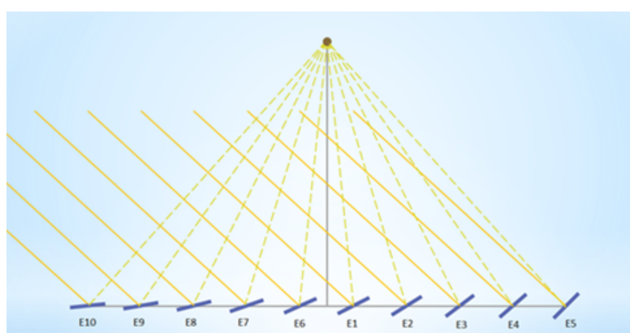
Table 4: Final parameters of the mirrors on the left side of the prototype.

Ei	*Li*(cm)	*Φi°*	*βi°*
E1	7.5	5.71°	26.74°
E2	22.5	126.7°	32.23°
E2	37.5	26.56°	37.16°
E4	52.5	35°	41.38°
E5	67.5	42°	44.88°

Source: own

Finally, Figure 3 shows the position of each reflector at initial working conditions according to the information established in Tables 3 and 4, which presents a description of the incident solar radiation when it reaches the reflector and reflects to the direction of the tube receiver.

Figure 3: Diagram of the prototype collector geometry.

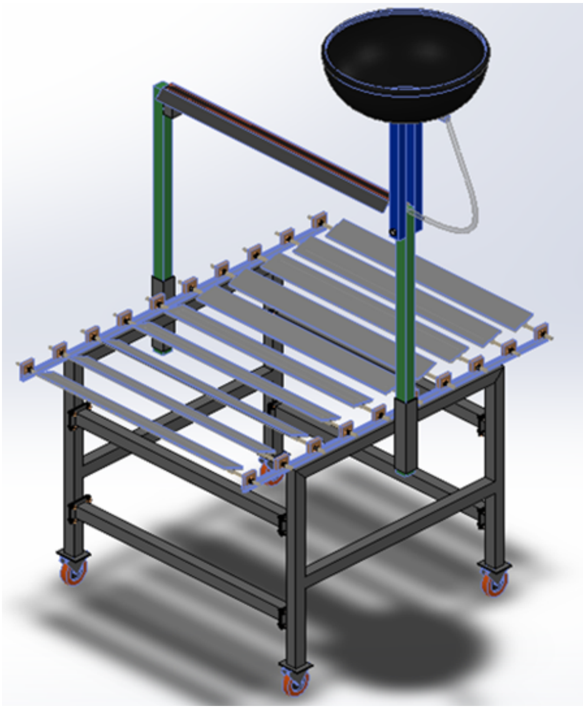


Source: own

2.2. *CAD Modelling*

Figure 4 shows the CAD-modelled linear Fresnel solar collector prototype. The concentrated solar radiation enters a trapezoidal cover housing the secondary receiver while minimizing radiation, convection and conduction losses. Mirror widths were calculated and constructed using 1.2-m long, 3.5-cm high and 12-cm wide 20-gauge galvanized sheets. The receiving tube was a 3/8-in wide and 2-m long matt-black U-curvature with a theoretical absorptivity coefficient of 0.98 and a theoretical emissivity coefficient of 0.98.

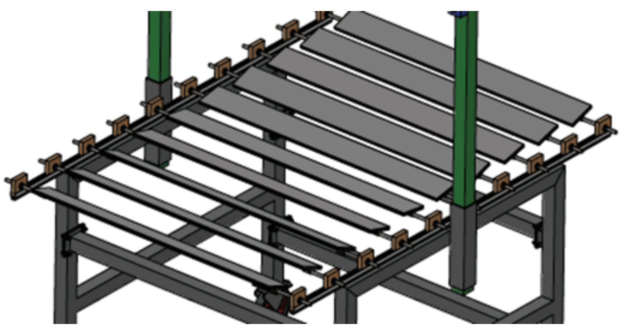
Figure 4: CAD modelling.



Source: own

The reflector base used a 0.125 × 1.25-in hot-rolled steel plate to provide consistency to the reflection system. An endless screw was welded to each to serve as a pivot, as shown in Figure 5.

Figure 5: Primary reflection system modelling.



Source: own

Quadrant brackets having holes in their centres were manufactured for mounting upon the base of the prototype for ease-of-maintenance and system modification. A 2-in × 1.5-mm thick square structural tube was used for the frame, and 10 cm × 8 cm × 3-mm plates were used for fastening. To fix the primary reflector elements, we used aluminium rails of the window industry, which provided easy sliding for the reflector brackets. After sizing and modelling, we selected the primary reflection system, requiring the following characteristics: 3-mm thick flat glass mirrors coated with Ag and a layer of protective paint having a reflection coefficient of 95 %.

3. Results

The constructed system is shown in Figure 6, wherein a previously unmentioned pre-heating subsystem was added to heat the transfer fluid entering the concentration point of the solar collector. This subsystem provided a 45°C minimum temperature at the entrance of the solar concentration point to increase system efficiency.

Figure 6: Assembled collector prototype.

Source: own

Field tests were conducted using the natural solar radiation available at the collector. In 2019, the weather in metropolitan Bucaramanga was affected by rainfall and thick clouds, which reduced solar efficiency. Therefore, we restricted our study to the range of 9:00 a.m. to 12:00 p.m. Results obtained on 17 March 2019 are grouped in Table 5, reflecting high temperatures and good results compared to the other days. At the beginning of the test, an ambient temperature of 28°C was recorded, providing a surface temperature at the receiving tube of 110°C. The inlet temperature of the heat-transfer fluid was 63°C when the inlet valve was opened. When fluid was supplied to the system, the temperature of the receiving tube dropped to 78°C. Then, after 7 mins, its temperature rose to 122°C. 2 mins later, the temperature was 128°C. The valve opened and steam was observed with a small amount of water. As can be seen, the experiment showed positive results until 11:54 a.m. Cloudiness negatively affected testing on several occasions.

When recording the flow generated by the collector, we noticed that the pressure at the exit of the system was greater than the pressure at the flow metre. We then observed that the flow indicator had reached its limit, resulting an inaccurate measure of system flow. The types of flow metres we used were of millimetre scale. Thus, they did not directly measure flow. They instead used correlation tables to deduce flow depending on the float level and the type of the fluid being treated. Therefore, the reference device, 063-64TA, must be used. According to its correlation table, a flow of 2000 ml/min exists at its highest measurement point, for which, the corresponding calculations were taken as the minimum volumetric flow of the system.

Additionally, the optical efficiency of the system was determined for the field tests performed. The coefficients of the materials involved were estimated, as were the primary reflectors containing a thin layer of Ag that provided a reflectivity coefficient of 0.95. There was an interception factor of 0.9 and an absorptivity in the receiving tube of 0.9. The reflected direct solar radiation only took advantage of 77 % of it. This is an important factor required to define the thermal efficiency of the system. In this case, it resulted in a value of 12.3 W/m^2*K. Thus, the convection losses were calculated at 37.58 W/m^2*K, with which the overall loss coefficient of the prototype was calculated at 49.88 W/m^2*K.

Table 5: One day data.

Time	Receiver tube temperature	Process	Observation
09:10 a. m.	110°C	Water supply	Temperature decrease to 78°C
09:32 a. m.	121°C	Outlet valve	Steam mixture, minimum quantity of water
09:44 a. m.	128°C	Outlet valve	Steam mixture, minimum quantity of water
09:57 a. m.	142°C	Outlet valve	Steam increase, no water present
09:58 a. m.	110°C	Inlet valve	Temperature decrease to 110°C
10:02 a. m.	100°C	Mirror Adjustment	Cloudiness
10:05 a. m.	132°C	Outlet valve	Steam mixture, minimum quantity of water
10:27 a. m.	160°C	Outlet valve	Steam increase, no water present
10:29 a. m.	115°C	Outlet valve	Temperature decrease to 115°, Cloudiness
10:44 a. m.	136°C	Outlet valve	Steam mixture, minimum quantity of water
11:00 a. m.	123°C	Outlet valve	Steam mixture, minimum quantity of water
11:54 a. m.	124°C	Outlet valve	Steam mixture, minimum quantity of water

Source: own

4. Conclusions

We found that it is possible to build a prototype linear Fresnel solar collector using simple and affordable materials for water heating and/or steam generation. We did so, highlighting its numerous advantages in the field of solar energy. The local parameters, components and materials that best meet construction and implemented requirements were identified. A summary of the results was made, and an analysis of the system was carried out to determine the optical efficiency of the system and the global losses. We obtained profitable and productive results for prototype development implicating the efficient modern generation of steam.

Solar radiation is the ultimate source of earth's energy system. In Bucaramanga, during our tests, there were several problems based upon the local weather. Thus, more tests in other regions should be performed to generalize our results.

The sudden drop in temperature at the receiving tube was caused by supplying the working fluid at room temperature. Thus, it was decided to reduce the diameter of the receiving tube and to increase the inlet temperature of the fluid by installing a coil pre-heating system, which improved working conditions by allowing a minimum temperature differential input to the system of 45°C under conditions of diffuse radiation with a high concentration of cloudiness.

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