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# Evaluation of the incidence of optical and physical characteristics onthe performance of a Fresnel Linear Collector prototype

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## ABSTRACT

This article aims to evaluate the optical and thermal behavior of a small Fresnel linear concentrator prototype developed under the appropriate technology paradigm. The system was developed by the Energy, Automation and Control Systems Research Group of the Technological Units of Santander, Colombia for water heating. The study of the device was developed from a series of simulations that took into account theoptical and thermal factors of the real system, and a series of alternative scenarios that seek to improve the performance of the device were evaluated. The simulation process was carried out by applying the "TRNSYS" Software in order to study the dynamic behavior of the concentrator and the "Soltrace" Softwareapplying the Monte Carlo Ray Tracing method. The results obtained showed that the improvement scenariosproposed to evaluate the optical characteristics of the primary reflection system do not significantly increasethe performance of the device, while the optical characteristics applied to the secondary reflection system doreflect a significant increase. Finally, the variation of flow and the area of the preheater show a direct relationship in performance, reaching values that predict the ideal value of the operating variable.

**Keywords**: Linear Fresnel Reflector, Optical Performance, Ray Tracing, TRNSYS, Solar Concentrators

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## 1. Introduction

Population growth and industrial development have directly affected the growth in the demand for electrical energy in the world, setting off alarms in the international community due to the generation of an energy deficit in different regions of the world [1]. Consequently, 190 countries in 2015 signed the Paris Agreement, committing to the conservation of the planet and encouraging the implementation of technologies that take advantage of renewable energy sources, to mitigate the use of fossil fuels [2]. Indeed, solar energy sources in the last decade have been projected as an alternative for the production of electrical and thermal energy through photovoltaic (PV) [3] and Thermosolar (SST) [3] systems, respectively, contributing to generate an energy mix worldwide [4].

Solar thermal systems (SST) are an alternative for the use of solar radiation, because they absorb energy from solar rays and increase the temperature of a fluid. The SSTs have applications at the residential level or are integrated into turbines for the production of electrical energy. Based on the working temperature, they are classified into two subgroups: low temperature thermal subsystems (1D) and solar concentration subsystem (2D and 3D) [5]. 1D systems have a working range between 0-100°C, 2D or medium temperature systems have a working range between 100-400°C and finally, 3D or high temperature systems have a working range of up to 1000°C [6].

Within the solar concentration subsystem, the 2D systems stand out for their low construction cost and high operating temperatures, technologically classified as parabolic trough collectors (PTC) and Linear Fresnel concentrators (LFC) [7]. For its part, the PTC presents higher levels of centralized application, while LFC, despite having large-scale operational projects, is still in the process of improvement, however, due to its simplicity in construction, easy assembly and maintenance, they are a technology with a high potential in development [8]. 2D systems direct solar radiation through the use of a primary reflection system (generally they are mirrors or sheets of some high-reflectance material), reflecting the radiation towards a linear concentration system [9]. Due to the small size that these tubes generally have, this system implements a secondary reflector to redirect and trap the greatest amount of radiation reflected by the primary reflectors, additionally generating a greenhouse effect, increasing the temperature and serving as protection to reduce convection losses. that could be generated in the system [10].

Currently, alternative 2D solar concentration technologies are being developed to overcome different technological limitations [11]. Thus, the process requires experimental evaluations and simulation to predict the optical and thermal behavior of the devices. Consequently, methods have been developed to carry out this type of evaluation, highlighting [12]: numerical simulations, dynamic simulations, computational Fluid Dynamics (CFD) and the Monte Carlo Ray Tracing Method (MTCR). In the first place, numerical simulation integrates mathematical tools that allow modeling, simulating or predicting the behavior of a solar collection system, based on the knowledge generated by differential equations and applying the resolution of numerical methods [13]. On the other hand, the dynamic simulation process artificially reproduces the thermal phenomenon that can occur in a transitory period in a solar collection system, technically simulating the real or ideal operation that this system would have, analyzing the impact, behavior, gain of temperature among other factors, obtaining a prediction of the performance of the system [14]. For its part, Computational Fluid Dynamics is the branch of computer-aided engineering that simulates fluid motion and heat transfer using numerical approaches [15]. Finally, the Monte Carlo Plotting Method (MTCR) is a quantitative technique that imitates through mathematical models the iterative random behavior of real non-dynamic systems, providing approximate solutions to any type of problem, whether stochastic or deterministic [16] [17].

Within the different optical and thermal analysis methodologies, the numerical simulation method and the MTCR stand out. Numerical simulation applied through the TRNSYS software is a highly applied alternative at a global level, as explained by Sultana et al., they used TRNSYS to investigate the effect that climatic states would have on the performance of a linear Fresnel concentrator (LFC) [18]. In turn, Paez Castro and Uribe Sanabria, used Trnsys to carry out an annual transitory study of an LFC handcrafted prototype, making variations in the input flow rate and the optical properties of the primary and secondary reflectors of the device, identifying design characteristics that affected in increasing performance [19].

On the other hand, the MTCR methodology has advantages such as diversity of free access software for its application. Tarazona-Romero et al., applied the MTCR methodology to evaluate a LFC prototype, using the SolTrace tool in order to evaluate the incidence of the size of the primary reflection area in the linear Fresnel collector [20]. In turn, González Martinez and Villabona used SolTrace to evaluate the incidence of the reflection area in a parabolic trough concentrator, highlighting the influence of the size of the reflection area on the performance of the device [21]. Finally, Said et. al., evaluated through the use of MTCR, multiple experimental optical configurations applied to a linear Fresnel reflector, seeking to improve the optical performance and concentration ratio [22]

Through the development of this work, four improvements will be proposed, both optical and physical and even flux variation, to evaluate the energy gain and operating temperatures of a Linear Fresnel concentrator prototype built under the paradigm of appropriate technology. First of all, it is understood by appropriate technology, simple systems in operation and functioning, built with materials in the local environment and of low cost. Finally, each upgrade scenario is simulated in TRNSYS and/or SolTrace to determine how it would affect collector performance, in order to identify upgrades for the current device.

## 2. Methods and materials

### 2.1. Linear Fresnel Concentrator

The linear Fresnel concentrator (LFC) evaluated in this work was designed and built by the control and automation systems research group (GISEAC), of the Santander Technological Units-UTS, Bucaramanga, Colombia. The prototype model is shown in Figure 1.

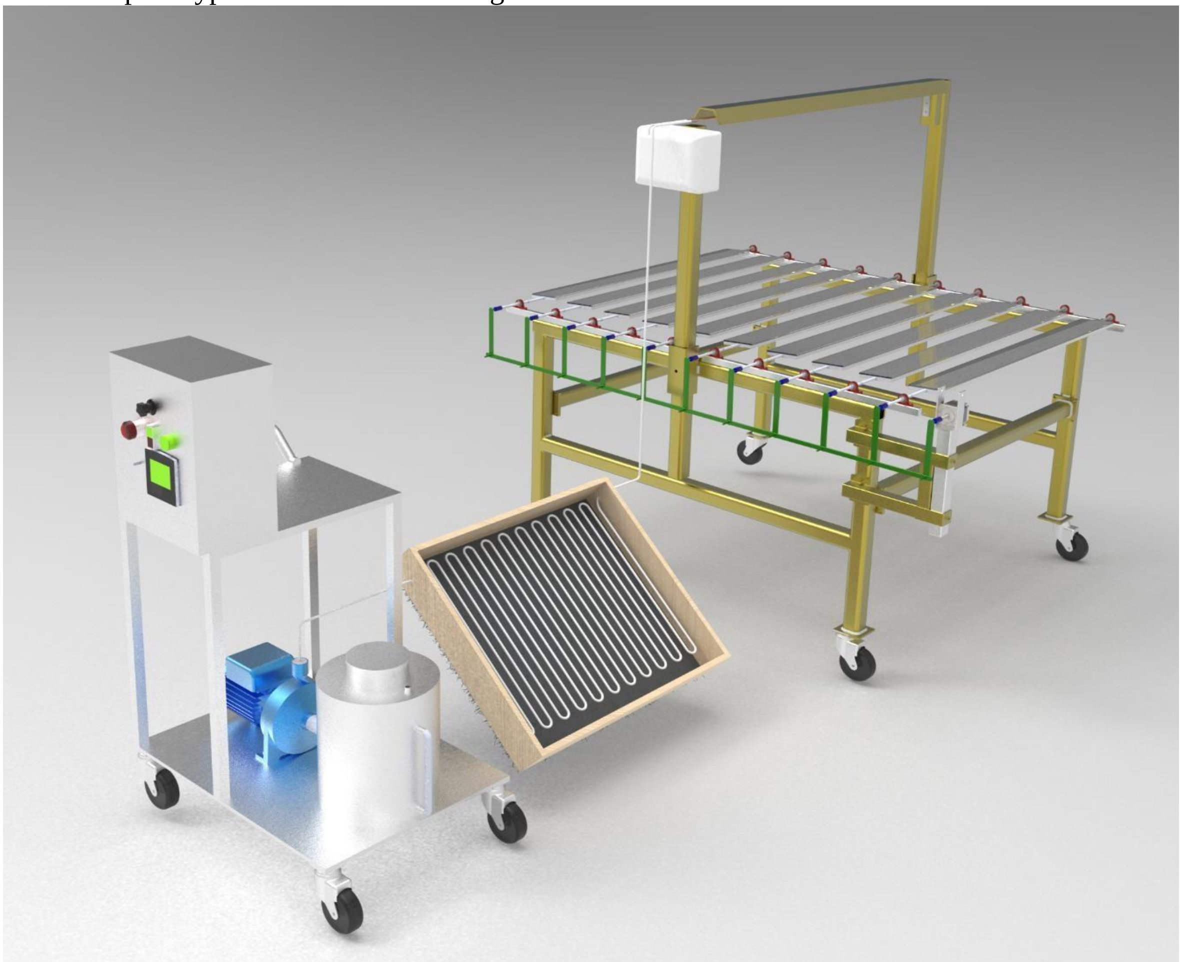

Figura 1. Colector Lineal Fresnel

The dimensions of the Linear Fresnel concentrator are presented in Table 1, while Table 2 describes some relevant optical and thermal characteristics, which allow accurately modeling the LFC prototype in the working software, assigning properties corresponding to the real device.

Table 1. Dimensions Components

| Component | Dimension |
|---|---|
| Number of Reflective Mirrors | 10 |
| Reflective Mirror Length | 1 m |
| Reflective Mirror Width | 0.1 m |
| Number of Absorber Tubes | 2 |
| Receiver Tube Outer Diameter | 0.003175m |
| Receiver Tube Internal Diameter | 0.0004699m |
| Length Absorbent Tubes | 1.2m |
| Focal distance | 0.75m |

Source: Table prepared by the authors and information taken from [23]

Table 2. Characteristics of Fresnel Linear Collector Components

| Coefficients | Value |
|---|---|
| Copper tube conduction coefficient | 0.8 |
| Copper tube emissivity | 0.12 |
| Mirror reflectance 8 mm reflectors | 0.712 |
| Aluminum foil reflectance | 0,799 |
| Secondary reflector absorption coefficient | 0.93 |

Source: Table prepared by the authors and information taken from [24]

### 2.1.1. Assessed Scenarios

A series of scenarios of geometric variation and change of optical parameters of the real model, as well as variation of the workflow and the area of the preheater coil are studied in order to identify possibleimprovements to increase performance. The study takes as a model the analysis developed by the Argentine Association of Renewable Energies and the Environment (ASADES), which compares the spectral reflectancecharacteristics of some materials that are usually used as reflectors in equipment for harnessing solar energy [25].
SolTrace and TRNSYS software are used for the simulation process. The scenarios evaluated in SolTrace are based on the MTCR methodology and assume the following characteristics:

- Ideal System 01: Primary and secondary reflector with an emissivity value of 1 (e=1) and collector tubes with an absorptivity value of 1 ($\alpha$=1). The ideal system 01 refers to a lossless LFC model modeled in Soltrace.
- Real System 01: 8mm thick glass primary reflectors, secondary reflector with polished external finish and uncoated collector tubes. Note: the real system in Soltrace contains the geometric and optical characteristics of the real built system.
- Improvement System 01: 2mm thick primary glass reflectors, secondary aluminum reflector and collector tubes, with external matt black coating. Note: upgrade scenario 01.
- Improvement System 02: High reflectance aluminum primary reflectors with a thickness of 2mm, aluminum secondary reflector and collector tubes, with matt black external coating. Note: upgrade scenario 02.
- The dynamically evaluated scenarios use the Trnsys tool and assume the following characteristics:
- Real System 02: Coil area of 0.42 m2 (0.7mx0.6) and pump mass flow of 152 Kg/hr. Note: the type that the software has by default is used and it is adjusted to the geometric characteristics of the real system.
- Improvement 03 System: Coil area of 0.56 m2 (0.7mx0.8) and mass flow of the pump of 170 Kg/hr. Simulated improvement system only in TRNSYS.

The selection of the materials that affect the geometry and characteristics linked in the proposed scenarios were subjected to an information classification applying the formal concept analysis methodology.

## 2.2. Analysis Methods

This section presents the analysis methods applied in the development of the project, through two software: SolTrace and TRNSYS.

### 2.2.1. MTCR methodology

The MTCR methodology allows performing different simulations of the behavior of the LFC system with the optical and thermal characteristics shown in table 3 of the real device. The purpose of this process is to compare the behavior of each of the evaluator scenarios, identifying the configuration with the highest performance. Each simulation is performed by varying the direct horizontal radiation (DNI), according to the monthly average of each month of the year, based on the data provided by the Meteonorm software. The intensity of rays used in Soltrace corresponds to 100,000 rays for each iteration.

#### 2.2.1.1. Soltrace

Soltrace is software developed at the National Renewable Energy Laboratory (NREL) to model concentrating solar power systems and analyze their optical performance. The code developed by NREL allows selecting and monitoring the rays generated through multiple optical iterations, obtaining as a result scatter diagrams and flux intensity maps. Additionally, it allows modeling optical geometries with shape, contour and optical quality attributes (NREL, 2021a). Figure 2 presents the ray tracing of the simulation process in SolTrace of one of the proposed scenarios.

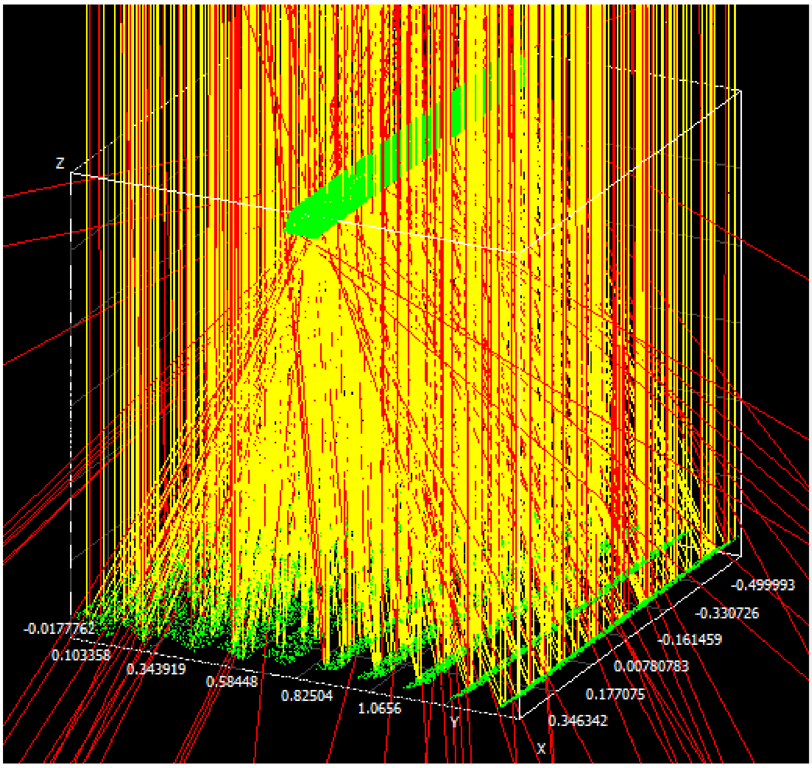


Figure 2. SolTrace

### 2.2.2. Dynamic simulation method

In the dynamic simulation process, the TRNSYS software is used to evaluate the general behavior of the device in time intervals of one year. TRNSYS allows you to supply meteorological databases in order to simulate the real behavior of the technology in specific regions.

### 2.2.3. TRNSYS

It is an interactive single energy modular simulation program, including a wide variety of components or commercial types for renewable energy generation [26]. The data obtained through the simulations in TRNSYS can be stored in Excel spreadsheets, displayed through interactive graphics or displayed as values in a graphical interface. Additionally, it has types that interconnect TRNSYS with other programs such as Matlab, EES, Sketchup, among others. Figure 3 presents the connection scheme of a series of types that simulate the behavior of the device to be evaluated.

To develop the simulation process, the following Types are used within the Software to obtain a process similar to the real system; Each type of Trnsys has a default function that resembles the behavior that the devices would have under real simulation conditions without controlling the devices.

- Type 1288 simulates a linear fresnel concentrator. It allows to vary design parameters and optical characteristics.
- Type 550 simulates an integrated collector storage system. This design represents flat plate solar collector; in which water circulates through an empty pipe, to be heated with the incident radiation. Simulates in the present work the Preheater.
- Type 114 represents a constant speed pump capable of maintaining a mass flow rate. It does not take into account the start and stop curve of the pump, nor the effects of pressure drop.
- Type 14h simulates a transient function that depends on time, this function can have a behavior characterized by a repeated pattern.
- Type 31 models the thermal behavior of flow in a pipe or conduit using fluid segments of variable size.
- Type 15-6 reads data at regular time intervals from an external weather data file.

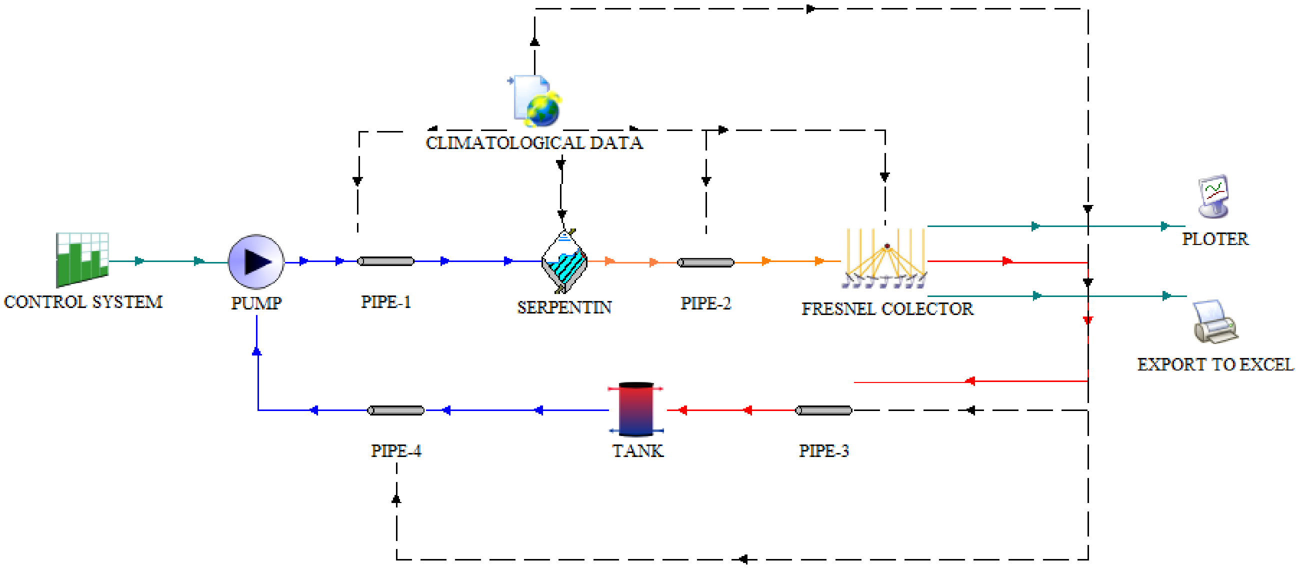


Figure 3. TRNSYS connections

## 3. Results and discussion

### 3.1. SolTrace simulation process

The results of the evaluation of the information obtained through the simulations initially carried out in SolTrace are presented. Figure 5 presents the comparison between the evaluated scenarios: Ideal System 01, Real System 01 and the two systems that make up the improvement scenarios. The analysis of the information is based on the comparison of heat flow absorbed by the concentrator tubes in each simulation, highlighting that:

- The month of June was the month with the highest energy production in all cases. This is due to the fact that the data file taken by means of the Meteonorm tool for the simulation places that month as the one with the highest DNI, during the year. This evidences a direct relationship between the incidence of the DNI with the flow capacity reflected in the concentrator tubes.
- The improvement system 01 compared to the real system presented a 0.2355% increase in heat flux than the primary reflectors and a 3.908% increase in the secondary reflectors.
- The variation of optical parameters reflects a small increase of 0.0680% in the primary reflectors of the enhancement scenario 02 and a 2.40357% increase in the enhancement scenario 01.
- The ideal system 01 generated an annual average of 3233.03 kWh. However, the real system presents an annual reduction of 53.74% compared to the ideal 01. Likewise, the improvement systems 01 show a reduction of 56.24% and the improvement system 02 a reduction of 56.97%.

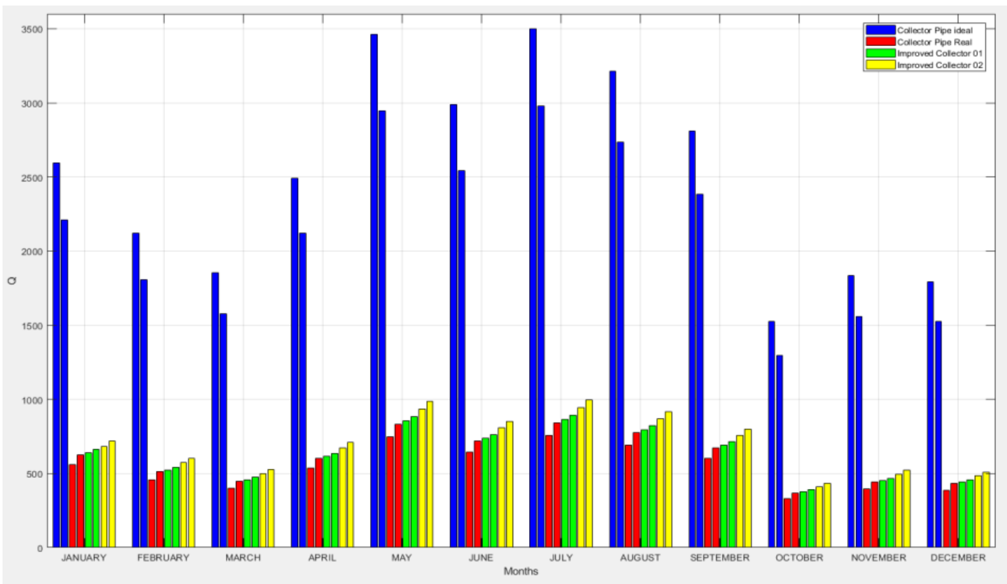


Figure 4. Comparison of Heat Flow Collector Tube Ideal, Standard and Improved System 1 and 2

On the other hand, the behavior of the reflectance in the heat flow of the primary reflectors is analyzed, the month with July is selected, being the month with the highest DNI and consequently, with the best levels of heat flow in the system as shown. presented in figure 5. The following stands out:

- The improvement system 02, presented better heat refraction due to the use of high reflectance aluminum in the primary reflectors. Additionally, there was evidence of a decrease in losses due to reflection in the secondary reflectors, based on the use of a matte black paint coating.
- The concentration ratio presented in the real system was 3.6426%, in the improvement system 01 it was 7.253% and in the improvement system 02 it was 7.2995%, evidencing the direct incidence of the materials selected for the simulation process.
- Because the ideal simulations do not take into account the convective losses between the reflectors and the wind speed, their analysis is not included in this section. However, the secondary reflector with the highest average is the improvement system 02 with 2,570,587 kWh.

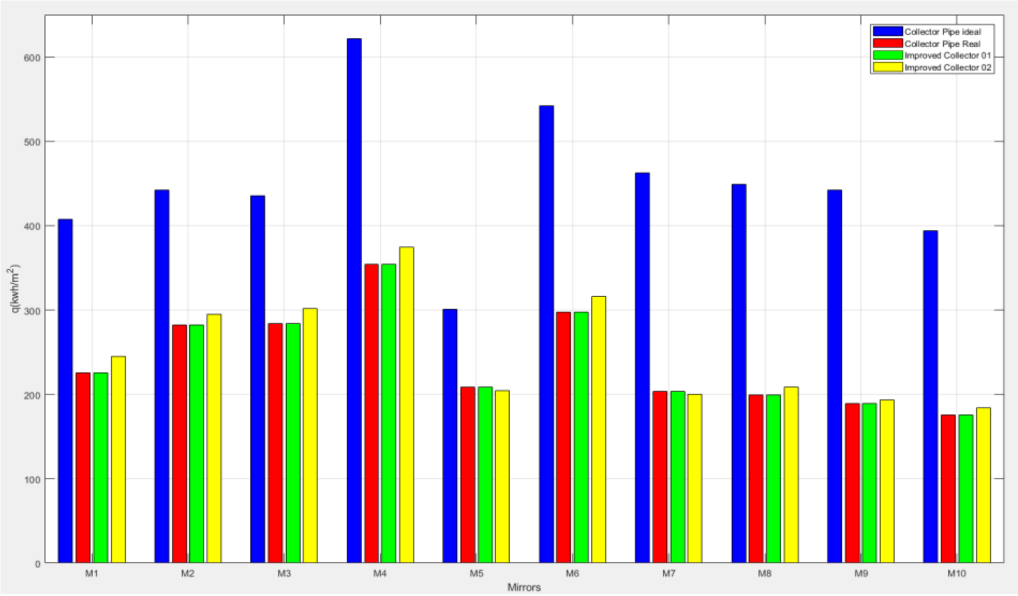


Figure 5. Heat Flow Primary Reflectors Month of July

Additionally, the behavior of the reflectance of the secondary reflectors is presented in figure 6, concluding that:

- The months with the highest heat flux in the secondary reflector were July and May, in contrast, the months with the lowest heat flux were October and December.
- Discarding the ideal system, the secondary reflector of the real system has an efficiency of 35.152%, the improvement system 01 a 39.04% and the improvement system 02 a 41.4474%.

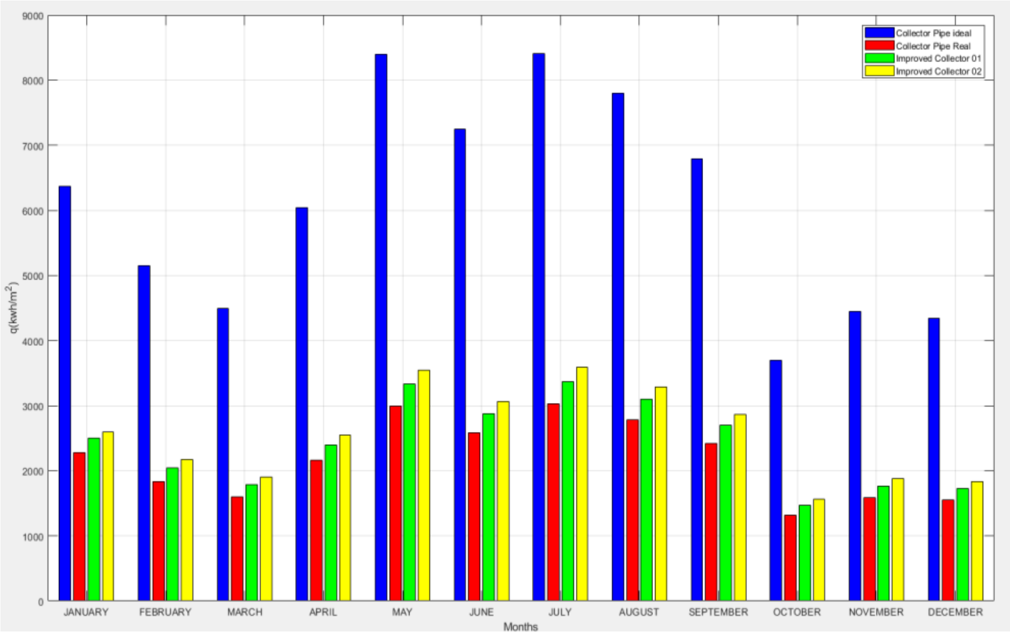


Figure 6. Heat Flow Secondary Reflector

### 3.2. TRNSYS simulation process

The results of the evaluation of the information obtained through the simulations carried out in TRNSYS are presented. Next, the comparisons between the evaluated scenarios are presented: real Ideal system and improvement scenario 02. The analysis process seeks to optimize the energy rate by alternating important parameters, such as the area of solar incidence of the coil and the flow pump mass.
Figure 7 presents the results of the behavior of the mass flow of the pump during the month of January. The increase in energy with a flow rate of 170 Kg/hr reached a value of 2220.32 Kj/hr. In conclusion, it increases the energy rate by 13.66 Kj/hr with respect to the real system, which operates with a mass flow of 152 Kg/hr.

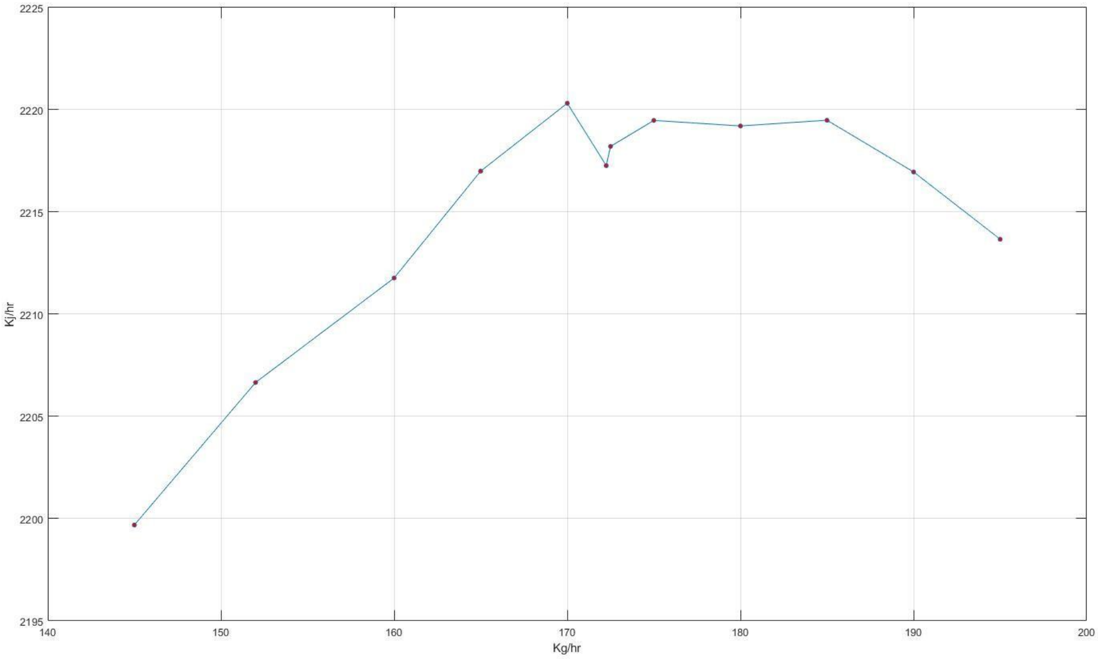


Figure 7. January mass flow variation

Additionally, the energy of the system during an interval of 10 months is not uniform as it is presented in figure 8. There are different factors that include thermal losses, place of implementation, weather conditions, DNI, among others, that directly affect the results at time to evaluate this type of technology for long periods of time.

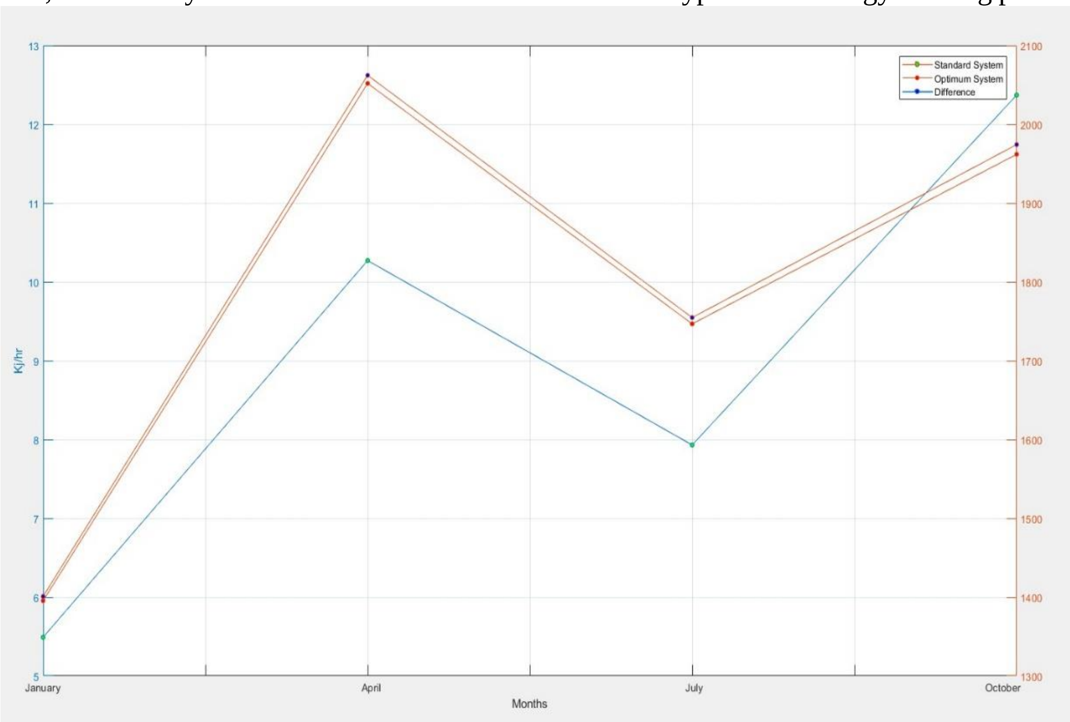


Figure 8. Systems Comparison

On the other hand, the diameter of the auxiliary system that preheats the fluid before entering the concentrator is varied. The geometric condition of the coil that the preheater has is varied, that is, physical parameters of solar incidence are characterized in order to increase the absorption capacity of the working fluid. The operating mass flow condition of the centrifugal pump for this analysis is 170 Kg/hr.
The variation of solar incidence in the preheater coil for the month of January is presented in Figure 9, highlighting that the value with the highest energy gain corresponds to an area of 0.56m2 (0.7x0.8), finding a maximum energy rate of 2227.11 Kj/hr.

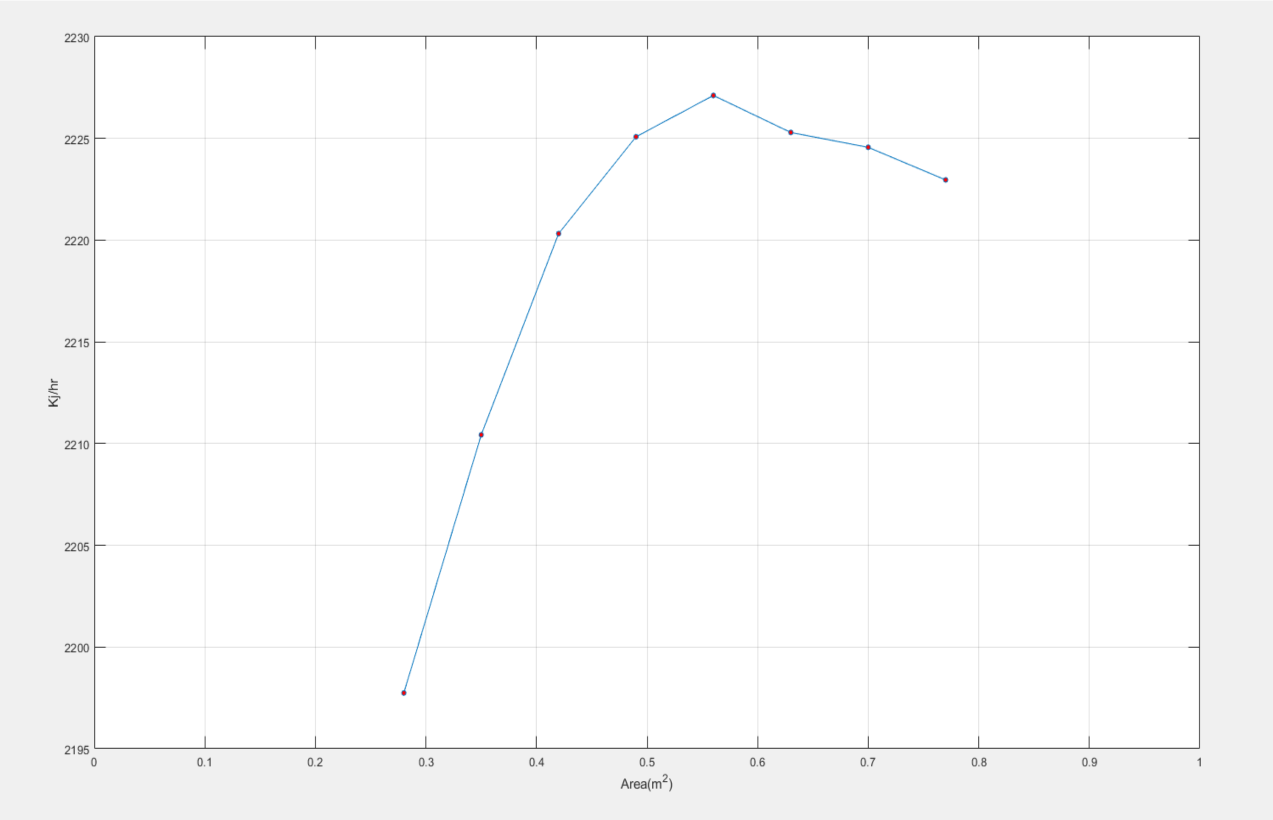


Figure 9. Variation of solar incidence area for the month of January

Finally, the energy difference for an interval of 10 months under optimal operating conditions of the pump and Serpentin are presented in Figure 10, evidencing energy differences between the real simulation and the improved simulation. It is highlighted that:

- Under optimal conditions of operation of the centrifugal pump and the coil, there is a significant increase in the energy absorption rate for the months of April, July and October.
- The month of January presents the greatest conditions of low favourability, although there is an increase, it is not as relevant, this is because January in the year 2020 was a month with an energy deficit from the incident solar radiation compared to the others. months and for this case

## 4. Conclusions

The application of solar concentration systems in the world for the production of energy in industry, residential and urban areas, is extensive and highly applied, however, different studies are currently being developed that seek to improve the existing technology and apply it to the needs of regions specific. Within the solar concentration systems, the Linear Fresnel concentration systems stand out for their easy maintenance, low initial investment cost, modularity, among others, based on many study projects, technological development and research present in the literature. This motivated the Research Group in energy, automation and control systems GISEAC, to develop a prototype of this type of solar concentrator under the paradigm of appropriate technology in the Technological Units of Santander, Colombia, for its application in alternative solar desalination systems. To study the behavior of the optical characteristics and the flow of the Linear Fresnel concentrator prototype, an analysis is carried out by applying the SolTrace and TRNSYS software. In conclusion, the most important results achieved in the study area were:

- There is a minimal difference in heat flux generated per square meter between the different primary reflector materials of AR aluminum and 2mm glass. This leads to consider the use of the 2mm mirror, because it has a lower price than the AR aluminum sheet.
- Highlights the average increase in secondary reflector performance between the actual simulation and the enhancement scenarios from 3.915% to 6.318% respectively. It is evident that in any of the two cases of improvement proposal, a positive effect is generated in the increase in performance.
- Through the variation of flow and area of the Coil, the energy use of the prototype is increased. The mass flow variation generates an ideal point of 170 Kg/hr with a Serpentin geometry of 0.7 meters long and 0.8 meters wide.

Finally, it is possible to demonstrate the link between the type of material used to carry out the reflection process and the performance of the device, it is important to highlight that the material selected for the test was based on the appropriate technology paradigm. Additionally, the behavior of the flow and the area of the preheating system, as well as the optical characteristics, directly affect the performance of the system. In summary, the proposed improvement scenarios improve the energy performance of the current system at a low investment cost.

**Declaration of competing interest**

The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

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