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Performance evaluation of solar thermal collectors in Colombian thermal floors by dynamic simulation

Brayan Eduardo Tarazona-Romero[1-2], Nelcy Daniela Socha-Rojas[3], Javier Ascanio-Villabona[1-2], V. Kafarov[3] and N. Y. Castillo-Leon[1]
[1]Faculty of Natural Sciences and Engineering, Unidades Tecnológicas de Santander, Bucaramanga, Colombia
[2]University of the Basque Country, Vizcaya, Spain
[3]Department of Chemical Engineering, Universidad Industrial de Santander, Bucaramanga, Colombia

*Corresponding author E-mail: btarazona@correo.uts.edu.co

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Abstract

Population growth has increased energy demands, posing challenges for Colombia due to its limited natural resources and the effects of climate change. Heating and cooling represent the main energy needs of households. Since the adoption of the Sustainable Development Goals, particularly SDG07, interest in renewable energy sources, especially solar energy, has grown. Solar energy, a clean and abundant resource, is typically harnessed through photovoltaic (PV) and solar thermal (ST) technologies. ST technologies are classified by their level of solar concentration into 1D, 2D, and 3D dimensions. This study focuses on simulating the performance of flat plate collectors (FPC), evacuated tube collectors (ETC), and parabolic trough collectors (PTC) across different regions of Colombia using TRNSYS software. Linear Fresnel Collectors (LFC) were excluded due to their lower efficiency and commercial maturity compared to PTC. The analysis covers five Colombian thermal floors: warm, temperate, cold, paramo, and snow, represented by five distinct regions. Dynamic simulation models were developed to evaluate the performance of these technologies, offering a detailed and practical insight into their potential implementation in the Colombian context. The results highlight the influence of regional climatic conditions on the performance of each solar technology, emphasizing the need for careful selection and system design tailored to the specific thermal floor to ensure optimal efficiency.

Keywords: Dynamic simulation, Evacuated tube collectors, Flat plate collectors, Solar energy, Thermal floors

1. Introduction

Population growth has generated a constant increase in energy needs. This, together with the limitations of natural resources in Colombia [1] and the effects of climate change worldwide, presents an environmental, social and economic problem [2]. In general, most of the energy needs of households come from heating and cooling [3]. Since the adoption of the Sustainable Development Goals (SDGs), specifically SDG07 which seeks affordable and clean energy [4], there has been an increased interest in the use of renewable energy sources, especially solar energy [5].

Solar energy is a clean, unlimited, and environmentally friendly renewable energy source present worldwide [6]. Generally, the technologies that harness the solar energy source can be classified into two [7]: (i) solar photovoltaic (PV) technology and (ii) solar thermal (ST) technology. PV technology directly converts solar energy into electrical energy through photovoltaic cells, while ST technology converts solar rays into thermal energy through solar thermal collectors (STC) [8].

STC technologies can be classified according to their level of solar concentration in 1, 2, and 3 dimensions. The 1D technologies harness the sun's rays on a surface, while the 2D concentrating technologies reflect the sun's rays on a line and the 3D concentrating technologies reflect the sun's rays on a point [9]. Among the 1D concentrating technologies, flat plate collectors (FPC) and evacuated tube collectors (ETC) are the most widely applied at the residential level. As for 2D concentrating technologies, parabolic trough collectors (PTC) and Linear Fresnel Collectors (LFC) are the most widespread. Finally, in 3D concentrating technologies, central receiver systems and parabolic dishes are the most common solutions.

The main difference between these three families lies in the achievable heat fluxes and, therefore, in the operating temperatures, as well as in the implementation and operation costs. Specifically, 3D concentration technologies offer higher heat fluxes and temperatures than 2D and 1D concentration technologies, but at the same time, it is the family that presents higher costs for retrofitting. Since thermal storage temperatures do not exceed 100 °C, there is no benefit in using 3D concentration technologies, especially considering that higher temperatures require more sophisticated and expensive materials.

On the other hand, the main challenge of using solar energy to meet energy needs is to estimate the performance of the implemented technology throughout the year. This performance is affected by the type of technology and its configuration, as well as by the area and weather conditions of the region. Although experimental processes make it possible to evaluate the actual performance of the technology, they are time-consuming and costly. Therefore, an alternative for long-term analysis of solar systems for thermal energy production is the use of simulation software [10].

This paper aims to propose simulation models based on commercially available ETC, FPC, and PTC. The LFC technology is excluded from this study, because technologically it shares many characteristics in terms of maintainability and manufacturability, since in essence, the two 2D concentration technologies use the same materials, structure, re-flow surface, and linear receiver, however, the LFC technology presents lower efficiencies and commercial maturity levels compared to the PTC technology [11]. The simulation model will be carried out using TRNSYS software to predict the technological performance in five regions of Colombia, each representing one of the five thermal floors. In this context, Section 1 provides an introduction with the main background of the subject and an overview of the paper's content. Section 2 describes the methodology used and includes the proposed simulation models. Section 3 relates the main results and discusses them. Finally, Section 4 summarizes the most relevant conclusions of the analysis.

2. Research method

2.1. Description of the scenarios

Thermal energy generation strategies often become inoperative depending on the local climatology, as well as the difficulties of sustainability after their implementation, either due to lack of experience in the communities or lack of infrastructure. Therefore, a dynamic simulation process of the behavior of 1D and 2D solar concentration technologies, specifically a flat plate collector (FPC), an evacuated tube collector (ETC) and a parabolic trough collector (PTC), will be carried out. Each of these technologies will evaluate their suitability as a case study in the different thermal floors of Colombia, to supply thermal energy to PCM thermal storage systems with a melting enthalpy temperature of 59.2 °C and 234.4 kJ/kg.

Colombia is known for its climatic and geographic diversity, which is reflected in the presence of "thermal floors". These are altitudinal levels that present specific climatic characteristics. The thermal floors in Colombia are generally classified into five levels, each associated with certain altitude and temperature ranges. Table 1 describes the main characteristics of the thermal floors and the associated regions for the different scenarios (E) to evaluate solar technologies.

Table 1. Characteristics of evaluation scenarios

Thermal Floor	Region	Height (mbsl)	Surface (km2)	Ambient Temperature Range (°C)
War	Guajira (E1)	0-1000	2250	> 24
Temperate	Medellín (E2)	1000-2000	2750	17°C - 24
Cold	Pasto (E3)	2000-3000	1650	12°C - 17
Paramo	Sumapaz (E4)	3000-4000	800	6°C - 12
Nevado	Ruiz (E5)	< 4000	57	> 6

2.2. Description of the scenarios

TRNSYS is a transient simulation tool that allows modeling and simulating the behavior of different energy systems as a function of time. To simulate the scenarios for the various thermal floors in Colombia, individual components whose collective performance describes the performance of the entire system to be evaluated were identified and adapted. The three technologies to be evaluated were modeled in TRNSYS 18 and the block diagram used is presented in Figure 1.

The proposed simulation models were based on a common operating circuit to cover a variable area. The objective is to modify the area to meet the collector outlet temperature requirements (69°C - 79°C). Two flow rates, minimum and maximum, are considered to understand how the final temperature varies, ensuring that it always remains within the working range. In addition, five key auxiliary components are used in the system. Type 14 controls the pump on/off, allowing the mass flow rate to be adjusted in a linear fashion, while Type 114 is a variable-speed water pumping system designed to maintain the desired flow rate and ensure a constant and efficient flow in the solar heating system.

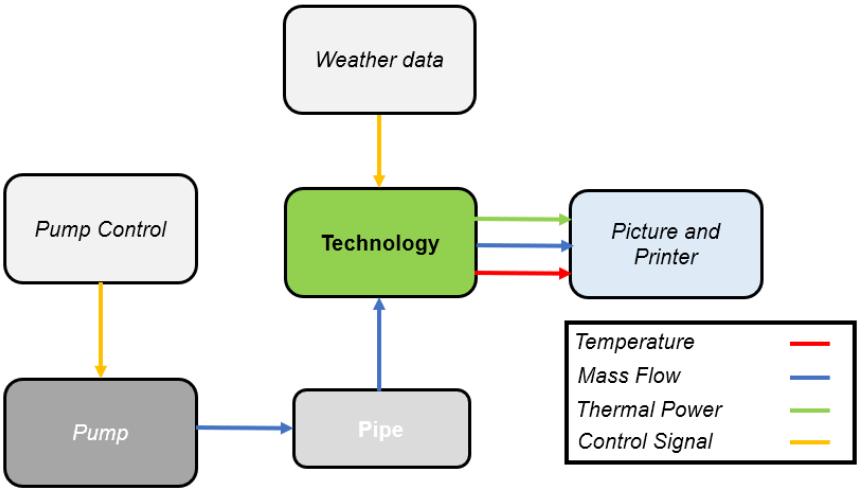


Figure 1. General simulation model

In addition, the Type 109 provides weather data readout in Meteonorm format, adapting the case study to five different regions of Colombia with accurate weather data. Type 31 manages the connection piping between system elements, ensuring proper integration, and Type 65 facilitates the visualization of the behavior of process variables in real-time. Finally, Type 25 acquires data on the behavior of process variables, allowing detailed analysis of system performance.

Together, these components allow a detailed and accurate simulation of the behavior of solar technologies in different regions of Colombia, providing a comprehensive and practical vision for its implementation.

2.3. Simulation parameters

In this section, fixed parameters are set to perform the simulation process using the model described in section 2.2: To be considered:

- PCM melting temperature range: 49 - 59 °C
- Required temperature range: 69 - 79 °C. It should be noted that operating temperatures must be at least 20°C higher than the PCM melting temperature
- Minimum flow rate: 150 kg/h
- Maximum flow rate: 162 kg/h

Additionally, three types of solar collectors were simulated with the following efficiencies, supported by their respective data sheets:

- Evacuated tube collector: 70% efficiency
- Parabolic collector: 62% efficiency
- Flat plate collector: 80% efficiency

The objective of these simulations is to obtain temperatures that remain within or above the working temperature range, maintaining a fixed flow rate in each case and varying the collector area required to achieve these conditions.

3. Results and discussion

Figure. 2 presents two graphs showing monthly average data for five Colombian cities: La Guajira, Medellín, Pasto, Sumapaz, and Nevado del Ruiz. A illustrates the direct normal irradiance (W/m²), while Figure 2. B shows the average temperature (°C) for each month of the year. These data are fundamental for the previously proposed simulation model since solar irradiance and temperature are key factors in the performance of solar energy systems. The information has been obtained from the Photovoltaic Geographical Information System and Global Solar Atlas databases.

The analysis of the figures shows that La Guajira has the highest Direct Normal Irradiance (DNI) and the highest temperature throughout the year, which makes it an optimal area for solar energy generation. On the other hand, Nevado del Ruiz shows the lowest irradiance and temperature values, suggesting that it is a less favorable region for the implementation of solar systems. Medellín and Pasto show intermediate irradiance and temperature values, while Sumapaz shows relatively low irradiance and temperature, although higher than Nevado del Ruiz.

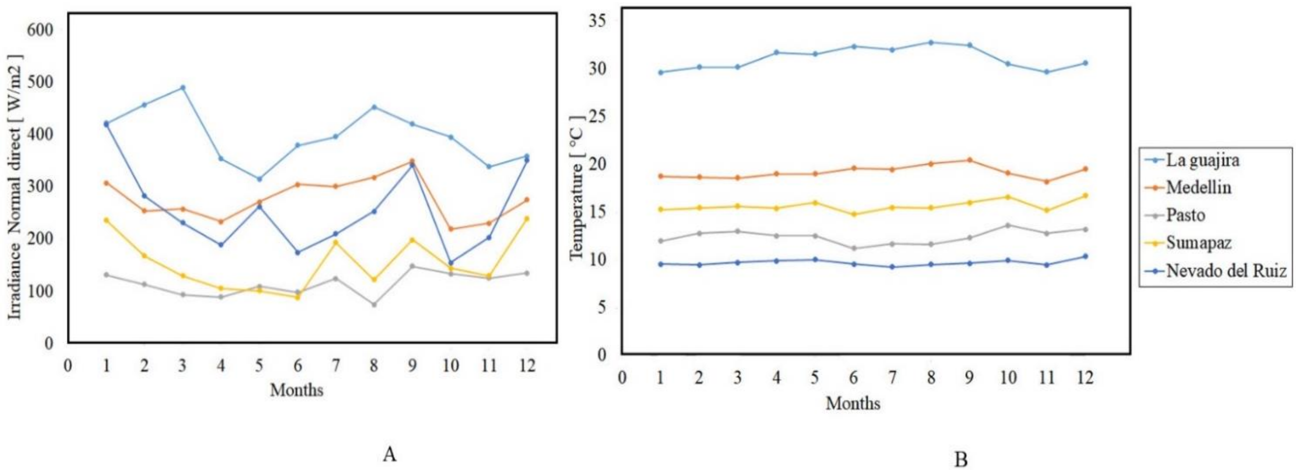
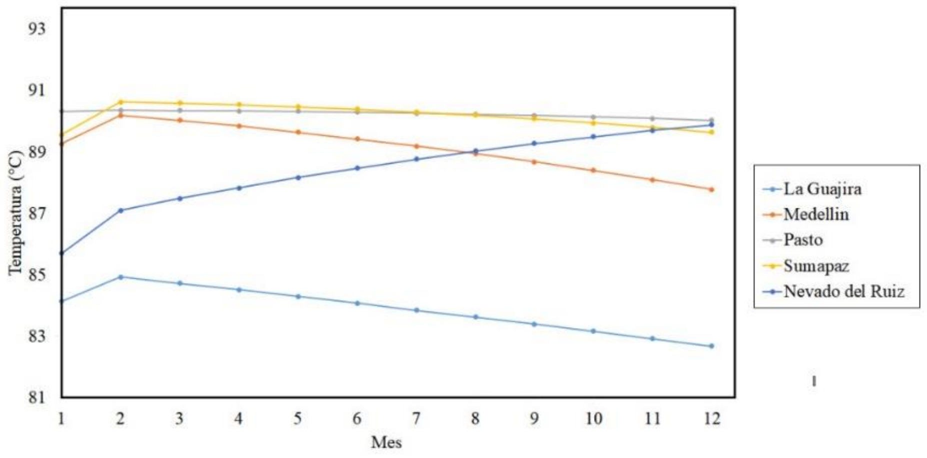


Figure 2. Monthly average values A) Direct normal irradiation B) Temperature

Figure 3A shows the behavior of the outlet temperature of the parabolic concentrator on five thermal floors in Colombia, with a flow rate of 150 kg/h, while Figure 3 a flow rate of 162 kg/h. The studies carried out indicate that the minimum area required to reach the working temperature range (69°C - 79°C) is 5 m² for both flow rates and for all the thermal floors analyzed.

It is important to note that, although it is possible to maintain temperatures within the working range with the same collector area and vary the flow rate, this is mainly due to the type of collector used. It is observed that there is a variation in the final temperature obtained; specifically, with the flow rate of 162 kg/h, the temperature decreases in a range of 0.02°C to 0.56°C compared to the flow rate of 150 kg/h. However, this decrease still remains within the optimal operating range, ensuring that the system operates efficiently under the conditions analyzed.

In La Guajira, it can be seen that the maximum temperature difference occurs in December with a value of 0.51°C, while the minimum difference occurs in February with 0.38°C. Medellin shows the most pronounced temperature drops, varying between 9.78°C in December and 12.35°C in February. Among the five thermal floors, Pasto has the lowest average temperature decrease, with a maximum difference of 0.03°C observed in February, March, and April. Sumapaz has similar behavior to Pasto, with a maximum difference of 0.05°C in February and a minimum of 0.0032°C in October. Finally, in Nevado del Ruiz, temperatures remain fairly stable despite the variation in flows, with temperature differences ranging from 0.01°C to 0.3°C.



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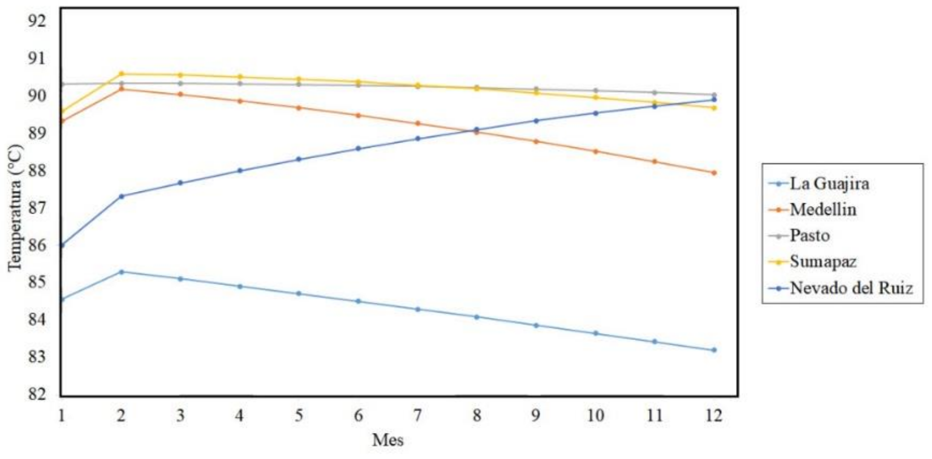


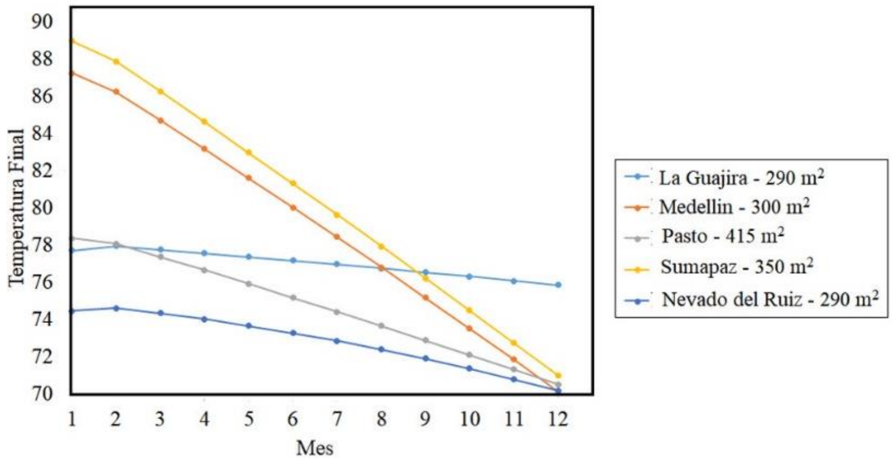
B

Figure 3. Simulation in the 5 scenarios for an area of 5 m^2 for the parabolic trough concentrator A) Flow rate 150 kg/h. B) 162 kg/h

Figure 4A shows the behavior of the flow temperature of the parabolic concentrator in the five (5) thermal floors of the country with a flow rate of 150 kg/h and Figure 4B a flow rate of 162 kg/h. In this case, there are differences at the time of establishing the necessary area to meet the temperature requirements in each thermal floor and there is also a variation in the required area after varying the flow rate.

In La Guajira, it was concluded that with a collector area of 290 m², it is possible to comply with the working temperature range for both flow rates. Although there is a decrease in temperature as the flow rate increases, the promised difference is 3.11°C, with the largest difference in February (3.19°C) and the smallest in December (3.02°C). In Medellín, it was necessary to establish two different areas to meet the working temperature requirement, with a difference of 20 m² between them. The areas were 300 m² and 320 m² for flow rates of 150 kg/h and 162 kg/h, respectively, and the lowest temperature obtained was 69.71°C, which is within the requested range. In Pasto, a behavior similar to that of Medellín was observed, requiring an adjustment of 20 m² in the collector area, going from 415 m² for the 150 kg/h flow rate to 435 m² for the 162 kg/h flow rate. The minimum temperatures obtained were in December, with values of 70.52°C and 69.47°C for each flow rate.

In Sumapaz, the difference in collector area required was 10 m²; for the minimum flow rate, 350 m² of collectors were required, obtaining a minimum temperature of 71°C. For the 162 kg/h flow rate, an area of 360 m² was required, with a minimum temperature of 69.22°C. Finally, in Nevado del Ruiz, areas of 225 m² and 240 m² were established for the above-mentioned flow rates, requiring a larger collector area as the flow rate increased. The lowest temperature obtained was 70.18°C and 69.68°C, respectively, remaining within the established parameters.



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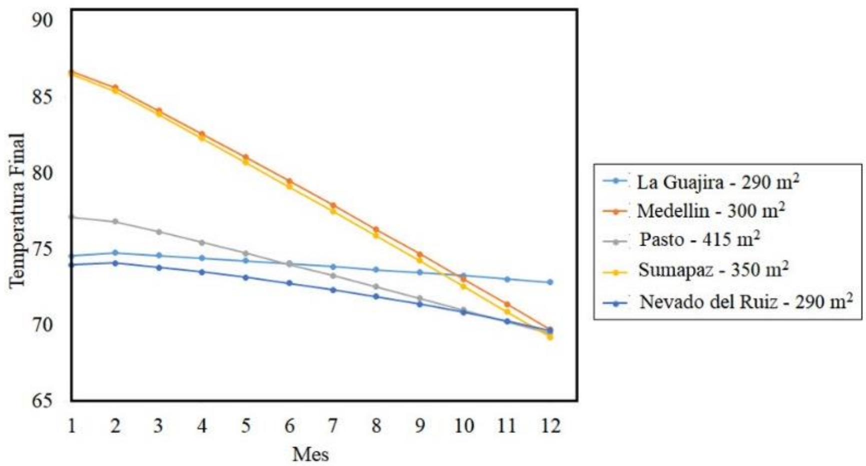
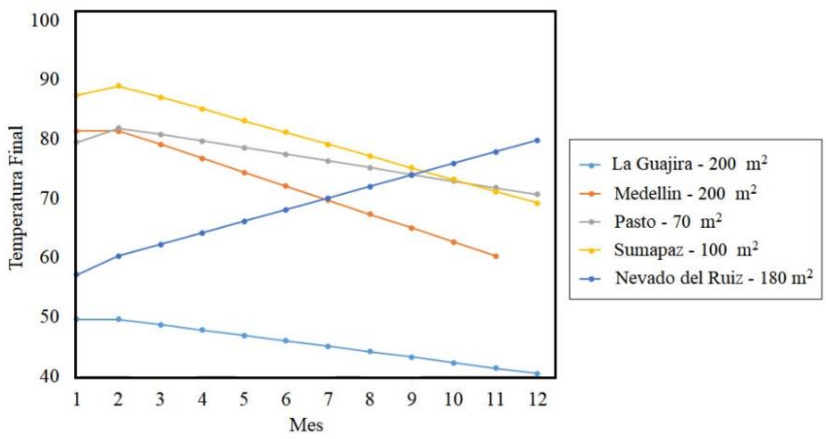


B

Figure 4. Simulation in the 5 scenarios for the evacuated pipe collector A) Flow rate 150 kg/h B) 162 kg/h

On the other hand, Figure 5A shows the behavior of the outlet temperature of the flat plate collector in five thermal floors in Colombia, with a flow rate of 150 kg/h, while Figure 5B a flow rate of 162 kg/h. In La Guajira, when using the flat plate collector with an area of 200 m², it was found that with both flow rates, the desired working temperature range was not achieved, reaching a maximum of 49.60°C. Further studies showed that an increase of 100 m² would be required to increase the temperature by only 0.5°C, which is impractical due to the additional cost and space required. For this reason, it is concluded that this technology does not meet the temperature requirements throughout the year. In Medellín, two different areas were established to meet the working temperature during most of the year, with a difference of 50 m² between them: 150 m² for the 150 kg/h flow rate and 200 m² for the 162 kg/h flow rate. However, in none of the scenarios did the temperature remain above 69°C after July. The minimum temperatures obtained were 57.95°C for the lowest flow rate and 58.71°C for the highest flow rate, both in December.

In Pasto, the working temperature range was achieved throughout the year in both scenarios, using the same 70 m² collector area. The highest temperature was obtained for the lowest flow rate, and in both cases the temperature exceeded 69°C. The maximum temperature drop was observed in February, with a value of 1.81°C. In Sumapaz, the difference in collector area required was 10 m²; with a flow rate of 150 kg/h, 90 m² of collectors were used, obtaining a minimum temperature of 69.21°C. For a flow rate of 162 kg/h, 100 m² of collectors were required, with a minimum temperature of 69.17°C obtained. Finally, in Nevado del Ruiz, no area adjustment was made, since with the two flow rates the desired temperature range was reached from July to December, with an area of 180 m². The collector area was not further increased because the increase in temperature would not be significant.



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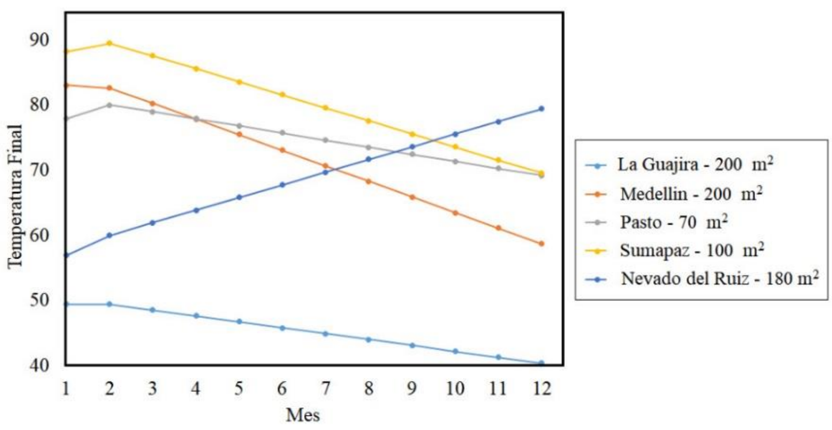

B

Figure 5. Simulation in the 5 scenarios for the flat plate collector A) Flow rate 150 kg/h B) 162 kg/h

In general, two flow rates, 150 kg/h and 162 kg/h, were analyzed to find the optimum working temperature range (69°C - 79°C) for each thermal floor. A comparison was made by keeping the area constant, but increasing the flow rate to observe its impact. The results indicate a tendency for the final temperature to decrease with increasing flow rate, although the magnitude of this variation depends on the technology and thermal floor evaluated.

Among the three types of collectors studied, the evacuated tube collector showed the greatest average temperature reduction, with a value of 3.19°C, followed by the parabolic concentrator with 2.37°C, and finally, the flat plate collector with 0.93°C. Figure 6 presents the graphs corresponding to the evacuated tube collector, which shows the greatest decrease in temperature, allowing us to observe how the increase in flow rate affects the final temperature on each thermal floor.

In Guajira (see Figure 6A), it was determined that with an area of 260 m², it is possible to comply with the working temperature range established for both channels. The average temperature decrease is 3.11°C, with the greatest difference recorded in February, when it goes from 77.95°C to 74.76°C (3.19°C decrease). It is important to note that, in both cases, temperatures remain within the required range. In Medellín (see Figure 6B), an area of 300 m² does not allow the established temperatures to be met throughout the year as the flow rate varies. In December, the temperature drops to 67.41°C, outside the working range. The highest temperature is recorded at a flow rate of 150 kg/h in January, reaching 87.25°C, which is 3.85°C higher than the maximum temperature corresponding to a flow rate of 162 kg/h in the same month.

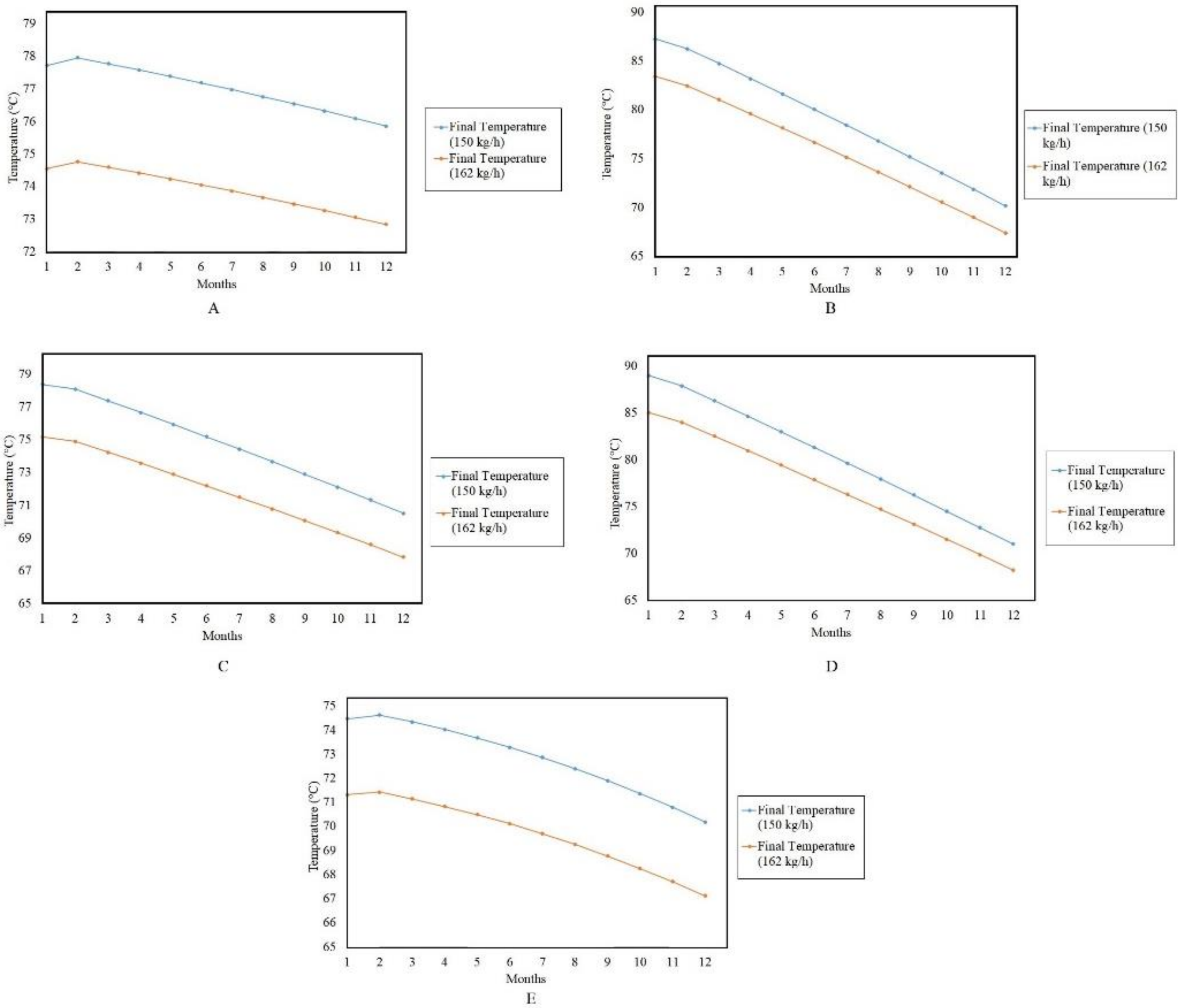

Figure 6. Simulation in the 5 relevant evacuated tube collector scenarios

Figure 6C shows the final temperature changes in Pasto, where an area of 415 m² with a flow rate of 162 kg/h does not meet the desired temperature range in November and December. The largest temperature decrease occurs in January at 3.20°C. In Sumapaz (see Figure 6D), the greatest average temperature difference between the five thermal floors studied is observed, with a value of 3.39°C. The greatest temperature drop occurs in January at 3.20°C. The greatest decrease occurs in January at 3.94°C. During 11 months, the temperature ranges are met for both flow rates, but in December the temperature decreases from 71°C to 68.21°C, leaving the 162 kg/h flow rate outside the working range. Finally, Figure 6E shows the temperature behavior in Nevado de Ruiz. The average temperature drop is 3.15°C, with the greatest difference in February and March (3.20°C). As the flow rate increases, this technology does not reach the desired temperature throughout the year, remaining below 69°C as of September.

Considering the above, it is evident that, as the working flow rate increases, the final temperature tends to decrease, a trend that is observed in all the thermal floors evaluated. Although in some cases the temperatures remain within the working range, this does not occur consistently, which implies that, in some studies, it is necessary to adjust the collector area to meet the working temperature requirements.

4. Conclusions

This study presents a detailed evaluation of the performance of three concentrating solar technologies, namely, the flat plate collector (FPC), the evacuated tube collector (ETC), and the parabolic trough collector (PTC), in different climatic scenarios in Colombia, represented by its five thermal floors. Using TRNSYS simulation software, these systems were modeled to determine their capacity to maintain the outlet temperature within the desired working range (69°C - 79°C) under different flow conditions and collector areas.

First of all, it should be noted that the efficiency and capacity of each technology to reach the target temperatures vary significantly according to the thermal floor and the technology used. La Guajira, with its high irradiance and ambient temperature, proved to be the most favorable region for the implementation of solar technologies, managing to maintain operating temperatures in the desired range in most cases. In contrast, regions such as Nevado del Ruiz, with lower irradiance and lower ambient temperatures, presented greater challenges to maintaining optimal temperatures, especially when increasing the flow rate.

The analysis of the flow variation revealed a general tendency for the outlet temperature to decrease with increasing flow, although the magnitude of this effect depends on the type of technology and the region evaluated. The evacuated tube collector (ETC) showed the greatest average temperature reduction with increasing flow, followed by the parabolic trough (PTC) and flat plate collector (FPC). This behavior is due to the inherent characteristics of each technology and its ability to transfer and retain heat.

Another key finding was the need to adjust the collector area to maintain temperatures within the working range at different thermal floors. While in some regions and with certain technologies it was possible to maintain temperatures with constant areas, others required significant adjustments to meet temperature requirements, especially when higher flows were used. This aspect is fundamental when designing and implementing solar thermal systems, as it involves space and cost considerations that affect the economic and technical feasibility of the project.

The study highlights the importance of properly selecting solar thermal technology based on the specific climatic and geographic conditions of each region. Variations in solar irradiance and ambient temperature throughout the year directly affect the performance of the collectors and, therefore, the ability of the system to supply thermal energy efficiently. This underlines the need for detailed and customized analysis in the planning of solar thermal systems, considering both the characteristics of the installation site and the specificities of each technology. In conclusion, the results of this study provide a solid basis for the selection and sizing of solar thermal systems in Colombia, highlighting the importance of adapting the technology and operating parameters to local conditions to maximize efficiency and ensure consistent performance throughout the year.

Declaration of competing interest

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

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Author contribution

The contribution to the paper is as follows: B.E. Tarazona-Romero, N.D. Socha-Rojas: study conception and design; N.D. Socha-Rojas: data collection; B.E. Tarazona-Romero, N.D. Socha-Rojas, J. Ascanio-Villabona, V. Kafarov: analysis and interpretation of results; B.E. Tarazona-Romero, J. Ascanio-Villabona, N.Y. Castillo-Leon: draft preparation. All authors approved the final version of the manuscript.

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