ISSN 2303-4521
Periodicals of Engineering and Natural Sciences *Original Research*
Vol. 11, No. 6, December 2023, pp.36-55

Energy exergetic and economic analysis (3E) in a flat solar collector with thermal storage for air heating

N. Y. Castillo-Leon[1*], N. D. Zanabria-Ortigoza[3], A. D. Rincon-Quintero[1,2], C. L. Sandoval-Rodriguez[1,2] and L. A. Del Portillo-Valdes[2]
[1] Faculty of Natural Sciences and Engineering, Unidades Tecnológicas de Santander, Student Street 9-82, Bucaramanga, 680005, Colombia
[2] University of the Basque Country, Ingeniero Torres Quevedo Plaza, 1, 48013 Vizcaya Spain
[3] Universidade Federal de Itajubá, Av. B P S, 1303 - Pinheirinho, Itajubá, 37500-903 Brasil

ABSTRACT

Solar energy has been considered as a carrier of primary energy to sustain life, representing a renewable energy resource that strengthens industrialization through its use as the main source of energy. This study evaluates the energy, exergetic and economic yields through an analytical approach applied to experimental data obtained in a flat solar collector (SAC) with paraffin as phase change material (PCM) and "V" absorber plate geometry, intended for air heating. The results of the investigation indicated that the energy, exergetic, and exergy destroyed efficiency of the SAC were 71.24%, 16.96%, and 79.66%, respectively. This research allowed us to carry out a sensitivity analysis applied to the results of the thermodynamic variables of the equipment: thermal efficiency, air mass flow and solar radiation; where an improvement in the thermodynamic yields is evidenced by obtaining a thermal efficiency of 91.25%, exergetic efficiency of 61.03% and a decrease in exergy destroyed up to 35.04% of the values obtained experimentally. Through the economic analysis, it was determined that the levelized cost of heating the SAC is 0.0927 USD/kWh, indicating that the project is economically profitable, due to the use of solar energy instead of electrical energy as an input source. Lastly, this research is expected to be a contribution that can support the authors of subsequent projects interested in this technology.

Keywords: Exergetic analysis, Solar collector, Solar radiation, Thermodynamic performance

Corresponding Author:

Nilson Yulian Castillo Leon
Electromechanical Engineering Program
Unidades Tecnológicas de Santander
Student Street 9-82, Bucaramanga, 680005, Colombia.
E-mail: nycastillo@correo.uts.edu.co

1. Introduction

The different forms of unconventional energy play an increasingly important role in global economic development and industrialization. Despite fossil fuels being the main source of energy worldwide, their environmental impact and declining reserves are driving the study and development of sustainable renewable energies [1], [2], [3]. Solar radiation is a clean source of energy that is directly and continuously available in the environment, making it easily accessible for harnessing its potential in various innovative technologies. Scientific literature highlights the efficient use of solar energy in agricultural product drying and specific space heating by transforming solar energy into thermal energy [4], [5], [6]. The flat solar air collector is a relevant adaptation that currently allows taking advantage of the sun's energy and transferring it in the form of heat to the fluid that circulates through the device, with the purpose of generating a flow of hot air that guarantees drying and maintaining the organoleptic properties of agricultural products such as cocoa, without damaging them [7], [8].

The solar air collectors are used for heating and drying of agricultural products due to their low use of materials, since they are composed of a glass cover, which is a transparent material that allows the capture of solar rays and an optimal heat transfer to the working fluid that transits through the system. Another element is the absorber plate, which is particularly made of metallic material with different obstacles that generate turbulence in the fluid and thus absorb solar radiation to transfer heat to the fluid stream. The structure is also a fundamental element that consists of a casing that deposits and secures each of the components of the SAC [9], [10]. The disadvantage of flat air solar collectors is the low thermal capacity of the working fluid, so it is established that the surface area that allows heat transmission must be increased by designing an absorber plate to generate high turbulence of the working flow, in order to obtain greater efficiency and heat transfer by convection in the equipment [11], [12], [13].

The thermal performance of flat-plate solar air collectors can be found through calculations based on the first and second laws of thermodynamics, obtaining data on the energy efficiency of the equipment, losses due to irreversibility and design optimization. The first law is widely used in the field of engineering, based on the analysis of mass and energy through heat exchange between systems. Thermal efficiency is calculated in order to determine the functionality and amount of energy in the system; the disadvantage of this law is that it does not include all the internal energy losses involved in the process [11], [14], [15]. Therefore, studies are carried out based on the second law of thermodynamics, establishing that, in any transfer or conversion of energy within a closed system, entropy increases, being this term, which defines the inequalities through the basis of reversibility of a system [16], [17], [18].

The exergy analysis is performed with the objective of quantifying the irreversibility of the technology studied, such as heat transfer losses within the system and the process with its surroundings. For this reason, it is necessary to identify the components with the greatest destruction and loss of exergy together with the processes that cause it, since efficiency can be improved if the exergy destruction in the process is reduced, although certain irreversibility is unavoidable [19], [20]. Based on the points, it is considered in the present research to conduct a conventional exergy analysis for the case study, applying the laws of thermodynamics. The objective is to obtain a detailed diagnosis of the thermodynamic performance of the equipment and reduce unnecessary resource usage in the flat plate solar collector. By conducting an exergy analysis, it becomes possible to identify areas of inefficiency and quantify the exergy destruction within the system. This analysis can provide valuable insights for optimizing the design and operation of the solar collector, ultimately leading to improved energy utilization and a more sustainable use of resources.

The most used way to store latent heat in flat plate solar collectors is the application of phase change material (PCM), which allows for increased thermal efficiency between the absorber plate and the working fluid. Because solar radiation and ambient temperature vary at every instant, the PCM acts as thermal storage in the system for a prolonged period when the energy source is no longer available [21], [22]. Table 1 presents experimental investigations on solar collectors using thermal storage to increase the temperature of the fluid in the equipment.

Table 1. Estudios experimentales que usaron material de cambio de fase (PCM) en colectores solares destinados al calentamiento de aire.

Author	Type of storage PCM	Final application	Type of solar collector	Key results
[23]	Discrete cylindrical units of microencapsulated kerosene wax	Drying of green plantain slices	Flat plate solar collector	Energy storage was 9.16 kW and 0.44 kW at 0.03 kg/s
[24]	Kerosene wax	Drying of fresh tomato slices	Flat plate solar collector	Thermal efficiency is increased to 40.2%
[25]	Kerosene wax	Drying of the medicinal plant Teucrium polium L	Unglazed transpired solar collector	Drying energy efficiency improved by at least 6%

Author	Type of storage PCM	Final application	Type of solar collector	Key results
[26]	Kerosene or wax with latent heat of fusion of 189 kJ/kg and melting point of 49 °C	Hot water supply from 11:00 am to 5:00 pm	Flat plate solar collector consisting of absorber plate, water tube and reflector	Thermal efficiency without PCM 28% and with PCM 48%
[27]	Three PCMs were tested: lauric acid, kerosene wax and stearic acid	To obtain hot water at night and on cloudy days	Vacuum tube solar collector	Lauric acid melted ≈95%, kerosene ≈87% and stearic acid 57.4%

Source: Table Prepared by the authors.

To determine the operating condition of a flat plate solar collector with thermal storage, the melting temperature of the phase change material (PCM) must be considered. In this project, paraffin is used beneath the absorber plate as a component to store the thermal energy of the system, depending on various applications [27], [28]. The temperature required is between 30 and 60 ºC to change from solid to liquid state. Therefore, it is established that the flat plate solar collector analyzed in this research will be working until the air outlet temperature is below 30ºC, since, with lower values, it will not be taking advantage of the properties of the kerosene to accumulate heat and dry air.

Different authors have investigated various types of configurations, which help to increase the performance of solar collectors by implementing innovative technologies. Some publications focus on the novel construction of the absorber plate with different obstacle shapes and dimensions [3], [29], [30], deduce that thermal efficiency can be improved by 20% if these geometrical modifications are made. It also [10], presents an experimental analysis between a conventional flat plate solar collector and an equipment that was specially designed with a textile fabric support instead of the absorbing plate; demonstrating that the latter has an energy efficiency 10% higher than the conventional one.

Several researchers decided not to include glass as a cover for the solar equipment [31], [32], stating that the efficiency of the unglazed or perforated transpired type collector is relatively higher than that of the glazed solar collector. Also [33], [34], provide studies on the assistance of solar collectors to air-source heat pumps in residential heating processes, indicating that a positive impact on system performance is obtained, since electricity consumption and CO2 emissions are reduced. Additionally [35], [36], have carried out simulations that allow the design of flat plate solar collectors to be optimized in advance, due to the fact that, by means of perforations in the absorber plate, the efficiency of heat transfer offered by the equipment to the working fluid is increased.

In accordance with the bibliographic review presented above, the objective of this research is to analyze the thermodynamic and economic performance obtained from the real operation of a flat plate solar collector with thermal storage, through the evaluation of thermodynamic factors characteristic of systems intended for air heating. This is done by means of approaches and formulations from an analytical approach, providing open access to all the assumptions and equations involved in the process, which is a differential factor in this study, since most of these studies use numerical approaches by means of computational tools such as commercial software, which sometimes are not available to less privileged researchers and institutions. The energetic, exergetic and economic results, added to the possibility of applying analytical approaches, allowed different sensitivity analyses and comparisons of thermodynamic performance, modifying the quality of the primary energy, technology efficiency and characteristics in the kinetics of the working fluid, enabling the comparison and applicability to other systems in different latitudes of the world, providing a useful tool for researchers and decision makers.

The structure in which this research is presented is as follows: the first section consists of a description of the configuration and experimental tests performed on the flat solar device (case study), with the objective of obtaining the thermodynamic variables that influence the air heating process. In the second section, an average of the hourly data obtained to develop the mass, energy and exergy balance operations is made, as well as the direct uncertainty, economic and sensitivity analysis of the solar collector, to efficiently manage the system's resources. In the third section, a study of results and discussion of the work done is provided, to accurately evaluate the performance of the equipment. Finally, the conclusions of the research are presented.

2. Research method (11 pt, Sentence case)

2.1. Description of experimental setup and tests

2.1.1. Meteorological data of the case study

In the present investigation, an experimental setup consisting of a flat plate solar collector, fan, control, and measurement instruments is used to analyze the behavior and performance of the system. The equipment is in the municipality of Bucaramanga/Santander within the country of Colombia, exactly latitude and longitude of 7°7'31.4" N 73°7.188' O, respectively.

In Figure 1a and Figure 1b, the variations of the meteorological data of the site where the study equipment is located between 06.00 and 17.00 hours are observed; indicating the change of the average ambient temperature, average solar radiation, and ambient wind speed in monthly and annual periods from 2015 to 2022. From the above, it can be deduced that the periods with the highest peaks of average solar radiation, adding the hours of radiation during the day and calculating a monthly average for the year 2022 are: January, February, and July, with 458.33 W/m2, 475 W/m2 y 450 W/m2, respectively. Also, it can be observed that the average daily solar radiation during the year is of 420.14 W/m2. Likewise, stabilization over the last three years has been equal to 418.66 W/m2.

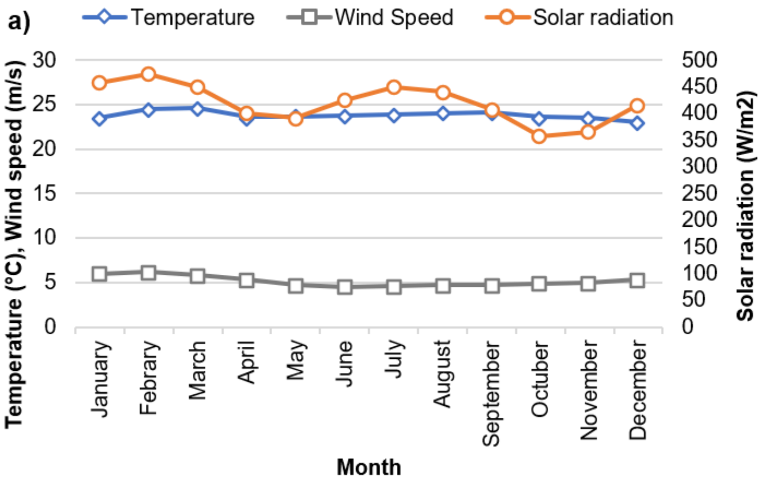

Figure 1a. Monthly meteorological data for the year under study in the municipality of Bucaramanga/Santander in Colombia

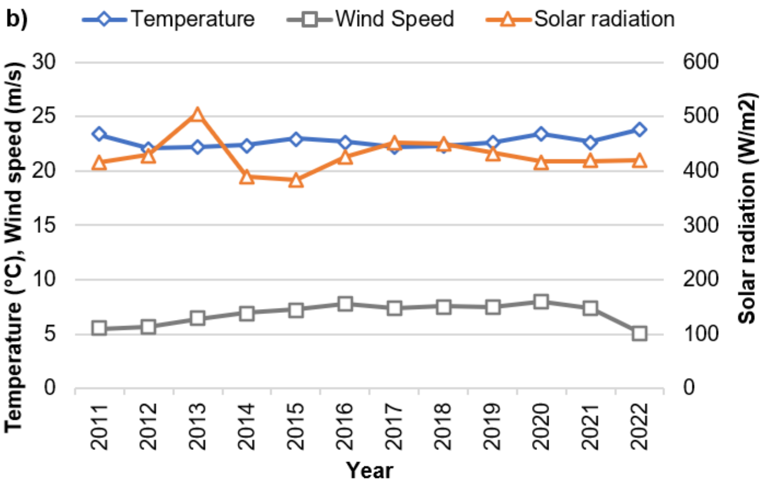

Figure 1b. Annual meteorological data for the period 2011-2022 in the municipality of Bucaramanga/Santander in Colombia

2.1.2. System description

An experimental configuration for air heating using solar collectors is proposed. The main components of the proposed system are illustrated in Figure 2, schematic view that allows detailing the flat plate solar collector, composed of (1) the outer body of the collector, (2) the glass cover, (3) the absorber plate (corrugated iron sheets, painted black), (4) phase change material tank, (5) air inlet, (6) piping between tanks one and two, (7) piping between tanks two and three, (8) air outlet, (9) centrifugal fan, (10) collector on/off equipment, including temperature and humidity monitoring equipment, (11) bearings with base.

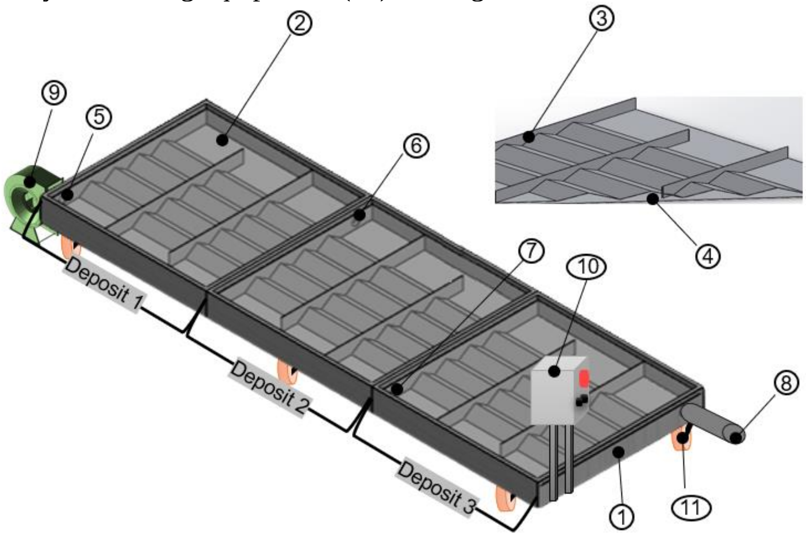

Figure 2. Schematic view of the experimental setup under study

Figure 3 shows a photograph of the assembly of the flat plate solar collector analyzed at the study site. The operation of the system uses a fan at the inlet to increase the speed of the air entering the process, three drying tanks, an absorber plate with obstacles, which also contains the PCM and a temperature and humidity control and measurement system. Initially, the centrifugal fan drives the ambient air to enter the collector in its first tank, entering directly to the iron absorber plate with V-geometry, then, it transits between the other tanks until it leaves the equipment with a higher temperature than the inlet one, so that the working fluid can be used for a specific application.

Figure 3. Photograph of the experimental set-up

2.1.3. Technical specifications

The technical characteristics of the system studied, and its accessories are shown in Table 2. The flat solar collector covers an area of 3 m2, consisting of three tanks containing solar absorption tanks with corrugated "V" sheets, to provide greater thermal efficiency of the system. Molten kerosene is used as a phase change material to be added to the tanks in a liquid state. Also, there is a centrifugal fan at the beginning of the process to create turbulence in the workflow and increase heat transfer between the metal and the air. There is also a pipe that allows the fluid to pass between the three vessels, with a diameter of 0.0508 m and a length of 0.08 m between sections.

Table 2. System technical specifications

Flat plate solar collector		
Specification	Value	Units
Size	1·3·0.1	m
Area	3	m^2
Absorption tank thickness	0.05	m
Top cover	Glass of 0.4	mm
Absorbent plate coating	Dark color (black)	
Absorbent plate thickness	0.02	m
Thermal storage fluid	Medium kerosene wax	
Working fluid	Air	
Type of heat transfer	Forced convection	
Fan		
Specification	Value	Units
Power	120	W
Voltage	110-120	V
Flow rate	1.4	m^3/min
Fan pressure	380	Pa
Efficiency	75	%
Pipe		
Specification	Value	Units
Diameter ($\boldsymbol{d}$)	0.0508	m
Length ($\boldsymbol{l}$)	0.08	m
Area	0.00202683	m^2

2.1.4. Propagation of errors

In the experimental tests performed to measure solar radiation, temperatures, velocities and humidities in the flat plate solar collector, errors and uncertainties may arise from the selection, calibration, environment, readout, data approximation and test preparation of the instruments used. Accordingly, the following equation indicating the average of the experimentally obtained data for each thermodynamic variable is initially considered, where $\bar{x}$ is defined as an average function of the individual factors provided as x_i.

$$\bar{x} = \frac{\sum_{i=1}^{n}(x_i)}{n} \tag{1}$$

Then, using equation (2), the standard deviation of the experimental measurements with respect to the mean is calculated [37]:

$$\sigma = \left(\frac{\sum(x_i - \bar{x})^2}{(n-1)}\right)^{\frac{1}{2}} \tag{2}$$

Therefore, the assessment of the relative uncertainty with respect to solar radiation, temperatures, velocities and humidity obtained in the tests was carried out using the following equation:

$$\delta = \frac{\sigma}{\bar{x}} = \left(\frac{1}{n}\sum_{i=1}^{n}\frac{(x_i - \bar{x})^2}{(n-1)}\right)^{\frac{1}{2}} \tag{3}$$

By applying the above equations for each variable measured experimentally in the flat plate solar collector, Table 3 presents the direct uncertainties during the measurements of the thermodynamic parameters. Table 3 also shows the references and accuracies of the instruments used to obtain the input data to the system, which allow subsequent analysis of the performance of the flat-plate solar air collector. Then, Figure 4 shows the location of the measuring equipment in photographs: the anemometer, which measures the inlet and outlet velocities of the collector; pyranometer, indicating the intensity of solar radiation; thermocouples, which monitor the temperatures between the three tanks and the ambient temperature of the place where the solar collector is located; as well as hygrometers, which measure the relative humidity at the inlet and outlet of the equipment. It is relevant to specify that the pressure drop is found by analytical methods, since the values obtained are lower than the measurement range maintained by the measuring instrument used.

Table 3. Relative uncertainty during parameter measurements

Measuring sensor	Reference	Parameter	Unit	Accuracy	Uncertainty
Anemometer (Fig. 4a)	GM-8901, China	Outlet air velocity	[m/s]	±2%	±0.052
Pyranometer (Fig. 4b)	TES-132, Taiwan	Solar energy radiation	[W/m²]	±5%	±0.412
Thermocouple (Fig. 4c)	Tipo K con tornillo	Collector inlet temperature	[ºC]	±1.5 °C	±0.063
		Collector outlet temperature	[ºC]		±0.188
		Ambient temperature	[ºC]		±0.065
Hygrometer (Fig. 4d)	DHT-22	Relative humidity	[%]	2% RH	±0.064

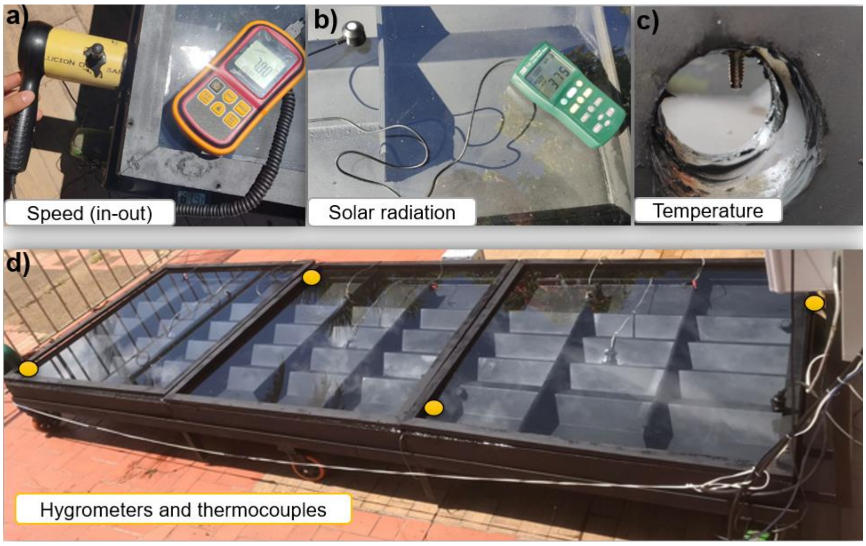

Figure 4. a) Speed meter, b) Solar radiation indicator, c) Temperature indicator and d) Location of thermocouples and humidity sensors

To carry out a current direct uncertainty analysis on the equipment, a study of the data obtained to validate the measurement process on the experimental days is carried out, which will be developed later in this manuscript.

2.2. Performance of the experimental test

Before starting the tests, it must be verified that the equipment complies with: the heat transfer fluid, in this case medium kerosene, that is inside the three tanks of the flat solar collector; the adhesion of the glass covers is with black silicone, so that the glass is not damaged by contact with the metal; the centrifugal fan at the entrance of the system, in order to generate a speed of 10 m/s, to the air entering the solar ray collector. In order to collect data, the main points of access are defined, which are called airflows of the fluid flowing in the system. Figure 5 shows a scheme of the places established to perform the tests in the SAC and, it can be seen through the arrows and their colors, that as the air passes through each tank of the collector, it acquires higher temperature by means of the heat transfer provided by the absorber plate to the fluid.

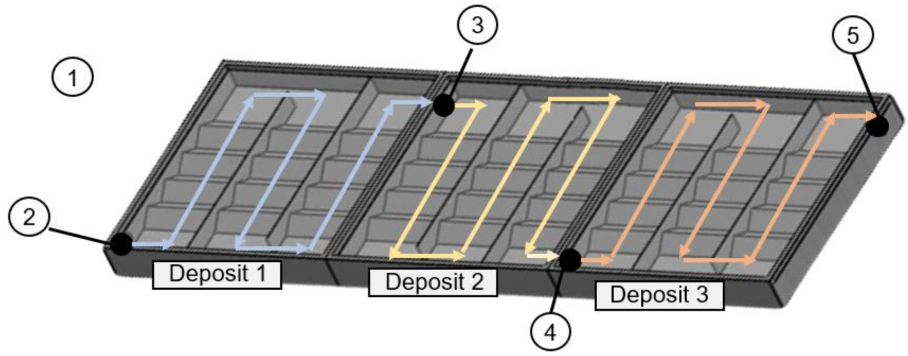

Figure 5. Schematic view of test points in the system

The following system currents are then established:

- Current 1: The environmental conditions of the system are found.
- Current 2: Located at the inlet of the flat plate solar collector.
- Current 3: It is considered between deposits 1 and 2 of the solar equipment.
- Current 4: It is established between deposits 2 and 3 of the collector.
- Current 5: It is located at the exit point of the flat plate solar collector.

Experimental tests were carried out starting at 08.00 hrs and ending at 17.00 hrs, with data collection intervals every 45 minutes. This is carried out using the measuring instruments, which are used to obtain the values of solar radiation, temperatures, velocities, and humidity within the system, these being the variables that influence the air heating process within the solar collector under study and, subsequently, allow the equations proposed in the data analysis to be fed.

2.3. Analysis of data

The procedure to perform the operations that allow the energy, exergy, direct uncertainty, economic and sensitivity analysis of the studied flat plate solar collector is specifically divided into three phases; the first one consists of the literature research of the initial parameters of the system, which are shown in Table 4; then, the formulation of the analyses proposed in the research; and finally, the consideration of the performance of the studied equipment.

Table 4. System initial parameters

Specification	Value	Units	Reference
Surrounding temperature	298.15	K	Measured
Sun temperature	5770	K	[5]
Pressure surrounding	101.325	kPa	[17]
Theoretical chemical exergy of air	34.050	[J/mol]	[17]
Ideal gas constants	8.314472	[J/mol·K]	[38]
Specific heat of air (Cp_{air})	1007	[J/kg·K]	[38]
Total weight of one mole of air	28.7364	[kg/mol]	Calculated
Collector plate emissivity $(\boldsymbol{\tau})$	0.4	-	[10]
Collector plate absorptivity $(\boldsymbol{\alpha})$	0.9	-	[10]
Air inlet velocity	10	[m/s]	Measured
Hours of operation	9	Hrs	Authors

2.3.1. Energy formulation

After defining the initial parameters of the system (Table 4) and with the measurement of solar radiation, temperatures, velocities and humidity, the main thermodynamic properties in each hour are found in tables: pressure (P), density (ρ), enthalpy (h) and entropy (s), the latter two per unit mass and mole. It is also established that, to calculate the heat transfer in the flat plate solar collector, the balances are performed by steady flow and steady state admission, at each measurement point. Under steady and continuous air flow conditions, the inlet and outlet mass flow rates are equal, and the mass balance of the system is defined as:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (4)$$

Where the subscripts signify the process input and output, and $\dot{m}$ is the mass flow rate, which is defined as the product of the fluid density (ρ), air velocity (v) and the area of the flat solar collector (A_{coll}).

$$\dot{m} = \rho \cdot v \cdot A_{coll} \tag{5}$$

With the properties already defined on each airstream within the flat-plate solar collector, one can initially calculate$\dot{Q}_{solar,rad}$, which corresponds to the thermal energy transfer through space to the Earth.

$$\dot{Q}_{solar,rad} = I \cdot (\tau \cdot \alpha) \cdot A_{coll} \tag{6}$$

Where A_{coll} is the projected area of the heater in m^2 and I is the projected area of the heater in (W/m^2).
The air entering the solar collector is driven by the centrifugal fan, in the form of forced internal convection. The following equation is used to define $\dot{Q}_{air,coll}$, que se establece como la transferencia de calor de la placa absorbente al aire que transita por el equipo.

$$\dot{Q}_{air,coll} = \dot{m}_{air} \cdot Cp_{air} \cdot (T_{out} - T_{in}) \tag{7}$$

Where $\dot{m}_{air}$ and Cp_{air}, are defined as the mass flow and calorific value of the air, respectively; T_{in} y T_{out}, correspond to the air temperatures at the inlet and outlet of the flat plate solar collector.
According to the first law of thermodynamics, the energy efficiency of the flat plate solar collector can be defined as the ratio between the heat transfer supplied by the equipment to the working fluid and the solar energy reaching the collector surface plate:

$$\eta_{therm} = \frac{\dot{Q}_{air,coll}}{\dot{Q}_{solar,rad}} \cdot 100 \tag{8}$$

Since the air pressure drop in each stream cannot be obtained with the measuring equipment, it was decided to find this parameter by means of the following equation:

$$\Delta p = \frac{\mu \cdot l \cdot {v_i}^2 \cdot \rho_i}{2.d} \tag{9}$$

Where μ is equal to 1.15 and is defined as the air friction coefficient. The length and diameter of the pipe through which the working fluid of the flat plate solar collector passes are set as l and d, respectively.

2.3.2. Exergetic formulation

The following four considerations were taken into account for the study of the second law of thermodynamics in the flat plate solar collector: the air flows at the inlet and outlet of the system are in a steady and continuous state; the kinetic and potential exergy in the equipment are neglected; the air works as an ideal gas with a constant specific heat in each flow; and the directions of heat and work transfer are positive [3], [9], [17].

The kinetic and potential exergy are not considered, because the process does not present significant velocities in the different control volumes. Thus, the exergy per unit mass of each current e_i, is expressed as follows.

$$e_i = e_{ch} + e_{ph} \tag{10}$$

Where e_{ch} and e_{ph} are the chemical and physical exergy of the system, respectively. Also, the total exergy flux E_i for each stream is defined with the following equation:

$$\dot{E}_i = e_i \cdot \dot{m} \tag{11}$$

For the workflow used in the research, chemical and physical exergy are formulated as follows [17]:

$$e_{ch} = \frac{\sum X_i \cdot e_{ch-the} + R \cdot T_0 \cdot ln(X_i)}{\sum X_i \cdot Y_i} \tag{12}$$

$$e_{ph} = \frac{\sum X_i \cdot \left(\overline{h_i} - \overline{h_0}\right) - T_0 \cdot \sum X_i \cdot (\overline{s_i} - \overline{s_0}) - R \cdot ln\left(\frac{P_i}{P_0}\right)}{\sum X_i \cdot Y_i} \tag{13}$$

Where h_0, s_0, T_0 re the specific enthalpies, entropies, and temperatures of the system in its reference state (298.15 $°K$); X_i and Y_i epresent the mole fraction and molecular weight of the air components, respectively. R is the ideal gas constant, P_i is the pressure in each of the streams and P_0 is the atmospheric pressure.

The input exergy to the flat-plate solar collector is defined as $\dot{E}_{in,coll}$ and can be calculated from the following equation [10]:

$$\dot{E}_{in,coll} = \dot{\mathrm{Q}}_{\mathrm{solar,\ rad}} \cdot \left(1 - \frac{4}{3}\left(\frac{T_0}{T_{sol}}\right) + \frac{1}{3}\left(\frac{T_0}{T_{sol}}\right)^4\right) \tag{14}$$

Where the temperature of the sun is expressed as T_{sol} and is estimated to be equal to 5770 $°K$. Also, the output exergy of the flat-plate solar collector $\dot{E}_{out}$, is defined as follows:

$$\dot{E}_{out,coll} = \dot{m}_{air} \cdot [(h_{out} - h_{in}) - T_0 \cdot (s_{out} - s_{in})] \tag{15}$$

Due to irreversibilities and process losses, the actual exergy change of the system is not equal to the total exergy transferred to the system. The concepts of exergy exchange, transfer and destruction are related to the control of the exergy balance in volume. The following expression allows us to calculate the exergy destruction $\dot{E}_{dest,tot}$, with the control volume in equilibrium.

$$\dot{E}_{dest,tot} = \dot{E}_{insumo} - \dot{E}_{productos} \tag{16}$$

By studying equation (16), the following equation can be established as the destroyed exergy of the flat plate solar collector studied:

$$\dot{E}_{dest,tot} = \left(1 - \frac{T_0}{T_{sol}}\right) \cdot \dot{Q}_{solar,rad} - \dot{m}_{air} \cdot [(h_5 - h_2) - T_0 \cdot (s_5 - s_2)] \tag{17}$$

According to the second law of thermodynamics, the exergy efficiency η_{ex} in a flat-plate solar collector can be determined by the following equation:

$$\eta_{ex} = \left(\frac{\dot{E}_{out}}{\dot{E}_{in}}\right) \cdot 100 \tag{18}$$

Exergy losses are often confused with exergy destruction, but exergy losses consist of exergy flowing into the surroundings, whereas exergy destruction indicates exergy loss within the process boundaries due to irreversibility's. From the above, the following analysis of the energy balance is made:

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{19}$$

$$\dot{E}_{in} = \dot{E}_{out} + \dot{E}_{dest,tot} + \dot{E}_{lost,tot} \tag{20}$$

With the exergy balance done previously, the following equation can be defined to find the lost exergy of the system:

$$\dot{E}_{lost,tot} = \dot{E}_{in,coll} - \dot{E}_{out,coll} - \dot{E}_{dest,tot} \tag{21}$$

2.3.3. Methodology diagram

The methodology used to analyze the first and second laws of thermodynamics in the process of capturing solar rays to heat air using the flat solar collector studied is shown in Figure 6.

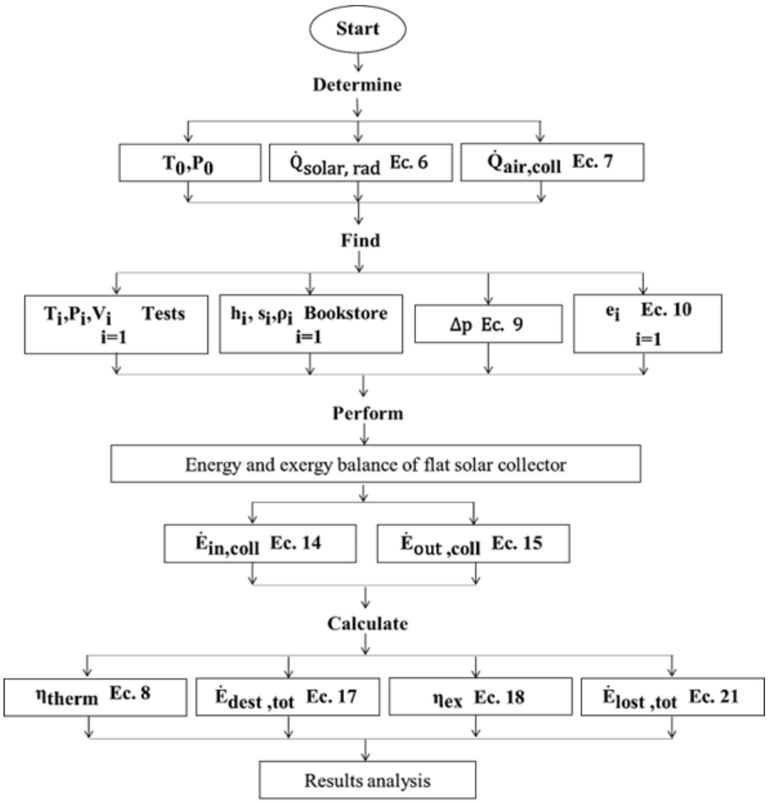

Figure 6. Methodology used for thermodynamic analysis

2.3.4. Economic analysis

In this section, the economic feasibility of the air heating process, through the flat plate solar collector studied, is established. Initially, the following considerations are made: the electrical power of the fan ($\dot{P}_{elec}$) is 0.04 kW [39]; the average unit cost of electricity (c_{elec}) was obtained from XM (electricity market managers) with a value equivalent to 0.103 USD/kWh for the year 2022 in Colombia; the average heat transfer in the investigated collector ($\dot{Q}_{coll,air}$) is 471.3672 W; the annual operation time of the equipment t_{oy} is equivalent to 2880 h/year; and the economic life (t_{el} of this equipment according to the market is 20 years [10], [13]. With the estimates made above, the levelized process heating cost (LCOH), which indicates the cost of producing one kWh of thermal energy, is calculated according to equation (22).

$$LCOH = \frac{\dot{P}_{elec} \cdot c_{elec} + (CIA + O\&M)}{\dot{Q}_{coll,air} \cdot t_{oy} \cdot t_{el}} \tag{22}$$

Where CIA is the annualized investment cost and is defined as:

$$CIA = (FRC) \cdot (Plant\ investment) \tag{23}$$

Where CRF is the capital recovery factor and is defined as:

$$FRC = \frac{i \cdot (1+i)^t}{(1+i)^t - 1} \tag{24}$$

Where (t) is the useful life of the flat plate solar collector and (i) is the interest rate. Considering that the equipment was obtained with an initial investment (CIA) of 2000 USD and was acquired without any type of loan; the CRF has a value of 1. Likewise, an operation and maintenance cost in the useful life of the equipment (O&M) equivalent to 400 USD is estimated [10].

This is done to subsequently find the following variables that allow us to deduce whether the project is profitable or not: the net present value of the equipment (NPV), the internal rate of return (IRR) and the investment recovery period (IR).

2.3.5. Sensitivity analysis

In order to propose scenarios in which better exergetic behavior can be visualized, allowing an increase in the useful work of the flat plate solar collector with the environment to which it is exposed, a sensitivity analysis was carried out using thermal parameters of the process used in the equipment, where the influential thermodynamic variables were identified, in order to change their values and analyze the new exergetic performance of the system [40].

Initially, it was decided to evaluate the sensitivity to the average time that the scenario with the highest exergy destruction occurs, in this case, at 10:15 am. Then, it is considered to vary by 5% the value initially calculated (base scenario), the influential parameters in the performance of the system that were varied are the following: solar radiation, which is identified as the input fuel to the heating process, the thermal efficiency of the solar collector (evaluates the technology of the collector) and the mass flow of air (evaluates the energy potential of the working fluid).

Subsequently, the results obtained for the air outlet temperature in ºC, and the percentage of exergy destroyed are evaluated, since they are variables that allow identifying if there is an increase in the efficiency of the system in general and an increase in the useful work potential of the process with its environment. Finally, three graphs are projected to visualize the change of the initial data and the resulting variation of the output parameters.

3. Results and discussion

3.1. Energetic and exergetic study

The thermodynamic performance of the solar air collector is evaluated with the objective of refining the exergy analysis of the equipment under study in this research. For the analysis of the system, the average hourly data collected experimentally in a time interval from 08:00 to 17:00 hours between the months of June, July and August of the year 2022 are used; given that in Figure 1a the meteorological data of the study site are analyzed and it is deduced that in the middle of this year there is one of the highest peaks of solar radiation in Bucaramanga/Santander.

As can be seen in Figure 7, the relationship between the hourly data taken from the ambient temperature (current 1), air outlet velocity of the equipment (current 5) and average solar radiation is presented. According to the experimental tests carried out, the highest values of ambient temperature and solar radiation are 31.2 ºC and 981 W/ m2, at 11:45 hours. In the process of verifying the performance of the solar collector, it is desirable to have the same amount of solar radiation every day at the same hours, however, it is considered a disadvantage for the exergetic analysis that these two input variables are not constant day after day, therefore, it was considered to average the data obtained experimentally.

According to the above, it is relevant to clarify that from 14:45 hrs, the flat plate collector is instantly under shadow at the study site and the input exergy tends to zero. However, the air temperature and the exergy destroyed in the system decreases slowly, due to the thermal storage that the kerosene retains before exposed to solar radiation on the collector. Similarly, the outlet velocity (current 5) and the temperature of the air entering the system (current 1) are factors that affect the efficiency of the solar air flat plate collectors. In the experimental tests, the fan provides an inlet velocity (current 2) equal to 10 m/s in all the values taken, but the velocity of the outlet fluid decreases due to the length that the air travels in the SAC. As shown in Figure 7, the exit velocity varies in the range of 6.76 m/s to 8 m/s, obtaining its highest peak at 11:45 hours, since it is related to the temperature and density of the air at the desired time.

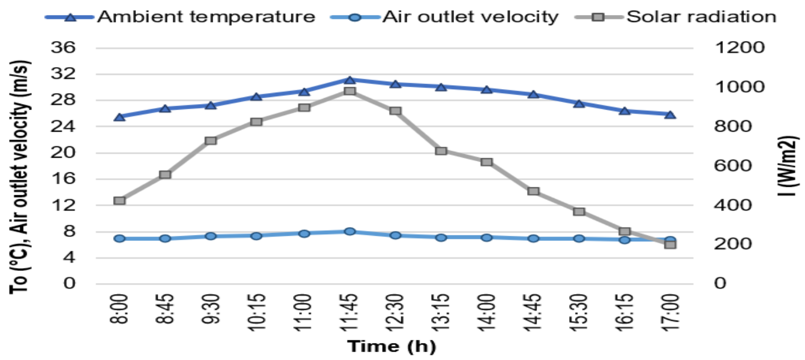

Figure 7. Change in ambient temperature and solar radiation in hourly average values

As a result of developing the energy calculations, Table 5 illustrates the properties of the main flows in the flat plate solar collector for the following schedules: start of tests at 08:00 hrs, highest exergy efficiency at 10:15 hrs, highest exergy destruction at 11:45 hrs and end of data collection at 17:00 hrs. All properties of stream 1 are assumed to be equal, since this is the reference environment and, therefore, the exergy at this point can be assumed to be zero, since it is in equilibrium with the environment where the solar ray collector is located [17].

Table 5. Total exergy flow in all streams

Current	Hrs	$\dot{m}\left[\frac{kg}{s}\right]$	P [kPa]	T [°C]	h $\left[\frac{kJ}{kg}\right]$	s $\left[\frac{kJ}{kg}\cdot °K\right]$	e $\left[\frac{J}{kg}\right]$
1	08:00	0.0194	101.3250	25.00	59.1986	0.2111	0.0000
	10:15	0.0199	101.3250	25.00	59.1986	0.2111	0.0000
	11:45	0.0207	101.3250	25.00	59.1986	0.2111	0.0000
	17:00	0.0193	101.3250	25.00	59.1986	0.2111	0.0000
2	08:00	0.0194	101.4312	25.80	61.6821	0.2193	2952.7916
	10:15	0.0199	101.4312	28.90	72.2073	0.2549	6482.4636
	11:45	0.0207	101.4312	31.30	81.278	0.2853	9215.6108
	17:00	0.0193	101.4312	26.10	62.6469	0.2225	3294.3416
3	08:00	0.0194	101.4122	34.50	94.8299	0.3305	12876.985
	10:15	0.0199	101.4145	52.00	213.032	0.7118	32848.9910
	11:45	0.0207	101.4176	56.75	265.1227	0.8753	38266.0939
	17:00	0.0193	101.4117	32.00	84.1017	0.2948	10025.3274
4	08:00	0.0194	101.3848	35.75	100.6708	0.3498	14330.1657
	10:15	0.0199	101.3905	54.50	239.0199	0.7937	35767.7331
	11:45	0.0207	101.3987	60.75	319.4696	1.0441	42895.7013
	17:00	0.0193	101.3835	36.25	103.0451	0.3577	14903.2351
5	08:00	0.0194	101.3718	42.80	139.7567	0.4777	22414.4296
	10:15	0.0199	101.3786	56.00	256.1709	0.8475	37517.5851
	11:45	0.0207	101.3885	67.20	434.3912	1.3961	50316.1263
	17:00	0.0193	101.3703	36.80	105.7569	0.3667	15546.5300

For each hour in which data were collected, a mass and energy balance were performed based on the laws of thermodynamics, where the main results obtained for the schedules shown above are presented in Table 6.

Table 6. Thermal performance of the system in the morning hours

Parameter		Hrs			
		08:00	10:15	11:45	17:00
Thermal efficiency	%	72.249	60.832	70.599	94.819
Input exergy	W	454.138	883.756	1045.8	216.408
Exergy efficiency	%	4.323	16.417	43.396	1.069
Total exergy destroyed	W	416.674	703.971	550.904	205.598
Total exergy lost	W	17.8312	34.699	41.062	8.497

Figure 8 shows, first, the temporal change of the inlet (current 2) and outlet temperatures of the air in the solar collector (current 5). The inlet temperature varies from 25.8 ºC to 31.3 ºC and the air outlet temperature is in the range of 36.8 ºC to 67.2 ºC. From the graph presented in Figure 8, it can be inferred that the fluctuations in the collector outlet air temperatures are due to the transition of clouds, for this reason, the highest inlet and outlet temperatures are obtained when the sky is clear, that is, when there is greater solar radiation, located at 11:45 hours.

Energy efficiency varies according to the structural material, collector type design, absorber plate structure, glass characteristics, working fluid and thermodynamic variables. Figure 8 also shows the energy efficiency in an average range of 59.15% and 94.82% during the day. Similarly, the temporal change of the energy efficiencies of the collector studied is shown, observing that the heat storage in the equipment is effective, since in the last 3 hours, the input fuel to the collector changes from solar radiation to phase change material (PCM), because the action of the kerosene allows to conserve the thermal storage and also, instead of equalizing the outlet temperature (current 5) with the inlet temperature (current 2), what the PCM does is to slowly reduce the air outlet temperature in the SAC, when there are very few solar rays on the system. Furthermore, it can be deduced that the fluctuations in performance are caused by the relationship between solar radiation and the differences between the inlet and outlet temperatures of the air in the collector.

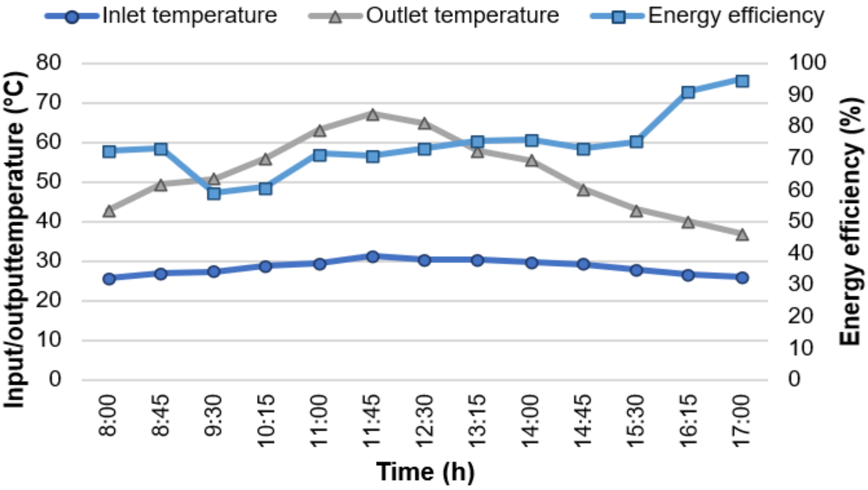

Figure 8. Energy efficiency change compared to the variation of air inlet and outlet temperature in the system

Figure 9 shows that the highest estimates of useful energy potential destroyed in the flat plate solar collector studied are found between 9:30 and 11:00 hrs, where the highest peak was obtained at 10:15 hrs with a value of 703.971 W. From the above it can be inferred that the exergy destroyed depends on the solar radiation, pressure drops and humidity of the air passing through the system.

Figure 9 also shows the change in the exergetic efficiency of the flat plate solar collector. The average exergetic efficiency of the system studied is equal to 16.96%, indicating the highest yields between 11:00 and 12:30 hours, inferring that at these hours a greater differential is obtained between the input (current 2) and output temperatures of the system (current 5). Likewise, it can be inferred that the exergy efficiency depends directly on the solar radiation as an initial parameter in the input exergy, and also on the input and output temperatures of the SAC, since they allow finding the enthalpy and entropy parameters necessary to calculate the exergy destroyed in the system.

Likewise, Figure 9 shows that at 09:30 and 14:45 hours, the exergy efficiency is close to 9%, but with a different exergy destruction rate of 672.75 W and 428.53 W, respectively. The above shows the usefulness of the kerosene in the equipment, since from 14:45 hours, the input fuel to the collector is the phase change material, instead of solar radiation; allowing the system to include from this time onwards lower losses of useful potential with the environment to which it is exposed.

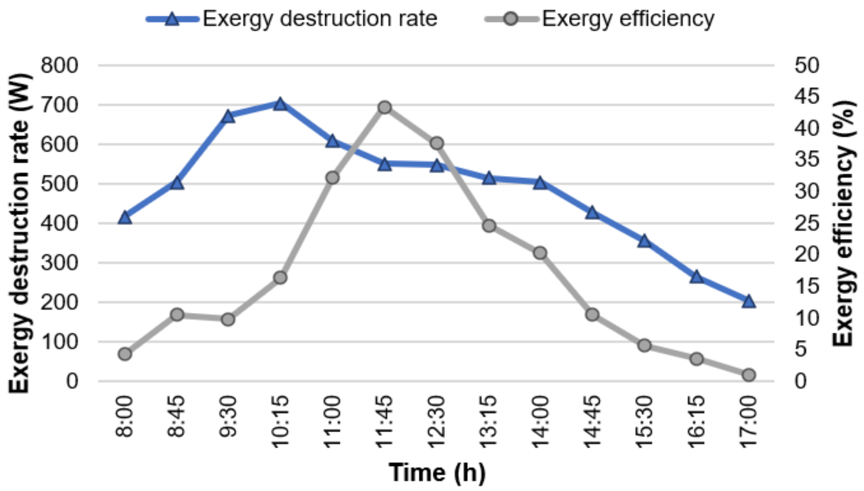

Figure 9. Change in the rate of exergy destruction and exergy efficiency in the solar collector

After analyzing the energetic and exergetic results obtained in the research, Table 7 is presented, allowing to compare the thermodynamic performance achieved in previous investigations, which are within the framework of the variation in the efficiency of solar collectors, by changing the design of the equipment and the use of different shapes of the absorber plate.

Table 7. Comparison between the results of studies conducted in the literature and this research

Research	Type of absorber plate	Material	Solar radiation [W/m^2]	Flow rate	Energy efficiency	Exergetic efficiency
[41]	Surface plate with trapezoidal obstacles	Aluminum foil	266-941.8	0,0156 [kg/s]	60%	39%
[42]	Flat plate surface with trapezoidal obstacles	Copper plate	1000	1.5 [L/m]	62%	45%
[43]	Surface with square obstacles with fins	Single aluminum sheet	17.4-818	0,0094 [kg/s]	53.35%	31.23%
This study	Flat plate surface with V-shaped obstacles	Iron plate	20-981	0,0198 [kg/s]	71.24%	16.96%

3.2. Economic study

The economic results for the flat plate solar collector system with thermal storage for air heating show a levelized cost of heating (LCOH) equivalent to 0.0884 USD/kWh. In order to present the energy and cost savings achieved with the solar system studied in heating or drying applications, it was decided to compare this economic study with the consumption of an air-to-air heat pump, which, instead of using solar energy as input fuel, uses electrical energy to transform it into thermal energy. It is found in the literature [44], [45], that for each kW of electrical energy consumed, 3 kW are produced in the form of heat; with this relationship, it can be inferred that if artificial light were used in the collector, 0.157 kW of electrical energy would have to be consumed to produce the 0.471 average thermal kW found in the energy analysis. From the above, a heating cost of 0.1298 USD/kWh is obtained if only electrical energy is used at the input of the equipment, inferring that 0.0414 USD/kWh of this value is saved if the flat plate solar collector is used for heating applications.

After analyzing the values of the net cash flows, annual benefits and economic life of the solar collector under study, the following economic parameters are obtained as a team: the net present value (NPV) is equal to 1011.18 USD, indicating that the project is profitable since the initial cash inflows are greater than the outflows; the internal rate of return (IRR) is equal to 10.54 %, denoting that the investment is profitable, since no interest is paid for the research equipment to obtain its profit; and an investment recovery period (IR) equivalent to fourteen years, eleven months and 6 days is obtained.

Figure 10 shows the cash flow results for the flat plate solar collector, where the cash flow for each period of equipment functionality can be observed. Likewise, the net present value, expenses and annual benefits of the collector are illustrated, as well as the money accumulated until the main axis passes zero and the total recovery of the investment is fulfilled, to then obtain progressive profits with the use of the system in specific applications.

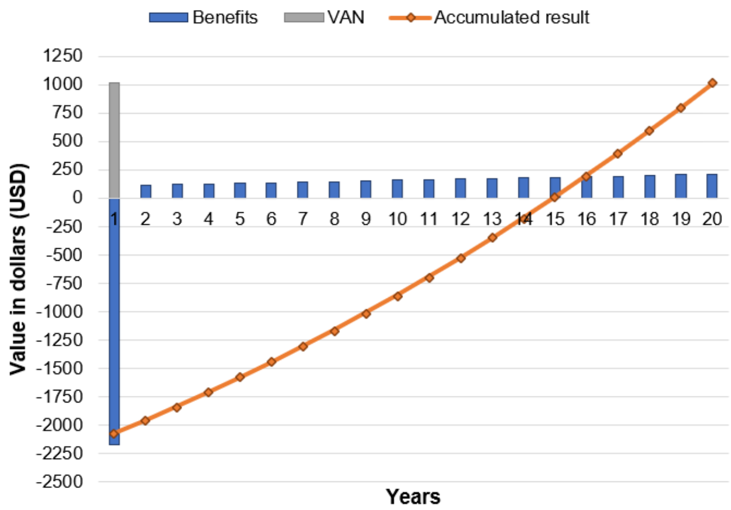

Figure 10. Cash flow results

3.3. Sensitivity study

It is identified that to increase the performance of the system it is desirable to increase the output temperature of the equipment, to obtain a wide range of application at the end of the system. It is also important to reduce the exergy destroyed, since it is indirectly proportional to the exergy efficiency, reducing this parameter increases the useful potential of the collector with its environment. Once the scenarios that allow to observe a better performance of the studied flat plate solar collector are recognized, the following graphs are obtained, which show the variables used for the sensitivity study of the system.

First, solar radiation is recognized as the input fuel to the flat plate solar collector and is an indispensable variable to achieve better performance in the system. It can be inferred that different solar radiation can be achieved on the equipment, by its location in other angular geographic coordinates and with the inclination of the collector with respect to the ground where it is located.

Figure 11 shows that with a 5% increase in the base solar radiation, the output temperature of the equipment increases, and the percentage of exergy destroyed in the process with the environment decreases, reaching a maximum peak of 69.55 ºC and a minimum of 55.39%, respectively. In the same way, an exergy efficiency of 40.67% is obtained with the thermodynamic equations, keeping constant the thermal efficiency found for 10:15 hours at 60.83%.

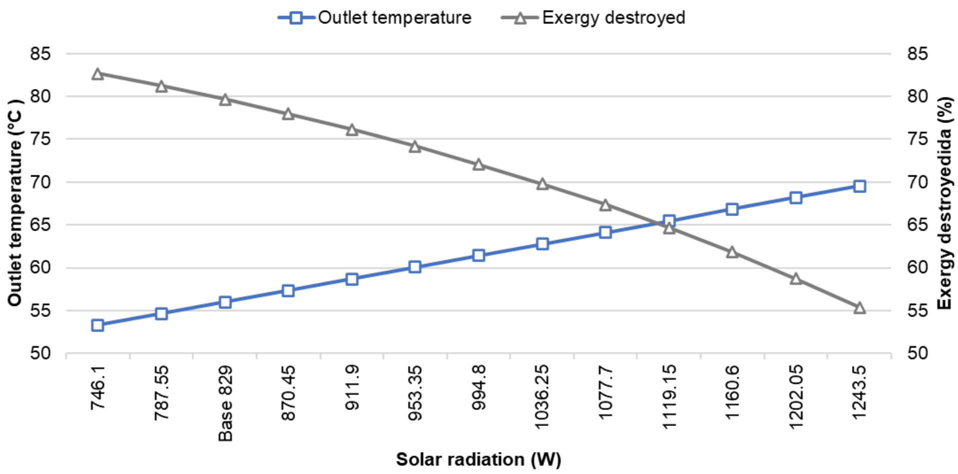

Figure 11. Sensitivity of solar radiation in the system

Secondly, the change in the thermal efficiency of the system is evaluated, which can be achieved in these configurations through the development of processes at the engineering level in the field of simulation, design and materials of the components that make up a flat plate solar collector. From the thermodynamic calculations made previously, a base thermal efficiency equivalent to 60.83% is obtained for the hour of study. Figure 12 shows that by increasing the energy efficiency by 5%, the output temperature of the equipment increases, and the percentage of exergy destroyed in the process with the environment decreases, reaching a maximum peak of 69.55 ºC and a minimum of 35.04%, respectively. Also, with the formulation of the thermodynamic analysis, a thermal efficiency of 91.25% and an exergy efficiency of 61.03% is reached.

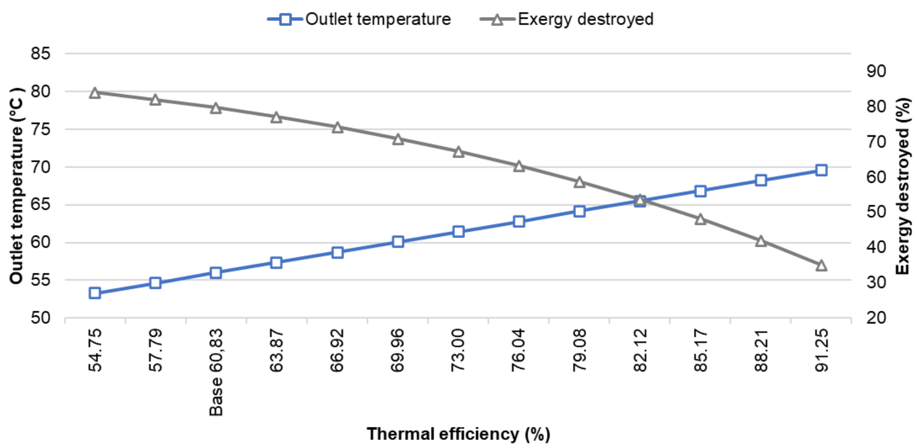

Figure 12. Sensitivity of thermal efficiency in the system

Likewise, it was decided to evaluate the sensitivity of the air mass flow in the flat solar collector in the system and it was established that this base parameter at the time studied is equivalent to 0.02 kg/s. Figure 13 shows that by decreasing the mass flow of the working fluid by 5%, the output temperature of the equipment increases and the percentage of exergy destroyed in the process with the environment decreases, reaching a maximum peak of 74.07 ºC and a minimum of 41.93%, respectively. Through the bibliographic study made in the present investigation, it can be induced that the mass flow varies by means of the engineering modification of the absorber plate of the collector, which allows generating greater turbulence in the mass flow, to increase the heat transfer by convection in the equipment. Likewise, the thermodynamic formulas were used to obtain an exergy efficiency of 54.15%, keeping the thermal efficiency found for 10:15 hours constant at 60.83%.

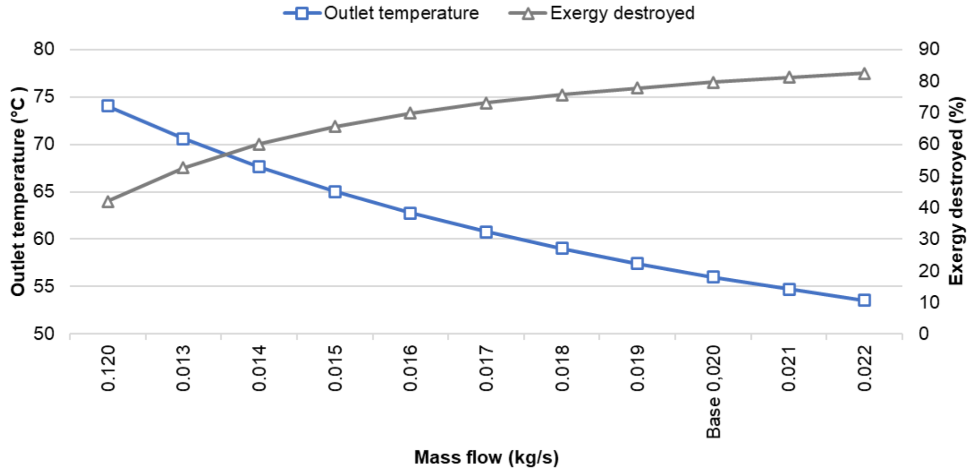

Figure 13. Sensitivity of the mass flow in the system

It can be inferred that this theoretical input is relevant within engineering, because three influential variables are identified in the system, which require the implementation of engineering processes in the field of design and materials, in order to achieve the proportional values in the system performance defined in the sensitivity analysis.

4. Conclusions

This study proposes an experimental analysis of the performance of a 3 m2 flat plate solar collector for air heating, located at the Technological Units of Santander, Colombia. To achieve the objective of this research, approaches and formulations are provided from an analytical approach supplying all the assumptions, generating a contribution on which the authors of subsequent projects within the same framework can rely.

Due to the different operating and atmospheric conditions in the development of the tests, it is considered a disadvantage for the thermodynamic analysis that the solar radiation and inlet temperature vary every day, therefore, it was decided that the most relevant for the study was to perform an hourly average of the data obtained experimentally.

The results of the study on the flat plate solar collector show an average energy and exergy efficiency of 71.24% and 16.96%, respectively. It can be deduced that the performance of the system depends mainly on the design of the SAC and the thermal storage material, as well as on the differences between the inlet and outlet temperatures of the air in the equipment, since these variables allow finding the enthalpy and entropy parameters necessary for the thermodynamic calculations of the system.

A sensitivity analysis is carried out for the 10:15 am average scenario, since this is the time of greatest exergy destruction in the system. This exercise demonstrates the inverse relationship between exergy efficiency and exergy destroyed, these output variables improved considerably by theoretically increasing solar radiation, thermal efficiency of the equipment and decreasing the mass flow of air passing through the flat plate solar collector. From the above, it is recommended the implementation of engineering processes in the field of design and materials, which allow to vary these input parameters of the process to obtain results proportional to the study carried out.

After the economic evaluation, the LCOH of the system is equal to 0.0884 USD/kWh with a payback period of no more than fourteen years of economic life of the flat-plate solar collector. According to the cost comparison if electrical input energy is used instead of solar rays, a saving of twenty-five percent of this value is deduced if the flat plate solar collector is used for common space heating applications. Although it is recognized that conventional heating equipment has a lower initial cost than a SAC, in the long term it is more profitable to use solar collectors in these adaptations, due to their low electricity consumption and low cost of maintenance of the equipment.

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.

Funding information

The financing of this research was carried out by Unidades Tecnológicas de Santander UTS, led by the Rector Ph. D. Omar Lengerke Pérez.

Acknowledgements

Special thanks to the UTS Research and Extension Directorate, led by Javier Mauricio Mendoza Paredes.

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