# Comparative Analysis of the Thermal Performance of Solar Collectors with Single and Double Airflow

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*Abstract:* - Due to the lack of precise data on the thermal performance of single- and double-flow air solar collectors under the climatic conditions of the Ecuadorian highlands, a comparative analysis based on experimental results was conducted. The measurement system consisted of a data acquisition module connected to twenty thermistors, designed to record the inlet, internal, and outlet temperatures of each collector. A fan was also used to ensure forced air circulation and measure its outlet velocity. The results showed that the double-flow collector reached a maximum outlet temperature of 35.13 °C, higher than the 33.56 °C recorded by the single-flow collector. Similarly, the average thermal efficiency was 51% for the double-flow system and 27% for the single-flow system, under an average solar radiation of 461.76 W/m² and an average ambient temperature of 15.53 °C. These findings confirm the superiority of the dual-flow design in terms of thermal efficiency.

*Key-Words:* - Thermal performance, solar radiation, energy, double flow, solar collectors, forced convection.

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## 1 Introduction

Renewable energies, including solar power, represent a sustainable and highly promising alternative to traditional sources. Unlike fossil fuels, solar energy can last for many years and comes from a virtually inexhaustible source. It can be of interest for generating thermal and electrical energy efficiently, without emitting pollutants. Using solar collector technology, solar radiation is captured and transformed into usable energy. These collectors are notable for their efficiency in converting sunlight into thermal energy and their versatility in various applications.

Solar energy is being developed as a renewable and environmentally sustainable resource that will be used for many years. Among the most widely used technologies for converting solar energy into heat is the solar air heater, a device designed to increase air temperature in various applications. The collectors' simple structure and low manufacturing cost make them a promising option for research and development. Performance is improved by applying various strategies, such as the use of rough surfaces, finned surfaces, and porous media, among others, [1]. This article [1] analyzes the main techniques and methods for increasing the thermal efficiency of solar air collectors. The authors evaluate the thermal efficiency behavior as a function of different variables and their effect on solar air heating systems. Finally, relevant geometries are identified, and based on these, recommendations are proposed that can serve as a guide for future research.

In another important investigation [2], the authors developed two analytical models to analyze the thermal behavior of solar air heaters in parallel-flow and countercurrent-flow configurations. Using local energy balances, the authors obtained algebraic expressions that allow them to estimate thermal efficiency, the overall heat loss coefficient, and air temperature distributions along the collectors, as well as the average temperatures of both air streams and the absorber plate. The results of the parallel flow show that the mass flow rate of air circulating between the absorber surface and the transparent cover is greater than that of the remaining duct. Conversely, the countercurrent flow indicates that an increase in the mass flow rate of air produces a proportional increase in the total heat flow through the inlet channel.

The research presented in [3] describes the design, construction, and analysis of a parallel-flow, dual-air solar water heater, which includes a V-shaped corrugated absorber surface. Heat transfer is achieved through free or natural convection. The author states that this configuration achieves high efficiency at a lower implementation cost. Experimental tests showed that the collector achieved a maximum outlet temperature of 95.7 °C with an incident solar radiation of 758 W/m² and an average mass flow rate of 0.0094 kg/s under sunny conditions. It was also determined that this flow rate is strongly influenced by air velocity and density. The system exhibited an average thermal efficiency of 51.1%, demonstrating effective use of solar thermal energy through passive operation, without requiring external energy sources.

A detailed analysis of the thermal, electrical, and hydraulic behavior of flat-plate solar air collectors was carried out in [4]. The research compared four configurations: In the first configuration, the airflow moves over the absorbing surface; in the second configuration, the airflow circulates below the surface; and in the third and fourth configurations, the air flows on both sides of the absorbing surface, corresponding to single and double flow movements. Energy balance equations were formulated for each configuration and solved numerically using real-world climate data. The impact of airflow and absorber surface characteristics on the system's thermal efficiency was analyzed. The results show that, under similar operating conditions, the first variant exhibits the lowest thermal efficiency, while the other configurations achieve similar performance values.

Another significant contribution is that presented by [5], who analyzed the design, construction, and performance of a double-pass solar air heater with a V-shaped corrugated absorber plate. The design and manufacturing stage includes a detailed description of the materials used for thermal insulation and the outer casing, as well as the system dimensions. The collector's performance was evaluated over two consecutive days during the Indian summer, taking into account the variable behavior of solar radiation throughout the day. The collector was tilted at 23.5°, corresponding to the latitude of Bhopal city, facing south, and operated using forced convection heat transfer and fans that supplied variable air mass flow rates.

In another analysis [6], the thermal performance of a solar air collector constructed from recyclable materials was evaluated. The results predict that the collector's thermal performance increases considerably with increasing air velocity through the collector, and that the heat transfer coefficient between the absorber plate and the air also increases. Furthermore, the effects of incident solar radiation and air mass flow rate on other variables such as heat absorption, temperature difference, and thermal efficiency were evaluated. It was determined that both thermal efficiency and heat absorption increase with increasing air mass flow rate.

Experiments conducted with a double-pass solar air heater investigated the performance of heat transfer using natural and forced convection by comparing both operating systems, [7]. The tests were performed during the winter period, with the comparison conducted under identical climatic conditions and equivalent measurement periods in each case. The results show that the process exhibits higher efficiency when operating with natural convection than with forced convection, with maximum values of 73.5% and 65%, respectively. Furthermore, a greater temperature difference was observed with natural convection than with forced convection.

Using thermal equipment, the thermal performance for drying agricultural products was evaluated, including a cabinet solar dryer. Through the design, construction and simulation of the system, two solar heater systems and three different air extraction duct geometries were compared to identify the most suitable variant, [8]. The analysis considered the different materials used, their dimensions, and physical, thermal, and mechanical properties. The design of the solar dryer was based on heat and mass transfer equations, which allowed for the simulation of the thermal behavior of both the solid materials and the airflow through the equipment. The results show that, of the six variants evaluated, the fourth exhibited the best performance, with an average increase of 11 °C in the temperature inside the drying chamber compared to the average ambient temperature of 20 °C used in the simulation. This value falls within the ranges suggested by the specialized literature.

This research utilizes solar air heaters and their performance enhancement to reduce energy consumption in the drying process of agricultural products, particularly cocoa. The most relevant aspect of these devices is their ability to convert incident solar radiation into thermal energy, which is then transferred directly to the circulating air. The system is based on a relatively simple structure and low design, construction, and maintenance costs. In a relevant study [9], the author reviews in detail the methods and techniques used to improve the thermal performance of solar air heating systems. This study evaluates performance parameters for various configurations and conducts a comparative analysis with the performance of conventional systems. Finally, the appropriate geometry was selected, and recommendations based on the results were formulated, which can serve as a reference for future research.

The increase in heat transfer and thermal efficiency in solar air heaters is related to the Nusselt number and the friction factor. The study by [10] addresses the analysis of these parameters in solar thermal systems for air heating through various geometric modifications that optimize their performance. This research is used as a reference because it includes a comprehensive review of the field of solar heaters, compiling significant advances in the development of this equipment. However, while the study presents adequate analyses regarding the design and construction of air heating systems with high heat transfer and low pressure losses, it does not present experimental data that would allow for a comprehensive evaluation of the analyzed configurations.

Regarding the design and appropriate materials for collector covers, it is important to highlight the study developed in [11], which evaluates the thermal performance of flat-plate solar air heaters. The authors analyze two different designs: one with a dark-tinted glass cover and another with clear glass. The latter exhibited higher thermal performance under the same comparative conditions of incident solar radiation. The experimental results concluded that dark-tinted glass significantly reduces the utilization of incident solar energy for air heating. On the other hand, [12] analyzed a solar air heater with a blackened copper tube. The flexibility of the tubes allows for their integration into flat-plate solar thermal systems. The results show an increase in thermal performance, as well as a significant reduction in equipment cost compared to other models.

Most previous studies have focused on finding alternatives to increase the thermal efficiency of solar air heaters. The research conducted by [13] analyzes a system using a novel configuration with perforated and non-perforated ribs. The researchers determined the Nusselt number for the increase in heat transfer flux and the friction factor for analyzing pressure losses, evaluating their impact on thermal performance. The results show that the inserts generate disturbances that increase the heat transfer flux and improve efficiency. Several configurations were used; the arrangement of ribs at a distance of 0.1 m was the most effective for heat exchange. The behavior of heat transfer mechanisms in solar water heaters, whether by natural or forced convection, is analyzed in [14]. In free or natural convection, the author characterizes the physical phenomenon where, cyclically, hot air rises as its density decreases, allowing the entry of cooler air. The study establishes the experimental parameters of: Rayleigh number in natural convection, Reynolds number in forced convection, Nusselt number, heat transfer rate, and temperature differences. The results show similarity to other research established in the literature.

The simulation using CFD computational techniques is also reported in the literature for the analysis of solar air heaters, [15]. The authors evaluated tubular heat exchangers, which represent 32% of the total used in the industry. To improve their design and modeling, two fluid flow configurations were used: parallel flow and counterflow. The study evaluated several parameters, including temperature, velocity, pressure drop, and turbulence behavior along the length of the exchanger, which allows for pressure loss analysis. The results show that the heat transfer is greater in the counterflow configuration, with a temperature increase in the cold fluid that exceeds the temperature variation of the hot fluid. Furthermore, velocity fluctuations and pressure drop are greater on the shell side due to the presence of baffles. The turbulence analysis determined variations along the length of the exchanger, confirming that CFD modeling allows for accurate prediction of thermal behavior and pressure loss analysis in the heat exchanger.

Other important work related to thermal systems, mathematical modeling, and simulation are reported in [16]. These investigations use experimental data from compressed air systems and apply numerical simulation techniques that allow for the analysis of energy performance and potential system improvements. The authors consider heat transfer mechanisms by conduction, convection, and evaporation according to the cooling zone, based on the equipment length and process variables. The use of experimental data from laboratory equipment, employing similarity and scaling criteria, is a recent trend, [17]. The authors present an analysis of drying kinetics in an airflow with variable temperature, which allows for improved design of drying equipment with variable air mass flow rates.

Regarding the environmental sustainability of thermal systems, it is important to highlight the work carried out in Portuguese municipalities, [18]. The research takes into account demographic, socioeconomic, and environmental variables that influence the environmental sustainability of these systems.

Previous research demonstrates that the modeling, design, construction, and implementation of double-pass air solar collectors can achieve higher thermal performance compared to single-pass collectors under similar operating conditions. It is important to consider in this experimental research that these systems present some disadvantages related to increased capacity and pumping losses when using liquid fluids, associated with increased pressure losses. These values are reduced when using gaseous fluids, such as air. This demonstrates the feasibility of the practical development of this research under Ecuadorian conditions, through experimental results and the inclusion of mathematical modeling techniques and thermal process simulation, in order to harness solar energy for drying processes, particularly the drying of agricultural products such as cacao.

# 2 Problem Formulation

## 2.1 Airflow Movement Through Single-Pass and Double-Pass Solar Collectors

Figure 1 shows the airflow movement in a single-pass solar collector. The air circulates in a single path, reducing the residence time inside the unit and thus decreasing the heat exchange process and the outlet air temperature. These systems are currently used due to their simple design, low construction cost, and adequate thermal performance. The main components used are as follows:

**Transparent cover:** Because it is transparent, it allows the passage of incident solar thermal radiation. It is made of glass or plastic; in this research, glass was used due to better energy performance and reduced heat loss through convection and radiation.

**Absorber plate:** This metal surface absorbs solar radiation and converts it into usable heat, which is then transferred to the air.

**Air movement duct:** This is the space through which the mass flow of air moves, located between the metal absorber plate and the transparent glass cover.

**Thermal insulation:** Used to reduce heat loss to the ambient air, it is placed on the back and sides of the collector.

**Heat transfer by natural convection or forced convection using a fan:** In this research, a fan was used to increase the air velocity inside the equipment, although it also works without the fan, through heat transfer by natural convection.

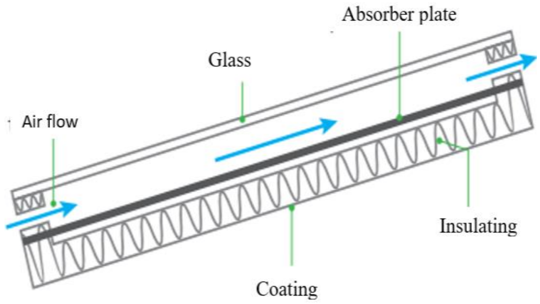


Fig. 1: Single-pass airflow solar collectors
*Source: created by the authors*

The double-pass airflow solar collector and its main components are shown in Figure 2. It is used to increase the heat transfer rate, the outlet air temperature, and thermal performance.

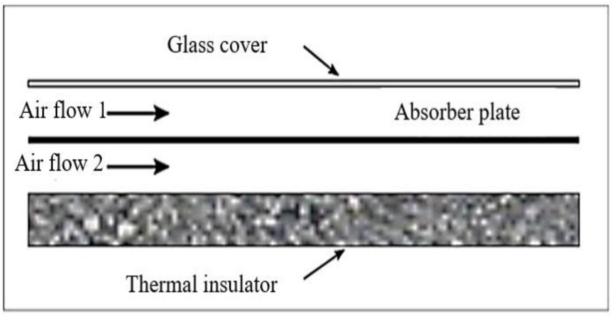


Fig. 2: Double-pass airflow solar collectors
*Source: created by the authors*

Compared to the single-pass collector, it is more efficient. The design allows air movement to occur in two stages in contact with the metal absorber plate. This increases the air's residence time within the unit and, consequently, improves the system's thermal performance.

## 2.2 Thermal Balance in Solar Air Collectors

The fundamental elements considered for performing a thermal balance of double-flow solar air collectors are the following: the glass cover, the metal absorber plate, and the mass flow rate of air moving inside the collector. The mathematical model representing the thermal performance of the collectors is obtained using the thermal balance equations applied to each element, based on the following assumptions:

• Solar air collectors operate under steady-flow conditions.
• The air temperature inside the collector changes only in the longitudinal direction of the fluid.
• The air temperature at the collector inlet is equal to the ambient temperature.
• Heat transfer through the glass surface, the absorber surface, and the insulating material is unidirectional and perpendicular to the airflow.
• Heat losses from the side surfaces are not considered.

**Energy balance on the collector's interior air**

The energy balance in the system related to airflow is represented as follows.

$$\Delta E_s = E_{es} - E_{ss} \tag{1}$$

The energy stored in the system is determined by the following equation, [19].

$$\Delta E_s = M_a \cdot C_{pa} \cdot \frac{dT_a}{dt} \tag{2}$$

When the collector surface absorbs thermal energy, the internal fluid heats up. However, some of this energy is lost through the walls of the equipment. The thermal energy gained by the internal fluid is expressed by the following equation, [19].

$$E_{es} =\cdot C_{p1} \cdot T_{a1} + h_{c1} \cdot A_s \cdot (T_s - T_{a1}) \tag{3}$$

The thermal energy flow that the equipment sells is calculated by adding the thermal energy flow that it sells with the air and the thermal energy flow that the air gives to the glass cover of the collector, [19].

$$E_{sa} = M_2 \cdot C_{p2} \cdot T_{a2} + h_{c2} \cdot A_s \cdot (T_s - T_{a2}) \tag{4}$$

The general equation for the thermal balance of the air inside the collector is obtained by considering the thermal energy gained, the thermal energy produced, and the thermal energy stored.

$$M_a \cdot C_{pa} \cdot \frac{dT_a}{dt} = \dot{M}_1 \cdot C_{p1} \cdot T_{a1} + h_{c1} \cdot A_s \cdot (T_s - T_{a1}) - \dot{M}_2 \cdot C_{p2} \cdot T_{a2} + h_{c2} \cdot A_s \cdot (T_s - T_{a2}) \tag{5}$$

## 2.3 Thermal Performance of the Air Solar Collector

The thermal performance of solar air collectors depends on their location; they cannot be shaded and must have an appropriate tilt. The useful heat flux transferred to the air as it passes through the collector can be expressed by equation 6, [19].

$$Q_U = \dot{M}_a \cdot C_{pa} \cdot (T_{a2} - T_{a1}) \tag{6}$$

To evaluate the equipment and obtain its main parameters, the air temperature inside the collector is assumed to be the average of the inlet and outlet temperatures. The thermal performance of the solar air collector is determined by considering both the useful heat transferred to the air and the solar radiation incident on its surface, [11].

$$\eta = \frac{Q_u}{(\mu\beta) \cdot I_e \cdot A_s} \tag{7}$$

The variation in comparative thermal efficiency between single and double airflow solar collectors is determined by equation (8).

$$\Delta\eta = \frac{Q_t - Q_U}{Q_t} \cdot 100\% \tag{8}$$

The equations described are used to perform a comparative analysis of the thermal performance of solar collectors. However, it is necessary to consider both the effect of solar radiation variability and the dynamic behavior of heat transfer in the airflow over time in order to obtain a more accurate assessment of system performance.

**Nomenclature**

$\Delta E_s$- Energy stored in the absorber surface, W
$E_{es}$- Energy entering the absorber surface, W
$E_{ss}$- Energy coming out from the absorber surface, W
$M_a$- Air mass through the collector, kg
$\dot{M}_a$- Mass flow of air through the system
$C_{pa}$- Heat capacity at constant air pressure, $kJ/kg$ ·K
$\frac{dT_a}{dt}$ – Derivative of air temperature with respect to time, K/s
$\dot{M}_1, \dot{M}_2$ - Mass flow of air at the inlet and outlet of the system, kg/s
$C_{p1,}\ C_{p2}$ - Heat capacity of the air at the inlet and outlet of the system, $kJ/kg$ ·K

$T_{a1}, T_{a2}$ - Air temperature at the system inlet and outlet, K
$T_s$- Temperature on the absorber surface, K
$h_{c1}, h_{c2}$ - Convective heat transfer coefficient at the system inlet and outlet, $W/m^2 \cdot K$
$A_s$- Absorbing surface area, $m^2$
$Q_U$- Useful heat flow at the system outlet, kW
µ - Transmissivity of the glass cover
$\beta$- Absorptivity of the absorber surface
µ$\beta$- Optical efficiency of the collector
$I_e$- Intensity of the incident radiation on the heater, $W/m^2$
$Q_t$- Useful heat transferred to the air in double-pass solar collectors, kW

The collectors were equipped with sensors to measure air temperature, mass flow rate, and incident solar radiation. Figure 3 shows a weather station used to record environmental variables such as ambient air temperature, relative humidity, ambient air velocity, and incident solar radiation. The measurements were synchronized by date and time with those obtained from single- and double-pass air heaters. The data obtained allowed for a comparative analysis of the system's thermal performance.

Fig. 3: Meteorological station, used to measure incident solar radiation and environmental variables
*Source: created by the authors*

## 3 Problem Solution

The variation of the air outlet temperature over time for a constant air mass flow rate is shown in Figure 4.

In this experiment, it was determined that the absorbent metal surface reaches higher temperature values compared to the other components of the system. For this experiment, the air temperature at the equipment inlet recorded the lowest values.

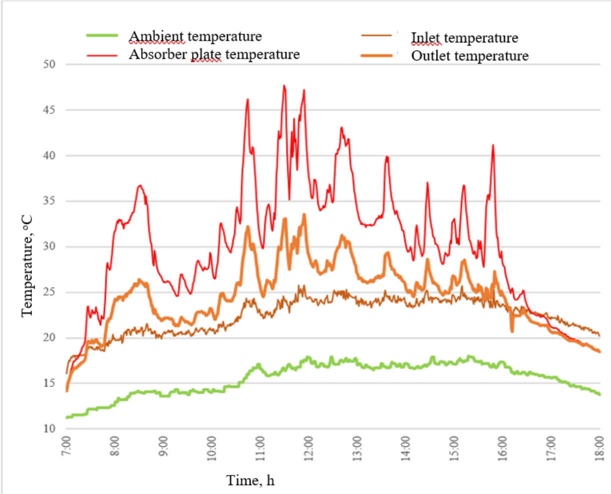


Fig. 4: Variation of the air outlet temperature as a function of time in the solar collector, using a constant air mass flow
*Source: created by the authors*

The outlet air temperature is an average of the absorber plate surface temperature and the inlet air temperature. The experimental results are as follows:
• The absorber plate surface temperature has a maximum value of 47.69 °C, a minimum value of 14.31 °C, and a mean of 30.07 °C.
• The inlet air temperature behaves similarly to the ambient temperature, although with a mean difference of 6.86 °C. This higher value is related to the heating of the air in the fan.

Figure 5 shows the behavior of the thermal variables in the double-flow solar air collector as a function of time. These variables are: air inlet and outlet temperatures, the temperature of the upper and lower absorber surfaces inside the collector, and the ambient temperature. The highest temperature values correspond to the upper plate, while the lowest values inside the unit coincide with the air inlet temperature.

Experimental results show that, in the double-flow air solar collector, the maximum surface temperature of the absorber plate is 54.07 °C, while the minimum is 14.57 °C. The average surface temperature of the upper plate is 30.50 °C, higher than the average temperature of the lower plate (24.79 °C), due to its greater exposure to the heat flow from the glass cover. It is important to note that the experimental values show a similar trend between the ambient temperature and the air collector inlet temperature, with a difference of 4.89 °C between them due to friction and heating from the air fan.

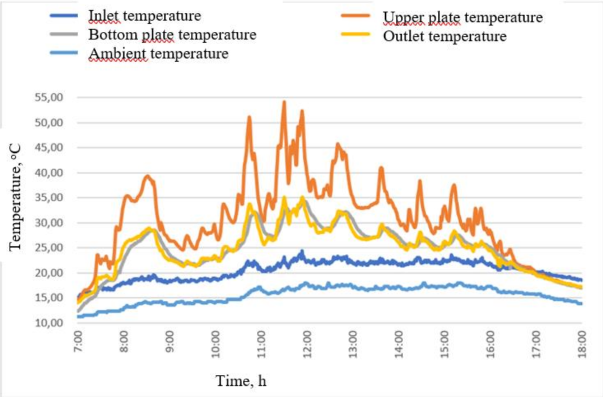


Fig. 5: Temperature behavior as a function of time in the double-flow air solar collector.
*Source: created by the authors*

Figure 6 shows the temporal variation of the outlet temperature for single- and double-flow air solar collectors. The double-flow collector reached a maximum outlet temperature of 35.13 °C and a minimum of 13.94 °C, while the single-flow collector registered a maximum temperature of 33.56 °C and a minimum of 14.14 °C. The maximum ambient temperature, measured by the weather station, was 18 °C; its evolution shows a similar trend to that of the collectors, although with a more linear behavior.
The difference between the maximum outlet temperature of the double-flow collector and the ambient temperature was 17.13 °C, while for the single-flow collector this difference reached 15.56 °C, demonstrating the better thermal performance of the double-flow collector.

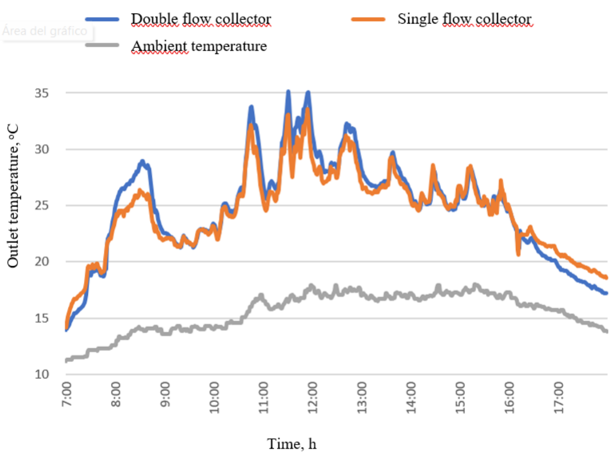


Fig. 6: Comparative analysis of temperature as a function of time in single and double flow air solar collectors
*Source: created by the authors*

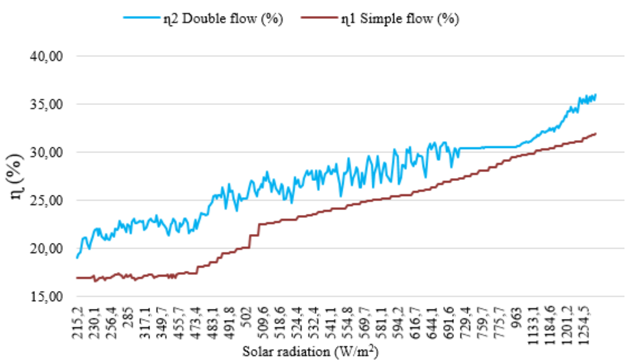


Fig. 7: Comparative analysis of thermal performance as a function of incident solar radiation in single and double flow air solar collectors.
*Source: created by the authors*

Figure 7 presents the thermal efficiency as a function of incident solar radiation for single- and double-flow air solar collectors. During the tests, the incident solar radiation ranged from 215.2 W/m² to 1254.5 W/m². Under natural convection conditions, i.e., without forced airflow, the highest thermal efficiency values were obtained in the double-pass solar collector over the absorber plate, reaching an efficiency of η² = 35% for a solar radiation of 1203 W/m². In contrast, the single-pass air solar collectors recorded the lowest efficiencies, with a maximum value of η² = 31.6%.

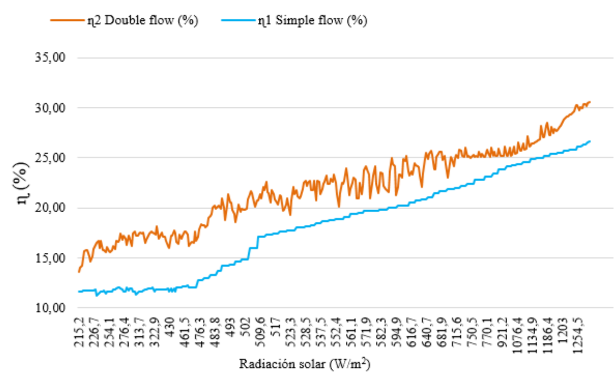


Fig. 8: Comparative analysis of thermal performance as a function of incident solar radiation in single and double pass air solar collectors for an air mass flow rate of 0.033 kg/s.
*Source: created by the authors*

Figure 8 presents the thermal efficiency as a function of incident solar radiation for single- and double-pass air solar collectors, considering an air mass flow rate of 0.033 kg/s. The results show that thermal efficiency decreases with increasing mass flow rate, with the highest values recorded in the double-pass air solar collector, at $\eta_2$ = 30.4%. In comparison, the single-pass air solar collectors achieve an efficiency of $\eta_1$ = 26.2%. Furthermore, it is observed that thermal efficiency increases as incident solar radiation increases.

## 4 Conclusion

The dual-flow collector reached a maximum outlet temperature of 35.13 °C and a minimum of 13.94 °C, while the single-flow collector recorded a maximum outlet temperature of 33.56 °C and a minimum of 14.14 °C. The maximum ambient temperature, obtained by the weather station, was 18 °C; its behavior over time shows a similar trend to the inlet temperature in the solar air collectors, although with lower values due to friction and heating caused by the operation of the fans. The difference between the maximum outlet temperature and the ambient temperature was 17.13 °C for the dual-flow collector and 15.56 °C for the single-flow collector, demonstrating the better thermal performance of the former.

The incident solar radiation values ranged from 215.2 W/m² to 1254.5 W/m². Under natural convection conditions, i.e., without forced airflow, the highest thermal efficiencies were obtained in the double-pass solar collector on the absorber plate, reaching a value of $\eta 2$ = 35% for a solar radiation of 1203 W/m². In contrast, the single-pass air solar collectors exhibited the lowest efficiencies, with a maximum value of $\eta 2$ = 31.6%.

Thermal efficiency decreases with increasing mass flow rate, with the highest values observed in the double-pass air solar collector, at $\eta_2$ = 30.4%. In comparison, single-pass air solar collectors achieve an efficiency of $\eta_1$ = 26.2%. Furthermore, an increase in thermal efficiency is evident as incident solar radiation increases.

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## Conflict of Interest

The authors have no conflicts of interest to declare.