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Simulation of a solar thermal collector of parabolic dish for drying process of calcium propionate

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Abstract : In this paper was simulated a solar energy concentrator and its overall thermal energy generation at different operating conditions was evaluated. The system consist of three solar collectors of parabolic dish coupled to a plate heat exchanger. It was found that the solar collector generate between 0.96 and 1.95 kg/s of air that was heated from a room temperature of 30°C to 170 ° C. This represents a saving of 63.13 % in the consumption of natural gas of a dryer used in the drying process. It was concluded that the city of Cartagena presents a favorable environment for the development of technologies such as solar collectors of parabolic dish, which use solar energy to generate thermal energy.

Keywords: Solar collector, calcium propionate, parabolic dish, solar energy simulation.

1. Introduction

Food and agroindustrial industries generate a lot of chemical material with high moisture content, which require high power consumption to be dried[1, 2]. Usually, these drying processes are carried out using energy obtained from fossil fuels, gas or biodiesel, which generates a high environmental impact due to CO_2 emissions that cause global warming through the greenhouse effect[3, 4]. An alternative to reduce CO_2 emissions is to use clean and renewable energy, which provide heat and energy enough for industrial drying processes[3-18].Among the produced chemicals for the food industry are the calcium propionate, which is a calcium salt used as a food additive in the baking industry and pastries[19]. Spray driers are used to dry the aqueous solution of calcium propionate and to obtain fine particles. Realpeet.al[20]. models and explained in detail, as is removed 1,200 L/h of water using hot air that is heated from 30 °C to 285 °C with combustion of a lot of gas, which is highly expensive and emits a lot of CO_2. Therefore, it necessary to identify a source of alternative energy to allow air heating to the desired temperature and provide the heat required to dry calcium propionate. Among these alternative energy sources, solar energy is an abundant and free energy source[3-7], which generates zero emissions of pollutants and greenhouse gases; it does not produce annoying noises, nor cause any effect on the quality of water or soil.

C.I. Real S.A. is a leader company in the calcium propionate production at Latin American and Central American. It is located at the Cartagena city in northern coast of Colombia. This company has a production of 180 Ton/month, which exports to Ecuador, Peru, Venezuela, Chile, Brazil and Central American countries. Production plant has four type of spray dryers that require hot air at 285 °C for drying calcium propionate. Heating the air at the desired temperature is done through the combustion of natural gas, which implies a high consumption of natural gas accounting for 45% of the commercial price of the product. This prevents that company to participate in markets more competitive, such as Europe and the United States, where the incorporation of technologies enables companies to reduce production costs.

The development of this proposal seeks a solution to the current situation that prevents the expansion of the C.I. Real SA company, posing a substantial contribution to the process of drying calcium propionate with the implementation of a system of concentrating solar power (CES), that allows to use solar radiation to heat the air used in the drying process, thereby decreasing gas fuel consumption and high production costs. Parabolic solar collectors will be used to concentrate solar radiation and transmit to a fluid heat transfer, which by action of radiation increase its temperature and be transported to a heat exchanger where it will transfer that concentrated thermal energy to the air enter the dryer, increasing its temperature and reducing the consumption of natural gas.

2. Conceptual design for parabolic solar collector

As explained byRealpeet. al[20], the Figure 1 shows a diagram of the conceptual design for the concentrating system of solar power. It is proposed an initial preheating cycle for the fluid Dowtherm Q, so that it quickly reached the desired operating temperature. For this, it was decided that the collectors and the pump should operate while valves 1, 2 and 5 remain open and the other closed. After reaching the desired temperature, the valve 5 was closed, the valves 3, 4 and 6 are opened, and the blower is turned on. In addition, the arrangement of equipment and distances between them are shown in Figure 2. It is important to mention that the recommended distance between the solar collectors is equivalent to twice the aperture diameter, or the diameter of the parabolic dish collector.

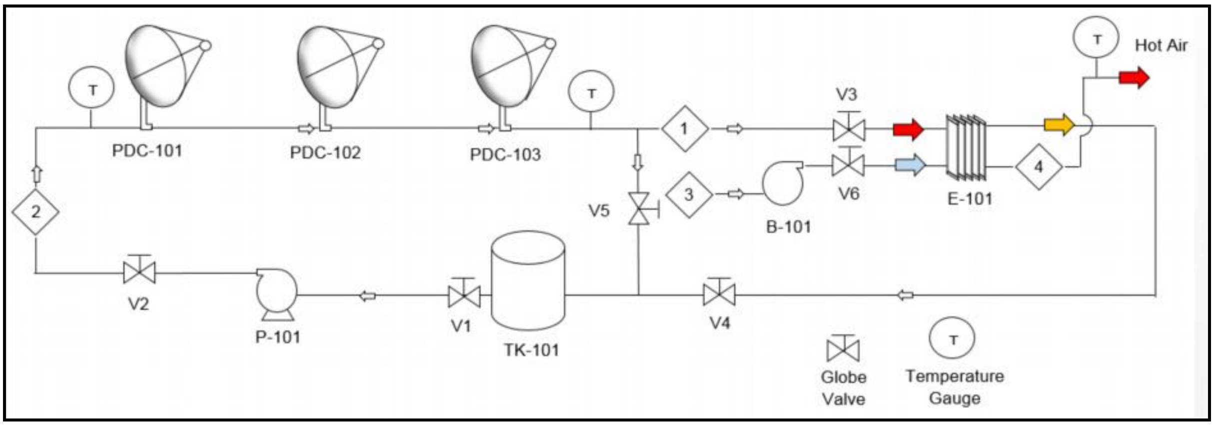

Figure 1. Process diagram of the CSP system proposed

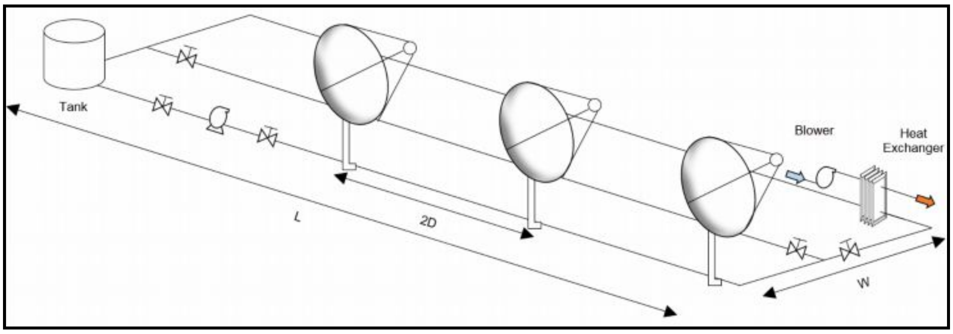

Figure 2. Isometric representation of the CSP system proposed

3. Simulation of the solar system of power concentrating

To simulate the concentrating system of solar power (CSP), in which the solar collector and the plate heat exchanger are coupled, and it was established and dimensioned the pipes and equipment required and in the same time was identified the different heat loss of the system. Thus, the equipment used were: a centrifugal pump that moves the heat transfer fluid, pipes and valves through which the heat transfer fluid flows, a storage tank, and a blower that propel air into the heat exchanger. Once specified the CSP system, it was elaborated an algorithm in MATLAB which contain the mathematical models developed by Realpeet. al[20], and then, the algorithm was run at different operating conditions generated by variation in the air flow, flow of the fluids in the heat exchanger, and the magnitude of solar irradiance. Thus, it was obtained the value of the air outlet temperature at the different operating conditions of the system.

3.Data of solar radiation and parameters for parabolic dish collector

The radiation levels of Cartagena were obtained in the Solar Radiation Atlas of Colombia, which was published by the IDEAM [21]. The Figure 3 represents solar irradiance values for each of the months of the year. Figure 3 shows that overall, solar irradiance values are not very different, and most are in the range from 750 to 1000 W/m^2. However, the registered values of September and December were outside this range. This can be explained due to climate changes in the region, since generally the month of September coincides with the dry season while the month of December coincides with the rainy season where there are more clouds [22].

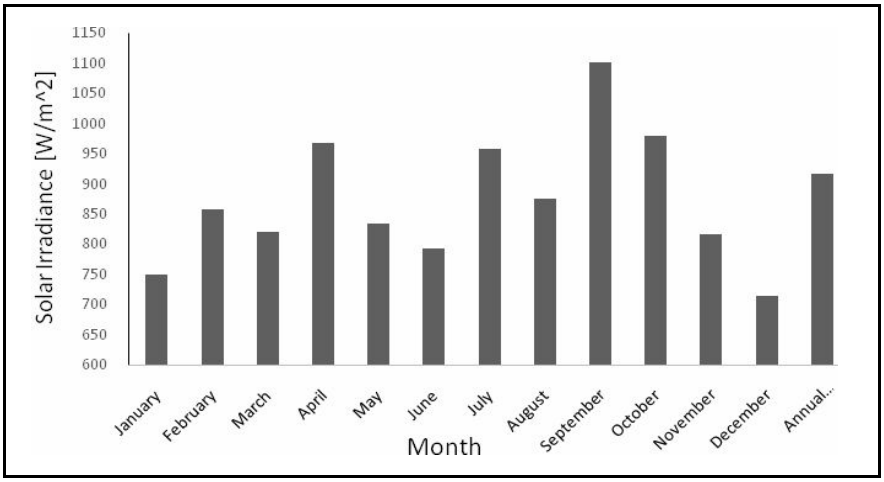

Figure 3.Monthly and annual value of solar irradiance in Cartagena

The simulation for a single collector was run using MATLAB and it was necessary to establish the operating conditions of the system. The values of parameters, such as the specifications of the dimensions and properties of the solar collector were obtained through data recorded in the literature [23-25]. In general, the main parameters for the simulation of the parabolic dish collector are shown in Table 1.

Table 1.Main parameters for parabolic dish collector simulation

Parameter	Value
Dish concentrator aperture area, m^2	87.7
Fraction of un-shaded area	0.99
Reflectivity	0.92
Absorptance	0.94
Transmittance	0.96
Cavitydiameter, m	0.45
Receiver'sapertureddiameter, m	0.20
Emittance of cavity	0.90
Intercept factor of receiver	0.92
Solar Irradiance, W/m^2	967
Air Temperature, K	303,15
Operating wall temperature in the cavity, K	673.15
Flow of Dowtherm Q, kg/s	1.95
Input Dowtherm Q temperature, K	453.15

4. Results and discussion

The results obtained by simulating the solar collector at the operating conditions are shown in Table 2. From this information, it was found that approximately 73.7% of the energy that fall on the collector is converted into useful energy, while the rest of that energy is dissipated and corresponds to heat loss in the collector. For these operating conditions, it was found that the useful energy was enough to produce the desired temperature increase in air (140 °C) under air flow similar to those provided in other studies [26].

Table 2. Parabolic dish solar collector simulation in MATLAB

Variable	**Value**
Incident energy, Qs [W]^2	84806
Optical efficiency	0.7562
Energy reflected to the receiver, Qr [W]	64126
Convective Heat Loss, Qlc [W]	1222.60
Radiative Heat Loss, Qlr [W]	343.17
Useful energy, Qu [W]	62561
Number of collectors	3.0
ΔT per collector, [K]	14.99
Neededcollector área, [m^2]	273.30

This work was compared with the results obtained by Almanza and Cabarcas (2013) [26], as shown in Table 3. Heat transfer fluids used in both studies have similar properties, and from the comparison. Parabolic dish collectors allow obtained higher temperature per area than cylindrical collector.

Tabla 3. Comparación de los resultados de la investigación.

Research	**G. Almanza and J. Cabarcas**	**Current research**
Type of collector	Parabolic Through	Parabolic Dish
ΔT per collector [°C]	14.49	14.99
Collectorarea [m^2]	340.625	273.3

The parameters for algorithm at the operating conditions are shown in Table 4. In addition, specifications of the dimensions of the heat exchanger plates were obtained from a manufacturer. These operation conditions were selected so that the fluid Dowtherm Q never reach a temperature higher than 225 °C, which is the maximum temperature at which the heat exchanger can operate without degrading the joints between plates.

Table 4. Plate heat exchanger operating conditions

Dowtherm Q temperature at collector entrance	**Thermal conductivity of plates**
453.15 K	16.2 W/m*K
Air input temperature	Air output temperature, ts
303.15 K	443.15 K
Heat flow between the fluids, Q	Dowtherm Q flow, W_h
187683 W	1.95 kg/s

Table 5 shows the most important parameters of the plate heat exchanger, such as the heat transfer area, the number of plates and the overall heat transfer coefficient. First, as expected, the overall heat transfer coefficient calculated had an elevated value, which indicates a high heat transfer efficiency. This heat transfer efficiency is a characteristic feature of this type of heat exchanger and occurs due to the presence of corrugations in the plates (which increase the transfer area) and the agitation of the fluids flowing through the heat exchanger. These events contribute to reduce the resistance to heat transfer by convection [27]. In addition, from Table 5 can be seen that the heat transfer area obtained was relatively low, which confirm the conception that plate heat exchangers are compact.

Table 5. Plate heat exchanger specifications

Heat Transfer Area, [m^2]	4.25
Number of Plates	72.17
Oveerall Heat Transfer Coefficient, U [W/m^2 *K]	470.73
Logarithmic Mean Temperature Difference, ΔT_{ml} [K]	94.67
Correction Factor of ΔT_{ml} , F	0.99
Air flow, w_C [kg/s]	1.34

The operating conditions are shown in the Table 6. It is important to note that the temperature of the outer surface of the insulation was taken from the thermal insulation specifications, according to the dimensions of the pipe and the temperature of the fluid flowing through it. The results obtained from the Matlab simulation are shown in Table 7. From Table 7 is observed a very low heat transfer to the surroundings, despite a temperature difference of approximately 175 K between the fluid Dowtherm Q and atmospheric air. This happens because the resistance to heat transfer provided by the thermal insulation is very high, due to its low thermal conductivity.

Table 6. Initial conditions to determine pipeline heat loss

Internal diameter of steel pipeD_i [m]	External diameter of steel pipe, D_e [m]
0.05	0.06
External diameter of insulation, D_{ins} [m]	Piping line length, L [m]
0.16	104
Temperature of insulation surface, T_{ins} [K]	Room temperature of air, T_{air} [K]
311.45	303.15
Dowtherm Q inlet temperature of the CSP system, Tic [K]	Dowtherm Q outlet temperature of the CSP system, Toc [K]
453.15	498.13

Table 7. Simulation of heat loss

Heat transfer coefficient at pipeline interior, h_1 [W/m^2K]	8.06
Heat transfer coefficient at pipeline exterior, h_2 [W/m^2K]	3.15
External area of pipeline, A [m^2]	52.96
Mean temperature of pipeline interior, $T_{\infty 1}$, [K]	475.64
Mean temperature of pipeline exterior, $T_{\infty 2}$, [K]	303.15
Heat transferred to surroundings, Q_{LC} [W]	2746.40

Once the convective heat loss was estimated along the pipeline of the CSP system, the useful energy for each month of the year was calculated, in order to establish the flow of Dowtherm Q necessary to keep temperature conditions of the air that enters the plate heat exchanger. In this way, the monthly average values of solar irradiance that are shown in Figure 2, the value of convective heat loss in the system and the algorithm developed in Matlab are used for simulation of the concentrating system of solar power. To determine the flow of Dowtherm Q that reaches the same outlet temperature when passes through the collectors, the flow value is set by trial and error, and then the matlab algorithm was run to observe the outlet temperature. The results obtained for each of the months of the year are shown in Figures 4 and 5.

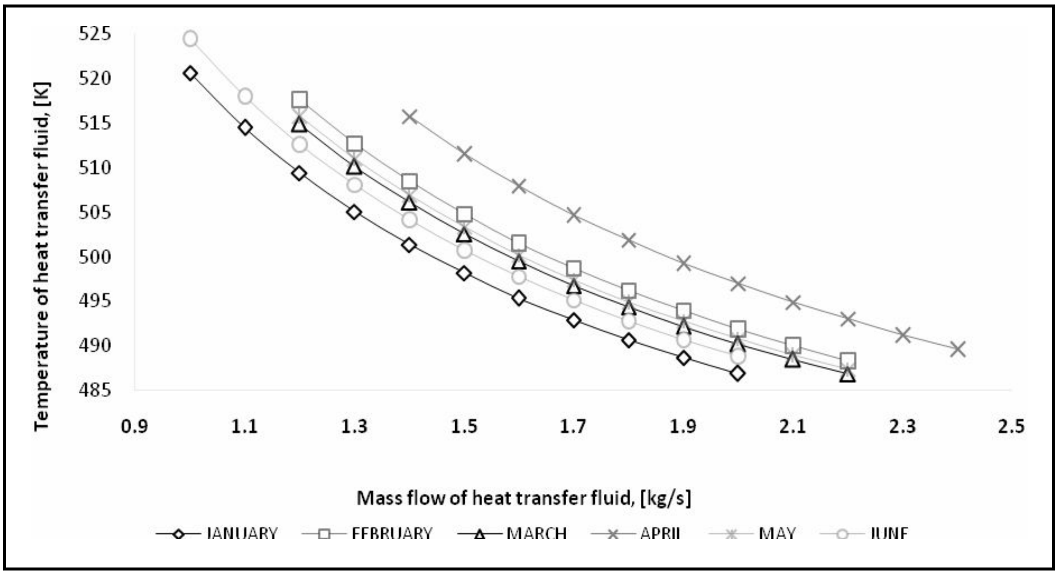

Figure 4. Behavior of the CSP system during the first semester

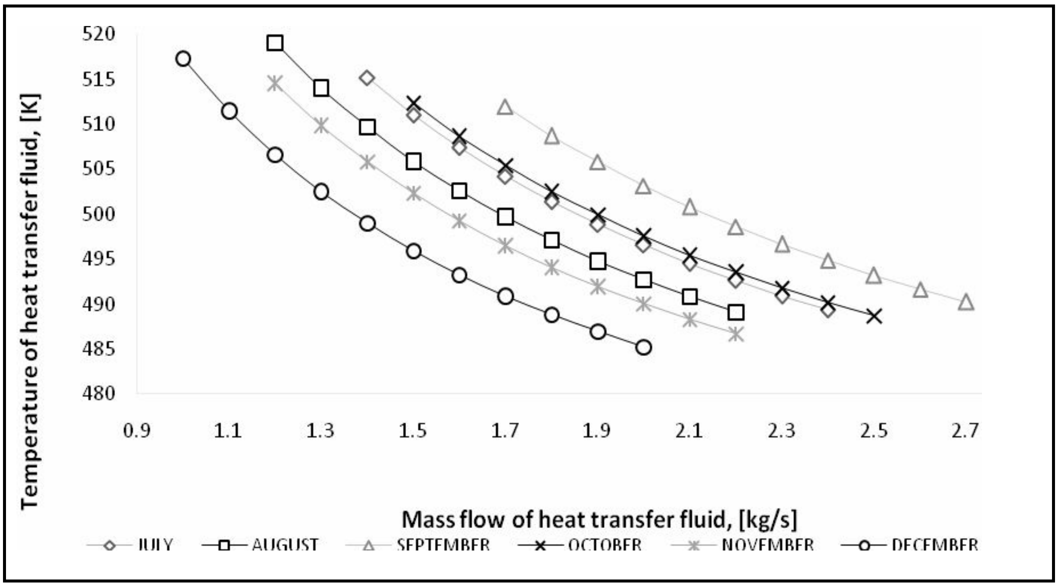

Figure 5. Behavior of the CSP system during the second semester

In general, it is observed that the temperature of the heat transfer fluid flowing through the collector decreases as the flow rate increases. Similarly, it is shown that in the months that reported higher levels of solar irradiance is necessary a greater flow of heat transfer fluid than that considered when that was designed the system. Thus, to determine the exact flow value of Dowtherm Q for each month, it was took the mass flow value for which the outlet temperature obtained was approximately equal to 498.15 K, which correspond to the maximum temperature at which the plate heat exchanger can operate without harming the plate joints.

Flow values of Dowtherm Q for each month is shown in Table 8. It was evident that the values of the mass flow of the heat transfer fluid (Q Dowtherm ®) range from 1.5 kg/s to 2.0 kg/s. The values outside this range were registered in the months of September and December, in which the maximum and minimum value of solar irradiance occurs. The mass flow of air of the CSP system was estimated considering the outlet temperature approximately equal to temperature considered in the design stage (443.15 K).

Table 8. Flow of Dowtherm Q for each month.

Month	Flow of Dowtherm Q, [kg/s]
January	1.50
February	1.72
March	1.65
April	1.95
May	1.68
June	1.58
July	1.93
August	1.76
September	2.22
October	1.98
November	1.64
December	1.42

The data of useful heat and air flow (Figures6 and 7) were calculated using the simulation of the plate heat exchanger and the value of mass flow of Dowtherm Q for each month. Figures 7 and 8 present the same trend in the variation of the data. Thus, it was found that the amount of air that can be heated by the concentrating system of solar power is directly proportional to the useful heat and the solar irradiance. On the other hand, according to information provided by the company C. I. Real S. A., the value of volumetric air flow which is fed to a spray dryer corresponds to 3200 ft^3 / min, which is equal to 1.428 kg/s. According to the results, the amount of hot air obtained with the CSP system is 1.188 kg/s annual average, which is very close to the value required by the company. In addition, we observed that the best operating conditions of the concentrating solar power system take place in September, because of the fact that in this month the highest levels of solar irradiance are presented.

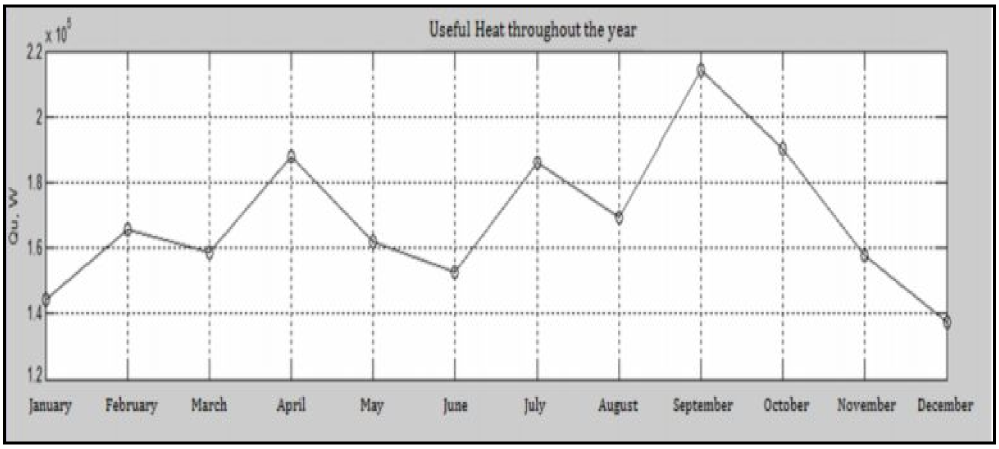

Figure 6. Monthly value of the useful heat

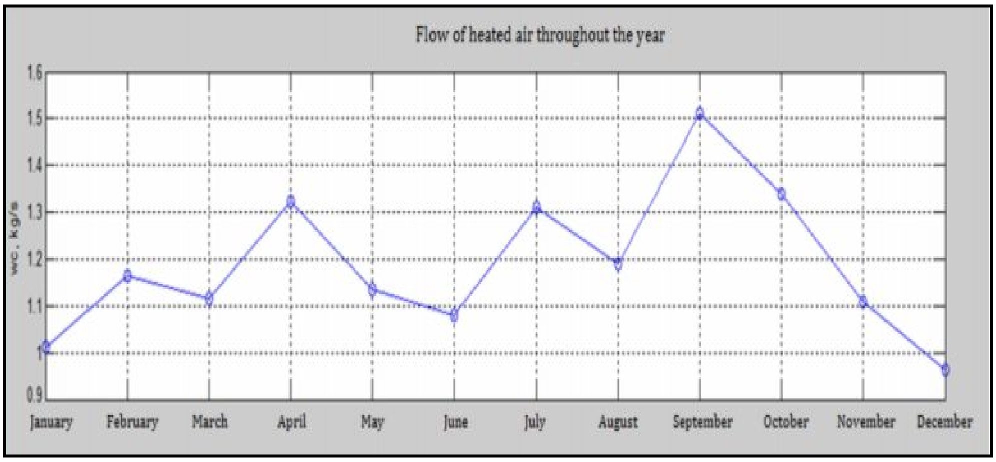

Figure 7. Monthly value of air flow

5. Conclusions

Simulation of the concentrating system of solar power located in the Cartagena city was developed. This is due to good weather conditions in the region, but mainly by high levels of solar radiation, which has an annual average solar irradiance of 917 W/m^2. The mathematical model based on the thermodynamic fundamentals was used to describe the concentrating system of solar power, and then it was simulated using MATLAB. It was determined that approximately 73% of the incident solar irradiance can be converted into thermal energy, which represent a considerable amount of energy saved in relation to the use of conventional energy sources. In addition, it was concluded that theair flow that can be heated is directly proportional to the amount of solar irradiance that is received by the solar collector of parabolic dish.

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