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Energy Analysis of Forced-Air Solar Panels for a Fruit Dehydration Oven

Análisis Energético de Paneles Solares de Aire Forzado para un Horno de Deshidratado de Frutas

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ABSTRACT

This article presents the design, construction, and energy analysis of three forced air solar collectors, which act as an auxiliary energy source for a fruit dehydrator with a capacity of 30 kg. The study began with a review of concepts related to solar energy, including solar collectors and finally the food dehydration process. In the construction stage, the sizing of the collectors is determined by 5,3 m^2 of black-painted copper for the absorbers, which will allow for the dehydration of batches of 30 kg of pineapple in a period of 18 hours. In the analysis, the results obtained indicate that the implementation of these solar collectors generates an annual savings of $1135 in the operational costs of the dehydrator, highlighting the efficiency and economic viability of using solar energy in this context.

Keywords: Solar Energy; Flat Solar Collector; Food Dehydration; Solar Collector Sizing.

RESUMEN

Este artículo presenta el diseño, construcción y análisis energético de tres colectores solares de aire forzado, que actúan como una fuente auxiliar de energía para un deshidratador de frutas con capacidad para 30 kg. El estudio inició con una revisión de conceptos relacionados con la energía solar que incluye los colectores solares y finalmente el proceso de deshidratación de alimentos. En la etapa de construcción el dimensionamiento de los colectores queda determinando por 5,3 m^2 de cobre pintado de negro para los absorbentes, lo que permitirá deshidratar lotes de 30 kg de piña en un período de 18 horas. En el análisis los resultados obtenidos indican que la implementación de estos colectores solares genera un ahorro anual de 1135 dólares en los costos operativos del deshidratador, resaltando la eficiencia y viabilidad económica del uso de energía solar en este contexto.

Palabras clave: Energía Solar; Colector Solar Plano; Deshidratación de Alimentos; Dimensionamiento de Colector Solar.

INTRODUCTION

Food dehydration is a technique used in Ecuador by large, medium, and small producers of cereals and fruits. While large producers use industrial dehydrators, most medium and small producers continue to use traditional techniques because they are not able to acquire this type of machinery as they cannot cover their operating and maintenance costs.[1,2,3,4]

Traditional dehydration techniques present several drawbacks that affect the quality and marketability of the product. When done outdoors, the food is exposed to dust, insects, birds, and other animals, which can contaminate it. Moreover, sunlight and rain alter its physical and chemical properties. The lack of a controlled environment also promotes the proliferation of microorganisms, making the product less safe for consumption. Finally, the dehydration is not uniform, which reduces its quality and price in the market.(2,5,6,7) Below is a bibliographic search of various research works developed on forced air solar panels.

According to (1) Azam MM, Eltawil MA, Amer BMA, it is mentioned that, to avoid the negative effect of fossil fuel use on the environment and health, solar drying systems are considered a viable technology among the techniques developed to date. On the other hand, in Iza et al.(2), it is indicated that solar energy is the most promising of renewable energy sources; it is an inexhaustible and highly reliable clean energy technology.

As mentioned in (4) Nitin Kumar, Anil Panghal, MK Garg, solar dryers are used to improve the quality of the dried product and reduce drying time compared to sun drying.

In (8) Masoud Iranmanesh, Hadi Samimi Akhijahani, Saleh M. indicate that, to improve the drying process, save energy, and reduce the cost of the dried product, an adequate and optimal design of solar dryers is essential. Various methods have been employed to increase the efficiency of solar dryers, such as the use of heat recovery systems, the combination of photovoltaic systems with curtains inside the dryer, the use of reflectors, the incorporation of heat pump systems, and the modification of the structure of the collectors.(9)

According to Abderrahmane Benhamza et al.(10), the quality of dried products varies significantly with the uniformity of the speed and temperature distribution in the drying chamber. Therefore, optimizing the operating conditions and the design of the dryer is essential to improve the uniformity of the drying process.(11,12,13)

According to the research by Raouf Amouiri et al.(14), they point out that energy consumption in industrial processes ranges between 10 % and 25 %, and that energy demand in this sector will increase dramatically by one-third in 15 years. This enormous consumption will result in a considerable increase in the carbon footprint and global warming potential. Solar dryers are among the promising techniques that can greatly benefit the ecosystem and reduce the consumption of conventional fuels, which benefits both producers and consumers.

METHOD

At this stage, experimental research is conducted, for which a collector prototype is built, and its parts are described as follows:

Food dehydration

Dehydration can be conceived as the technique of removing water from a certain material. In the case of food, dehydration is primarily used as a preservation technique because "microorganisms that cause food spoilage cannot grow and multiply in the absence of water." Ecuadorian regulations mandate that the moisture content of dehydrated fruits does not exceed 15 %.(15,16,17) The oven that is part of this project is mainly used to produce snacks, and it is recommended that the moisture content be kept within the limit since the Ecuadorian consumer prefers these foods not to be "too dry."(2)

The dehydration process is affected by the following variables: initial product mass, initial moisture, final moisture, maximum allowed temperature, and recommended time. Table 1 shows the variables corresponding to the products that are most frequently dehydrated with the oven analyzed in this project.(3)

Table 1. Characteristics of the products to be dehydrated

Product	Initial humidity (%)	Maximum temperature (°C)	Recommended time (h)
Apple	84	50	12
Banana	74	70	8 - 12
Pineapple	87	60	12 - 24
Mango	88	-	12 - 24

From table 1, it can be inferred that the working temperature of the furnace will be above 70°C.

Solar energy

The sun can be considered a gigantic sphere of hot gas with a diameter of 1,39x10-9 m. In the core of the sun, nuclear fusion reactions are constantly occurring; the energy generated is transported outward from the core by radiation, after which the energy continues outward through the sun by convection due to the gases in the outer layers. For simple thermal applications, the sun can be considered as a black body at a temperature of 5762 °K.(4)

Of all the radiation produced by the Sun, a small fraction estimated at 1360 kW/m^2 reaches the Earth and is

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known as the solar constant; a portion of this value is lost as the radiation passes through the atmosphere, so on a clear day, it is possible to measure between 800 and 1000 kW/m^2 on the ground. In Ecuador, the average solar radiation is estimated at 4575(W*h)/(m^2*día).[18]

Solar collectors

Solar collectors are heat exchangers that transform solar radiation into thermal energy and transfer it to a transport fluid.[5]

As can be seen in figure 1, for applications that require a temperature below 80°C, the most viable solution is the implementation of flat plate solar collectors with a cover.[5]

The main components of a flat solar collector are shown in figure 1 and are detailed below:

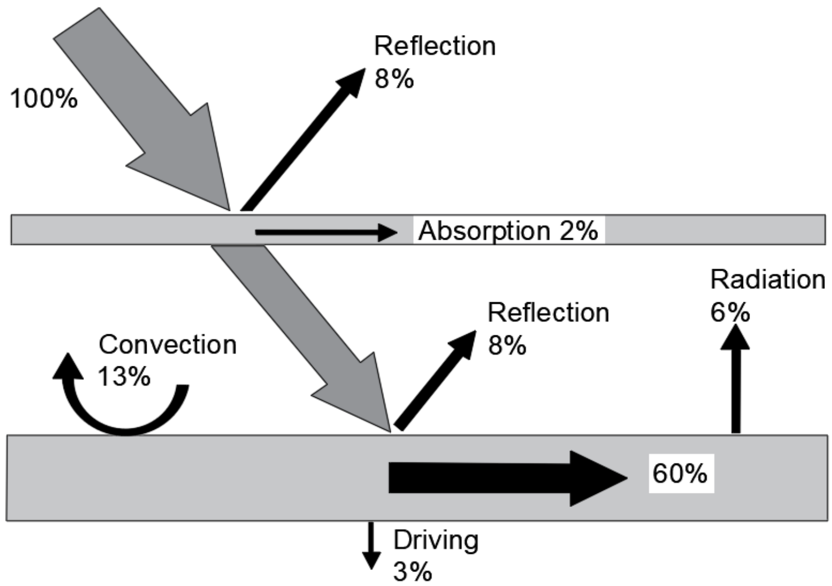

Figure 1. Efficiency of flat-plate solar collectors[7]

Absorber

This element transforms thermal radiation into caloric energy; the preferred materials for this component are stainless steel, aluminum, and copper. It is also advisable to use some coating to improve absorption.[6]

Cover

The collector cover creates a higher temperature environment inside the collector and prevents convection losses by separating the hot air inside from the cold air outside. An additional phenomenon produced by the plate is the creation of the "greenhouse effect," which allows solar radiation to easily enter the collector while making it difficult for the thermal radiation from the interior to leave the collector. The most commonly used materials are plastic and glass; plastic is cheaper than glass but tends to deteriorate more easily; glass retains its properties for a longer time but is fragile, and the cost of using tempered glass is high.[6]

Thermal insulator

When the temperature of the collector increases, it begins to transfer heat to the environment spontaneously. The heat loss through the cover is mitigated by the greenhouse effect, while on the back side it is necessary to place a layer of insulating material. Among the most commonly used materials for this purpose are polyurethane foam, rock wool, fiberglass, and cork.[6]

Regarding the efficiency of the collectors, it should be mentioned that the interaction between solar radiation and a covered collector occurs as shown in figure 2.

The radiation coming from the sun strikes the collector's cover; 8 % of this radiation is reflected by the cover. In addition to reflecting solar radiation, the body of the cover absorbs 2 % of the radiation it receives. The collector's absorber reflects 8 % of the radiation received by the collector and radiates 6 %. Despite efforts to insulate the system, about 13 % of energy is lost through convection and 3 % through conduction between the different components of the collector. The energy that the absorber manages to convert into heat is approximately 60 % of the total energy that reaches the collector.[7]

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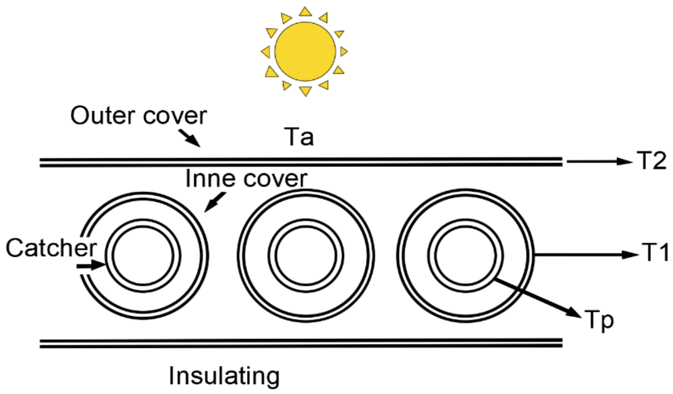

Figure 2. Diagram of the double-glazed solar collector[7]

The sizing of a flat solar collector begins by determining the heat required by the system; for this, it is useful to follow the following algorithm:

- Identify the mass of the product to be dried, the current moisture content, the desired moisture content, and the temperature at which dehydration should occur.
- Calculate the mass of water to be removed using equation 1.[19]

$$m_a = m_T * (H_i - H_f) \quad (1)$$

- Check the enthalpy value of water and water vapor at the dehydration temperature.
- Calculate the sensible heat and the latent heat using equations 2 and 3[19] respectively.

$$Q_s = m_a * C_p * (T_{max} - T_{amb}) \quad (2)$$

$$Q_l = m_a * (h_v - h_l) \quad (3)$$

- Select the duration of the process.
- Calculate the required power using equation 4.

$$P = \frac{Q_1 + Q_s}{t} \quad (4)$$

The next value that needs to be determined is the heat loss coefficient of the collector, for which it is necessary to have selected the model, as well as some of the materials that make up the collector. Figure 3 shows the thermal diagram of a two-cover solar collector.[8] The equivalent loss coefficient can be determined using equation 5.

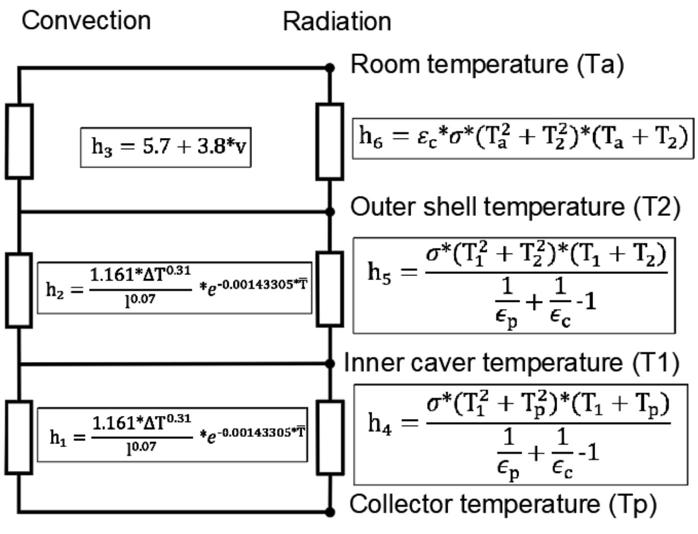

Figure 3. Thermal diagram of the solar collectors[19]

$$h_{equivalent} = \left(\frac{1}{h_1+h_4} + \frac{1}{h_2+h_5} + \frac{1}{h_3+h_6}\right)^{-1} \quad (5)$$

Knowing the power and the equivalent loss coefficient, it is possible to calculate the collector area using equation 6.

$$A_s = \frac{P}{\tau * \alpha * G - U_t * (T_p - T_a)} \quad (6)$$

An additional value that can be calculated is the collector efficiency using equation 7, which can be used to evaluate the performance of the equipment.

$$\eta = 1 - \frac{U_t * (T_m - T_a)}{\tau * \alpha * G} \quad (7)$$

The values obtained in the sizing of the solar collector for this project are shown in table 2.

Table 2. Collector sizing

Variable	Symbol	Worth	Unit
Calculation of water mass			
Total mass	m_T	30	kg
Initial humidity	H_i	0,87	
Final humidity	H_f	0,15	
Mass of water	m_a	21,6	kg
Calculation of sensible heat			
Specific heat	C_p	4182	J/(kg*K)
Ambient temperature	T_{amb}	20	C
Maximum temperature	T_{max}	60	C
Sensitive heat	Q_s	3,61	MJ
Calculation of latent heat			
Enthalpy of water at 60 C	h_l	251,4	KJ/kg
Enthalpy of water vapor at 60 C	h_v	2608,9	KJ/kg
Power calculation			
Time required	t	18	h
Power	P	841,6	W
Calculation of loss coefficient			
Cover material	Vidrio estándar		
Absorber material	Cobre + pintura negra		
Wind speed	v	0,833	m/s
Distance absorber – inner cover	l_1	0,5	cm
Distance between covers	l_2	1,5	cm
Covered emissivity	ε_1	0,88	
Emissivity absorber	ε_2	0,95	
Constant Stefan – Boltzman	σ	5,67E-8	$W/(m^2*K^4)$
Loss coefficient	U_t	3,18	$W/(m^2*K)$
Calculation of the absorber area			
Cover transmittance	τ	0,91	
Cover absorbency	α	0,85	
Direct radiation	G	370	W/m^2
Absorber area	A	5,3	m^2
Calculating efficiency			
Efficiency	n	0,432	

In the implementation stage of the collectors, the following guidelines were used:

- Absorber material: copper coated with black Paint.
- Absorber area: 5,3, the best way to implement it is with 1" tubing, so 67 meters of this material will be required.
- Cover material: since plastic covers deteriorate very easily, the most favorable choice falls on glass.[9]
- Collector body material: the collector body does not require special mechanical characteristics, so it can be manufactured from materials that are most suitable from the standpoint of ease of manufacturing.[10]
- Insulating material: the material called Styroplan is selected as it is considered the best thermal insulator in the Ecuadorian market.[11]
- Reflector plate material: for this component, stainless steel is selected as it has the highest reflectivity among all the materials available in Ecuador.[12,13]

RESULTS

To verify that the design of the collectors was correct, measurements of direct radiation, wind speed, and temperatures in the collectors were taken in order to determine their efficiency and compare it with their theoretical value. The efficiency measurements are shown in table 3.

Table 3. Efficiency measurement

Measurement	Efficiency
1	0,44
2	0,38
3	0,40
4	0,40
5	0,41
6	0,43
7	0,45
8	0,44
9	0,39
10	0,42
Average	0,41

As can be seen in table 3, the measured efficiency is very close to the calculated one in table 2.

The amount of energy provided by the solar collectors to the dehydration process can be estimated from the reduction in electricity consumption. Before the implementation of the solar collectors, the dehydrator had a monthly operating cost of 130 dollars; with the solar collectors in operation, this value was reduced to 31 dollars in March 2016. Equation 8 allows calculating the amount of energy delivered by the collectors based on the reduction in operating costs, the rate, and the number of hours the collectors were used; the cost difference is 99 dollars, the valley rate is 0,09 dollars, and the collectors were used for 120 hours throughout the month.

$$\text{amount of energy} = \frac{operating\ cost}{rate * hour} \qquad (8)$$

$$\text{amount of energy} = \frac{99}{0{,}09 * 120} = 9{,}16\ \text{kWh}$$

Figure 4 shows the hours when direct solar radiation is sufficiently high for the collectors to supply the energy required by the dehydrator oven. If it is taken into account that the oven operates around 200 hours monthly, it is noted that in some months a greater use of electrical energy will be required; nevertheless, it is estimated that the use of the collectors generates an annual savings of 1135 dollars.

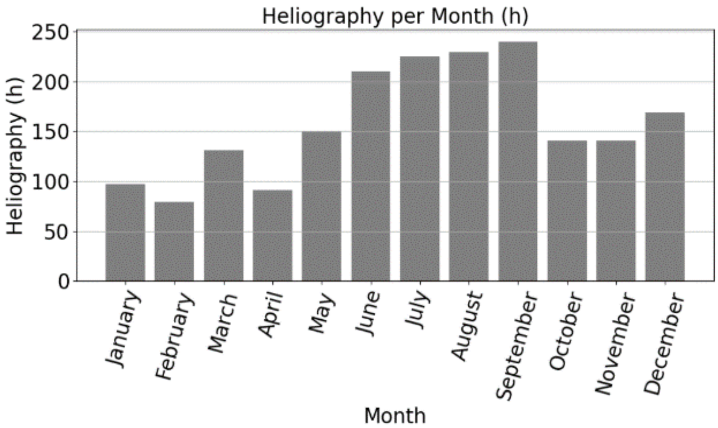

Figure 4. Heliofanía in the valley during 2015[20]

As a complement to the results obtained with the collectors, the dehydration process was verified with the following foods: apple, banana, and pineapple, the latter being the most difficult case to handle due to its high-water content. The results of the pineapple dehydration are shown in table 4.

Table 4. Results of pineapple dehydration

Drying time (h)		18
Days		3
Initial mass (kg)		30
Initial humidity		0,87
Proof	Final mass (kg)	Final humidity
1	7,86	0,13
2	8,07	0,14
3	8,44	0,15
4	7,96	0,14
5	7,84	0,13
6	8,36	0,15
7	8,12	0,14
8	8,41	0,15
9	8,49	0,15
10	8,27	0,15
Average	8,18	0,14
Standard deviation		0,01

As can be seen in table 4, the temperature reached after the dehydration process was always lower than that required by Ecuadorian regulations, and the standard deviation value allows us to affirm that the product is homogeneous.

CONCLUSIONS

In this project, a double-covered flat solar dehydrator was built, achieving an average efficiency of 0,41, which is close to the average recorded for this type of machine at 0,4.[21] It was also possible to estimate the savings in operating costs of the dehydrator oven at 1135 dollars annually. The use of solar collectors did not alter the oven's work cycle at all, so it can be concluded that this energy source is suitable for small and medium dehydration processes. It was found that solar energy utilization systems can have low efficiency during certain months of the year, so they should be complemented with systems that use other types of energy.

As recommendations for future work, it can be indicated that for a better result, a permanent temperature control system should be implemented in order to maintain a constant amount of heat to which the product is subjected. This work can be improved and applied to sites where there is no access to electrical energy by changing the electrical system to photovoltaic panels solely for the use of forced ventilation and the heating system with forced air panels.

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