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Duplex solar cooker with selective evacuated tube and compound parabolic concentrator

Cocina solar duplex de tubo evacuado selectivo y concentrador parábolico compuesto

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Abstract

In the present work, an indirect solar cooking proposal is shown. The proposal combines three technologies: evacuated tubes, selective absorber, and compound parabolic concentrator (CPC). The absorber used is an evacuated glass tube, with a highly selectivity inner surface. The temperature reached by the solar cooker is approximately 160°C, enough to cover the cooking needs of all types of food; Irradiance, wind speed, ambient temperature was measured, food cooking tests were carried out, using an evacuated tube and a parabolic solar concentrator; as well as evacuated tube without parabolic solar concentrator. A compound parabolic concentrator was designed with an acceptance angle of 15 degrees, the base of the solar cooker was made with acrylic, the concentrator was made with simple reflection mirrors, the clips were printed on a 3D printer, the trays were made with food grade stainless steel, food cooking tests were carried out, recording the weather variables every 15 minutes. The development of this evacuated tube duplex solar cooker project is not only important because it involves the achievement of an academic purpose, but also involves a social purpose. It is intended to provide an efficient and economical solution that is attractive to multilateral organizations capable of supporting its manufacture, industrialization and distribution to achieve the massification of the product with a real and lasting impact.

Solar energy, Cooking food, Solar cookers

Resumen

En el presente trabajo, se muestra una proppuesta de cocina solar indirecta. La propuesta combina tres tecnologías: tubos evacuados, absorbedor selectivo, y concentradore parabólico compuesto (CPC). El absorbedor utilizado es un tubo de vidrio evacuado, con superficie interior de alta selectividad. La temperatura alcanzada por la cocina solar es de 160°C aproximadamente, suficiente para cubrir las necesidades de cocción de todo tipo de alimentos; se midió la irradiancia, velocidad de viento, temperatura ambiente, se realizaron pruebas de cocción de alimentos, utilizando tubo evacuado y concentrador solar parabolico; así como tubo evacuado sin concentrador solar parábolico. Se diseñó un concentrador parbólico compuesto con un ángulo de aceptación de 15 grados, la base de la cocina solar fue elaborada con acrilico, el concentrador fue elaborado con espejos de simple reflexión, los clips se imprimieron en una impresora 3D, las charolas fueron elaboradas con acero inoxidable grado alimenticio, se realizarón pruebas de cocción de alimentos, registrando cada 15 minutos las variables climatologicas. El desarrollo de este proyecto de cocina solar dúplex de tubos evacuados, no solo es importante porque envuelve la realización de un fin académico, sino que también involucra un fin social. Se pretende brindar una solución eficiente y económica que sea atractiva para organismos multilaterales en capacidad de apoyar su fabricación, industrialización y distribución para lograr la masificación del producto con un impacto real y duradero.

Energía Solar, Cocción de alimentos, Cocinas solares

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1. Introduction

The use of technologies that combine the sun's energy and energy efficiency, including the solar cooker, partly help the development of the world's population, especially the poor. The first solar cooker was developed in 1767 by Horace de Saussure, which reached a maximum temperature of 88º C and according to his writings, when a black surface was added to the inside of the box, it reached 160º C. (Resabala, 2023).

Solar cookers are thermo-converters that harness the sun's energy to generate sufficient heating power to cook food at varying time intervals. Generally, these systems are semi-stationary, because they require continuous orientation towards the sun, in order to make the best use of solar energy. There are different types of solar cookers: box type; parabolic concentrator; indirect collector; with tube type convective insulator; with compound parabolic concentrators; and with folding collector. (Sosa, 2023).

There are various types of solar cookers, in particular in Mexico, the Tolokatsin solar ovens and solar cookers have been developed, with high thermal performance, based on the application of anidolic optics (González-Avilés, 2023). In several regions of our country, the growing overexploitation of forest resources is a latent problem that must be addressed (in some cases immoderate clandestine logging has caused inter-community conflicts that have had irreparable consequences).

Cooking with solar energy is a wonderful experience. It means not only a daily saving on gas, charcoal, wood or electricity, but also a change in people's consciousness and a learning process that is oriented towards sustainable human development. It is a new way of taking care of our lives, which is being applied in more and more countries every day (Almada, 2023).

The habit of collecting and using firewood prevents people from realising what this means for most people and for the environment, but it is important to think about why firewood and charcoal are used:

Money is not always enough to buy gas, people live so far away from urban centres that it is the only fuel available, they want to make a gas cylinder last as long as possible, they want to use it as much as possible, and they want to use it as much as posible gas cylinder as long as possible, and people have always thought that firewood is free... but it's not!

The inhalation of fumes from the combustion of wood is the cause of respiratory diseases, which also produces carbon dioxide emissions that are harmful to the environment. Solar cookers represent an alternative to reduce carbon dioxide emissions; for the cooking of food, for every kilogram of LP gas that is not combusted, 2.8 kg of CO2 (CO2 emitted into the atmosphere) are reduced, or for every kilowatt hour that is not consumed in electric grills, 498 grams of CO2 can be mitigated. Likewise, in the rural sector, where LP gas is generally not consumed, emissions are associated with the burning of timber forest resources, where in addition to emissions, respiratory diseases are generated in the users of forest biomass. The use of alternative energy sources such as solar energy for cooking can contribute to solving this type of problem (Ialla N. D., 2023).

In order to access higher temperatures, parabolic trough concentrators have been developed over the years; usually the absorber element, the cooking pot, is placed directly at the focus of the system, making it a direct solar cooker. With this configuration, the limitation of the efficiency of the system is due to the fact that the pot is exposed to the three mechanisms of heat transfer to the environment.

At the Technological University of San Juan del Río, solar ovens have been built that reach 80°C to 90°C, the complicated thing is to exceed 100°C and, above all, to reach the usual cooking temperatures of conventional cookers and ovens, which start at 120º, from these temperatures the solar oven or solar cooker starts to be a good development.

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(Duran, 2016), developed a four-phase prototype: The parabolic dish, the gear boxes and support device, the control system for solar tracking and finally the integration and operational testing. The conjunction of the four phases results in a fully operational prototype with the ability to reach up to 400 °C temperature above the focal point of concentration under partly cloudy day conditions.

One way to circumvent this last drawback is through the use of concentrators with anidolic optics, i.e. non-imaging. Devices employing this principle are called compound parabolic concentrators (Ialla N. D., 2011). In recent years, different designs of indirect solar cookers using CPC technology have been proposed. (Carrera, 2016), characterised a solar cooker made from two evacuated tubes that are used in solar water heaters to heat water for sanitary use, which were placed on supports, inside the tube a tray made of food grade stainless steel was inserted, which is used to place the food to be cooked, they have lids made with Nylomaq□, these evacuated tubes are placed on an aluminium base in a parabolic shape, the temperature values inside the tray where the food is placed, reported the cooking of foods such as: Mixiote, chicken in pipian sauce, chicken fajitas, beans, steak with potatoes, bread baking.

(Ialla N. D., 2023) presents a new indirect solar cooker design. The design combines three high-performance technologies: evacuated tube, selective absorber, and compound parabolic concentrators (CPCs). An alternative method developed for the calculation and layout of CPCs for absorbers of circular geometry is also shown.

The absorber used in the prototype is an evacuated glass tube with a highly selective inner surface. The heat transfer mechanism, from the absorber to the cooking vessel, is through the natural convection of ecological oil. The design features and the elements used allow a very efficient use of solar energy, thanks to which the system can easily access temperatures close to 170°C, sufficient to cover the cooking needs of all types of food.

(González-Avilés, 2015), presents the study of some aspects of thermal physics necessary for the development of small solar cookers, through the development of a semi-empirical computational thermal model. The free parameters of the model are adjusted with data obtained from an experimental design, which consists of heating a fluid, exposing the cookers to the radiation produced by an array of incandescent lamps to simulate solar radiation. The model allows estimating some parameters that serve to compare the operation of solar cookers, from the thermal point of view, with parameters established in standard test protocols at international level, such as: standardised cooking power and thermal efficiency.

There are two solar cooker systems: those based on the storage principle and those based on the concentration principle. In the former, an enclosure thermally insulated on all sides, except for the side facing the sun covered with a material transparent to solar radiation, usually glass or plastic, allows us to receive the sun's radiant energy and store it inside thanks to the greenhouse effect. In the case of using this system as a solar cooker, a container with the food to be cooked is placed inside. Depending on how the cooker is constructed, it can reach 90 to 120 degrees Celsius.

In the second case, a concentrating system, usually of a parabolic nature, also intercepts the solar radiant energy and brings it to its focal zone. Systems such as the K14 parabolic cooker, for an intersection of 2 square metres, offer an output of 1 kW with an efficiency of 50 percent. In this way, a high thermal utilisation is achieved in the pot where the solar energy is concentrated. In this second case, higher temperatures can be reached than with storage cookers, at least 200 °C, which allows not only boiling, stewing, steaming, but also frying and roasting (González, 2023).

In view of the above, the present work proposes a design for a direct solar cooker that uses CPC technology, absorbs solar radiation through a selective evacuated glass tube with vacuum insulation, and transmits the heat to the cooking receptacle, consisting of a tray made of food-grade stainless steel.

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The device has an acceptance angle of 15°, i.e. it allows one hour of concentration without the need for redirection, and is capable of accessing temperatures necessary for the cooking of all types of food, the proposed cooker allows frying, boiling and baking.

At the Technological University of San Juan del Río, a prototype of a duplex solar cooker with evacuated tubes and a parabolic concentrator is being developed in the research unit, in the renewable energy laboratory, using affordable and low-cost materials.

Figure 1 Prototype duplex solar cooker with evacuated tubes and compound parabolic concentrator
Source: Own Elaboration

In contrast to box-type solar cookers, parabolic cookers and compound parabolic cookers, the present work shows a solar cooker that exploits three technologies

2. Design and description of the solar cooker prototype

2.1Theoretical underpinnings of design

Let us consider a concentrator system operating with an absorber isolated from the external medium, in such a way that the heat exchanged by conduction and convection (typical characteristic of vacuum insulation) is neglected. Then we can say that the maximum temperature that the absorber can reach can be calculated by establishing the equilibrium between the energy it absorbs and the energy it emits by radiation. This situation is given by the equality (1).

$$IC\rho A \propto= \varepsilon A\sigma T^4 \quad (1)$$

Where:

I Solar irradiance in W/m^2
A Absorber area
C Geometric concentration of the system (ratio of the collector collector area to the absorber area)
ρ Reflectivity of the concentrator surface
ε Surface emittance
α Surface absorptance
σ Stefan-Boltzman constant, σ = 5.67·10-8 [W/m^2 K^4]

By subtracting T from (1) we obtain the maximum temperature that the absorber can reach in this situation, equation (2).

$$Tmax = \sqrt[4]{IC\beta\rho/_{\sigma}} \quad (2)$$

T Maximum temperature that the absorber can reach
β Abosorber surface selectivity, α/ε.

To obtain a device with high conversion efficiency and access to the highest temperatures: the absorber must have vacuum chamber insulation, it must operate at maximum concentration conditions, and it must have selective properties.

2.2 Design and calculation of the CPC profile

A two-dimensional CPC-type optical concentrator design was proposed for a receiver with a circular cross-section, in this case the evacuated tube, a geometry compatible with that of the vacuum-selective tubular absorber. The CPC was made from the complementation of two parabola sections and two circle envelopes, and has an acceptance angle of θ= 15°.

The starting point for the design, and for the drawing of the circle envelopes, was the absorber diameter, in our case the external diameter of a borosilicate tube (47 mm). Then, with the value of the radius of the base circle, R = 2.35 cm, its envelopes were plotted, taking into account the parametric equations (3) that model the pairs (x,y).

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$$x(\propto) = R(\cos \propto + \propto sen \propto)$$

$$y(\propto) = R(sen \propto - \propto cos \propto) \quad (3)$$

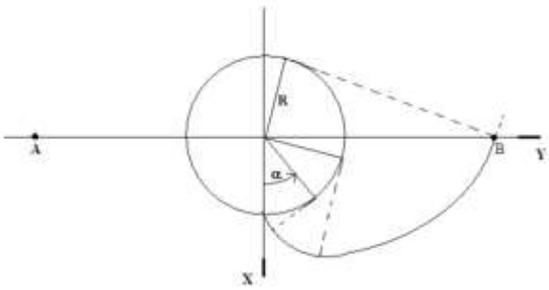

Figure 2 Truncated circle envelope at the height of horizontal diameter

The points A and B form a segment of length L, its practical value is obtained with the condition x = 0 in equation (3), thus obtaining the transcendental equation α = -cotg α. Finding an approximate solution of α (in this case α = 0.89π), and replacing its value in y(α) of eq.(3) gives the location of point B. The other branch is symmetrical, so the length of segment L is obtained, which in our case was 13.95cm.

2.3 Absorber tube

An evacuated borosilicate glass tube with an external diameter of 47 mm was used as absorber element, the length of the tube is 0.53 m. The tube has a double wall forming a double-walled absorber. It has a double wall forming a vacuum chamber, which gives it the fundamental quality of reducing the conductive and convective losses to the outside as much as possible. The tube has an absorber multilayer Cu / AlN (copper / aluminium nitride) structure deposited on the outer face of the inner glass, its average solar absorbance is α ≥ 94.5%, and its thermal emittance ε ≤ 5.5%. Figure 3 shows a schematic cross section of the absorber tube.

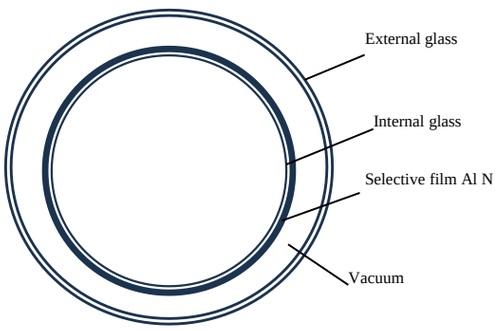

Figure 3 Cut of the absorber tube
Source: (Ialla N. D., 2011)

3. Description of the cooker

Once the curve has been obtained as indicated in fig 2, it is traced on white acrylic, three sections are cut out for the left side and three sections for the right side, which are joined at the base with 3/8 inch threaded rod with nut and pressure washer, and with metal hinges in the central part, mirrors are placed on these pieces in rectangular strips to form the reflecting surface, The evacuated tubes are supported by a metal structure in the shape of letter A, one at the front and one at the back, on the sides of this structure are placed the red supports, which are attached to the sides of the structure by means of screws, washers and nuts, the supports were made in a 3D printer.

Figure 4 Evacuated tube duplex solar cooker
Source: Own Elaboration

Figure 5 Duplex evacuated tube solar cooker, showing solar concentration on a copper tuve
Source: Own Elaboration

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3.1 Tray

The food tray is made of food grade steel, half-moon shaped, with a layer of nylomaq that seals the evacuated glass tube, and a wooden handle.

Figure 6 Tray for placing food
Source: Own Elaboration.

Experimental measurements

During the testing of the solar cooker, different food recipes were developed, as listed below:

a) Eggs with sausages

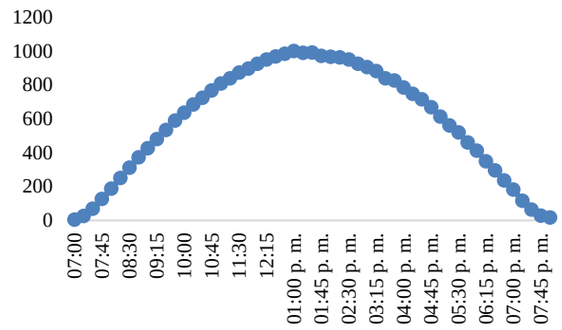
On 14 June this year, eggs with sausages were prepared in the solar cooker, the ingredients and how to prepare them are as follows.

No.	Quantity	Unit	Description
1	2	Pza	Hen's egg (Bachoco®)
2	2	Pza	Sausages with turkey (Swan®)
3	1	Pza	Iodised salt (La fina®)
4	100	ml	Sunflower oil (Girasol®)

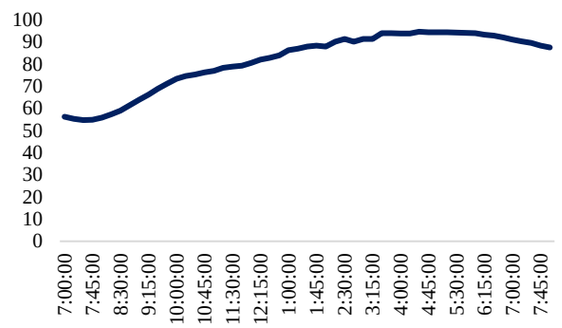
Table 1 Ingredients for making sausage and eggs
Source: Own Elaboration

How to prepare

Cut the sausages into slices, approximately one centimetre long, place a teaspoon of oil inside the pan, beat the eggs on a plate, add the sausages, cook for about 25 minutes, serve and serve as desired.



Graph 1 Irradiance for 14 June 2023, vertical axis Watts/m^2, horizontal axis, time of day
Source:
https://www.wunderground.com/dashboard/pws/IQUERETA29/graph/2023-06-14/2023-06-14/daily



Graph 2 Ambient temperature for 14 June 2023, vertical axis °C, horizontal axis, time of day
Source:
https://www.wunderground.com/dashboard/pws/IQUERETA29/graph/2023-06-14/2023-06-14/daily

Figure 7 Eggs with sausages
Source: Own Elaboration

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b) Mexican steak

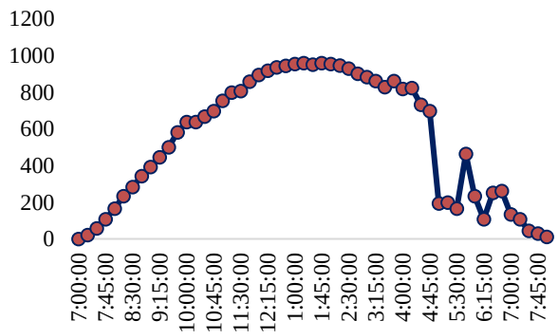
On 21 June this year, Mexican-style steak was prepared, the ingredients and how to prepare it are as follows.

No.	Quantity	Unit	Description
1	1	Pza	Serrano chili
2	2	Pza	Jitomáte
3	1	Pza	White onion
4	3	Pza	Tenmillo steak
5	100	ml	Sunflower oil (Girasol®)
6	10	Gramos	Iodised salt (La fina®)

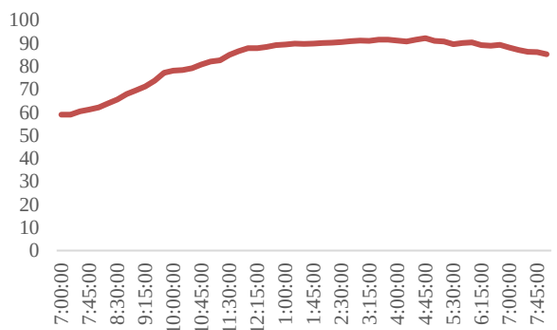
Table 2 Ingredients for steak a la mexicana
Source: Own Elaboration

How to prepare

Chop onion, tomato and serrano chili, cut the steak into fajitas, place a teaspoon of oil in the pan, add onion and serrano chili, cook for about 10 minutes, add the tomato and cook for 5 minutes, add the steak fajitas, add salt to taste, serve and serve to taste.



Graph 3 Irradiance for 21 June 2023, vertical axis Watts/m^2, horizontal axis, time of day
Source:
https://www.wunderground.com/dashboard/pws/IQUERETA29/graph/2023-06-21/2023-06-21/daily



Graph 4 Ambient temperature on 21 June 2023, vertical axis: °F, horizontal axis, time of day
Source:
https://www.wunderground.com/dashboard/pws/IQUERETA29/graph/2023-06-21/2023-06-21/daily

Figure 8 Solar cooker with CPC solar concentrator on the left side and without CPC concentrator on the right side, with Mexican-style steak in both tubes
Source: Own Elaboration

Figure 9 Mexican-style steak and degustation by a student of group ES01SM21
Source: Own Elaboration

Time	Irradiance W/m^2	Temperature °C, with concentration	Temperature °C, no concentration
10h45	698	76.5	71.2
11h00	754	77.2	72.4
11h15	798	79.5	74.6
11h30	807	80.9	75.6
11h45	858	85	81.0
Average	783	79.82	74.96

Table 3 Comparison of temperatures inside the tray, during the preparation of the Mexican steak

Note: With concentration refers to the tube receiving the light beam from the CPC and without concentration refers to the tube being exposed to sunlight.

It is observed that the solar concentration increases the temperature by 6.56% with respect to the temperature reached inside the tray with the tube without solar concentration.

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Consequently, the cooking time is reduced from one hour to three quarters of an hour for the Mexican style steak.

c) Carrot pancake

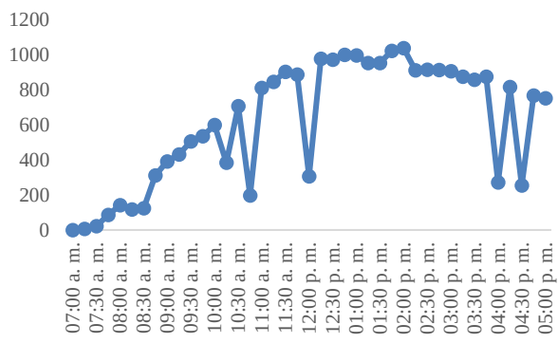
On 3 July of this year, carrot cake with walnuts was prepared, the ingredients and the way to prepare it are as follows.

No.	Quantity	Unit	Description
1	0.4	kg	Carrot
2	0.15	kg	Walnuts
3	0.1	kg	Wheat flour (Tres estrellas®)
4	0.1	kg	Brown sugar (Zulka®)
5	0.01	kg	Baking powder (Rexal®)
6	0.02	kg	Iodised salt (La fina®)

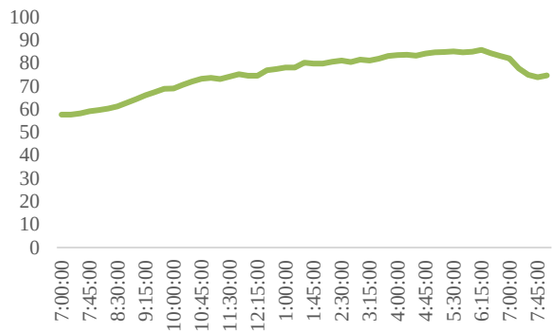
Tabla 4 Ingredients for preparing carrot and walnut cake

How to prepare

Beat the eggs with the sugar for a couple of minutes making sure they are well integrated, mix the dry ingredients, such as flour with the baking powder and a pinch of salt, join with the eggs and sugar previously beaten, until a homogeneous mass is obtained, peel the carrots, process until it is like a thick puree, chop the walnuts, mix all of the above, place on the baking tray and leave to bake for 20 to 30 minutes, process until a thick puree, chop the walnuts, mix all of the above, place on the baking sheet and bake for 20 to 30 minutes, test with a toothpick to ensure that it is not raw, once the toothpick does not stick residue, let it cool and serve and accompany it to taste.



Graph 5 Irradiance for 3 July 2023, vertical axis Watts/m^2, horizontal axis, time of day
Source: https://www.wunderground.com/dashboard/pws/IQUERETA29/table/2023-07-3/2023-07-3/daily



Graph 6 Ambient temperature on 21 June 2023, vertical axis: °F, horizontal axis, time of day. *Source: https://www.wunderground.com/dashboard/pws/IQUERETA29/table/2023-07-3/2023-07-3/daily*

Figure 10 Carrot cake with walnuts, baked in the evacuated tube duplex solar cooker
Source: Own Elaboration

Figure 11 Carrot cake with walnuts
Source: Own Elaboration

Time	Irradiance W/m^2	Temperature °C, with concentration	Temperature °C, no concentration
10h45	197	73.5	68.3
11h00	812	74.2	66.9
11h15	846	73.5	66.5
11h30	904	75.9	67.6
11h45	888	74	67.2
Average	729.4	74.22	67.3

Table 4 Comparison of temperatures inside the pan during the preparation of the carrot cake with walnuts

Note: Concentration refers to the tube receiving the light beam from the CPC and non-concentration refers to the tube being exposed to sunlight.

It is observed that the solar concentration increases the temperature by 10.28% compared to the temperature reached inside the mold with the tube without solar concentration.

Consequently, the baking time is reduced from one hour to three quarters of an hour for the carrot cake with walnuts.

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Conclusions

A proposal for a solar cooker with evacuated tubes has been presented, with the aim of reaching appropriate temperatures for cooking food. The temperature reached without food inside the trays is around 150°C, which allows a variety of foods to be prepared; boiling, baking or frying is possible.

The concentration of light on the evacuated tube allows the food to be ready 15 minutes earlier, compared to food that is prepared without the concentration of light on the evacuated tube. The students who tasted the food agree that the food tastes very good, and that they would be willing to buy a solar cooker like the one developed at the Research Unit of the Technological University of San Juan del Río.

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