African Journal of Agricultural Research Vol. 3 (7), pp. 477-485, July 2008
Available online at http://www.academicjournals.org/AJAR
ISSN 1991-637X © 2008 Academic Journals

*Full Length Research Paper*

# The design and proposal of a thermodynamic drying system for the dehydration of Rosell (*Hibiscus Sabdariffa*) and other agro-industrial products

**Meza-Jimenez J.[1], Ramirez-Ruiz J. J.[2]*, and Diaz-Nunez J. J.[3]**

[1]Instituto Tecnológico de Colima México, Avenida Tecnológico No. 1 Villa de Álvarez Colima, México.
[2]University of Colima, México, Avenida Gonzalo de Sandoval No. 444 Colima, Colima México.
[3]University of Ciudad Juarez Chihuahua. Hemry Dunant No. 4016. Ciudad Juarez, Chihuahua, Mexico.

Accepted 22 July, 2008

**The proposed solar thermodynamic drying system reduces the traditional dehydration process of Rosell used in the western region of Mexico, from approximately 4 days to 4 h. In addition to the 95% reduction in process time, this system also maintains the Jamaica's nutritional content, especially that of ascorbic acid (vitamin C). The proposed drying system is based on current operating conditions in Colima, Mexico as well as on three quantifiable control variables of Jamaica: product weight, product humidity, and product drying temperature. The product control variables were quantified and defined during the project as: Initial weight (1.0 kg of fresh product), final weight (0.152 kg of dry solid), initial humidity (84.8%), final humidity (14.3%) and dry temperature (48 to 68º C). Based on these control variables, the proposed system operates a continuously moving band at a constant speed. As the Roselle moves along the band through the system's drying chamber, it is dehydrated by heated air. Initially, the system uses solar energy to heat fluid (water or thermal oil). The heat generated is transferred from fluid to surrounding air via a forced convection process. By greatly diminishing drying time and controlling humidity, the system affords considerable control over optimal end-product quality (protection from pollutants and destructive microbial activity). The proposed system's settings can be easily adjusted to accommodate other products as well, making it even more commercially viable for agro-industrial producers. The drying process eliminates the water or humidity content of the calyxes yet maintains the nutritional properties specifically, the ascorbic acid content. A low cost and durability of the system is considered in the design.**

**Key words:** Low Cost Solar, Dehydration drying System, Roselle, Thermodynamics System, Agro-Products, Dehydration, Colima, Mexico.

## INTRODUCTION

Roselle (*Hibiscus sabdariffa*) is a tropical shrub found around the world with an approximate height of three meters (Figure 1). It is commercially harvested in several states in Mexico, most notably in Colima, Jalisco, Guerrero, Oaxaca, and Veracruz (Aristeo, 2000). As part of the plant's flower system, the calyx consists of the group of sepals which surround and protect the flower petals. This is what is usually harvested and processed, not the flower petals themselves (calyx which at times is simply referred to as Roselle). The dark red calyx is used in the production of teas and juices and also in the treatment of various physical ailments, such as those related to the kidney or stomach. Jamaica is also believed to help lower harmful levels of cholesterol and fatty acids found within the blood, and thus is used in the prevention of cardiovascular-related diseases (Mimeo, 1997). High levels of humidity make the Jamaican calyx more susceptible to decomposition and high levels of dryness reduce color and flavor (López Martinez and López de Alba, 1999).

Traditionally, Roselle calyxes are spread over open-area floors and dried naturally by the incidence of solar radiation Figure 2. At sundown, the calyxes are gathered up and stored and the process is repeated the next day.

*Corresponding author. E-mail: ramirez@ucol.mx.

**Figure 1.** Roselle with dark red calyxes (*Hibiscus sabdariffa*). Harvested in Colima, Mexico


**Figure 2.** Roselle calyxes being dried by traditional process.

This procedure takes an average of three to four days, depending on such conditions as ambient temperature and relative humidity. End-product quality is often adversely affected by open-air exposure to pollution and the like; lower quality output can in turn lead to lower economic profits for producers.

The drying process eliminates the water or humidity content of the calyxes yet maintains the nutritional properties specifically, the ascorbic acid content (Drying Food, University of Illinois, Circulate 1227). The dehydrated content of Roselle specific to the Coliman region is shown in Table 1. In dehydrated foods, due to minimal water activity, microorganisms cannot proliferate and most of the chemical reactions which alter a plant's chemistry are stopped (Martinez et al., 1991; Braverman, 1989). Thus, dehydration is a method used to preserve

**Table 1.** Dehydrated characteristics of Coliman Roselle per 100 g of calyx determined by biochemistry laboratory in Technological Institute of Colima.

| Characteristics | Content |
|---|---|
| Calories | 49.0 |
| Fat | 0.1 g |
| Carbohydrates | 12.3 g |
| Fiber | 2.3 g |
| Ash | 1.2 g |
| Calcium | 1.72 mg |
| Iron | 57.0 mg |
| Beta-Carotene | 300.0 µg |
| Ascorbic Acid | 14.0 mg |

foods for long periods of time. In this way, agricultural products such as Roselle can be sold year-round, in and out of season.

### The dehydration process

The dehydration process consists of eliminating water through evaporation and transferring it to the surrounding air, which can absorb humidity. When the surrounding air is completely void of water and there is 0% relative humidity, the potential for product dehydration is at its greatest. Conversely, when the surrounding air is completely saturated with water and there is 100% relative humidity, the potential for product dehydration is at its lowest. Because Colima's average relative humidity is about 70%, the amount of water that can be absorbed by the surrounding air is small and the traditional dehydration process of Jamaica can be rather slow (López Martinez and López de Alba, 1999). Such high levels of relative humidity can be artificially lowered by warming the surrounding air.

### Atmospheric pressure versus vacuum drying conditions

Generally, under atmospheric pressure, heat is introduced to the drying process by warmed air; the water that is extracted from the product is transferred to and eliminated by the same surrounding air. Additionally, water can be extracted via the use of vacuum drying systems; under low pressure (pressure less than atmospheric), heat is added by introducing radiation or heated metallic walls within the vacuum in order to eliminate product humidity. The proposed system utilizes controlled drying conditions under atmospheric pressure to achieve product dehydration.

### Batch versus continuous process drying

The process of dehydration can generally be classified into two categories: batch process drying and continuous process drying (Geankoplis, 1999). During batch process drying, only one batch of material can be processed per cycle. The amount of material that can be processed per cycle is limited to the size of the equipment with large inventories entailing more than one process run. During continuous process drying, material can be continuously introduced without interruption with large quantities of product being processed ceaselessly.

The proposed solar drying system uses continuous process drying which offers certain advantages over batch process drying. One of these advantages is that continuous process drying is not

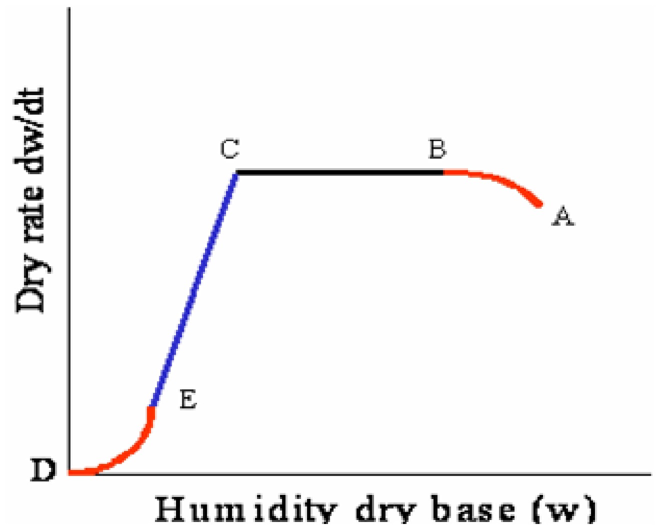


**Figure 3.** Theoretical speed of drying for products at periods of constant speed and decreasing speed with respect to product humidity.

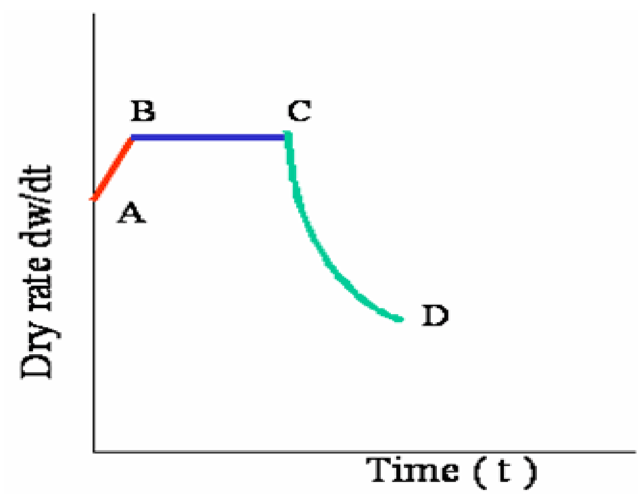


**Figure 4.** Theoretical speed of drying for products over time.

constrained to individual process runs potentially, all but one process cycle is needed to process any desired level of product. Another advantage to consider is that the method of heat transference used by continuous process drying offers better product dehydration results and end-product quality. With continuous process drying, the nature of the product and how efficient surrounding air is mixed with this product influences the level of drying. With respect to a product's nature, low to moderate temperatures used during the continuous dry process could favor the proliferation of fungi and bacteria because of the presence of product humidity. The presence of microbial activity can quickly lead to product decomposition. Thus, a level of drying which is not too low must be determined that avoids product decomposition (Food Science, 2000). On the other hand, utilizing temperatures that are too high may destroy a product's nutritional content (certain vitamins important to color and flavor may be lost). Therefore, an adequate level of drying which is not too high must be determined that prevents nutritional depletion.

**Parameters involved in the drying process**

To achieve an adequate drying process, Nonhebel and Moss (1979), defines as most significant the subsequent parameters:

a) Heat transference.
b) Drying atmosphere.
c) General physical properties of the solid-liquid system.
d) General physical properties of the solid.

Theoretically, heat transference can occur via convection, radiation, or conduction, but in practice, the predominant mechanism for heat transference used in the process of dehydration is convection (Nonhebel and Moss, 1979). Generally, forced convection is used in direct dryers in which material is dehydrated through direct contact with a flowing current of heated gas (or air, as is the case with the proposed process).

Thermal properties of agro-products are affected by variations in the transference of heat and mass. Though several researches have determined these thermal properties, few studies have led to the determination of parameters related to the transference of heat and mass, taking into account the gradient effect of humidity with respect to temperature and that of temperature with respect to migrating humidity (Irudayaraj et al., 1999 ;Ong, 1995; Palaniappa, 1993).

An important variable in this process is how product humidity reacts with the humidity of the air within the drying chamber. Whether through desorption or through absorption, this process of mass transference is meant to achieve a humidity balance between the product and drying atmosphere.

**Characterization of a theoretical drying process**

For the theoretical drying process that follows, chamber air transfers heat to the product while eliminating formed steam as well. If the heated air maintains a constant temperature and humidity, the theoretical speed of drying is observed to happen in two stages: The first for a period at constant speed and the second for a period at decreasing speed. Figure 3 illustrates the theoretical speed of drying with respect to decreasing product humidity, and Figure 4 shows the theoretical speed of drying over time. As explained by Geankoplis (1999), Figure 3 and 4 demonstrate the theoretical speed of drying under constant conditions. Beginning at time zero, the initial product humidity is at Point A. At this point, the product is usually at a temperature below that which it will be as the process continues and the speed of dehydration increases. Arriving at Point B, the surface temperature reaches its equilibrium value.

If the product is sufficiently hot at the beginning of the drying process, the speed of drying increases much faster over a shorter period of time. It remains constant between Points B and C. At Point C, the speed of drying begins to decrease until Point E is reached. Generally, the period of decreasing velocity between CE is linear in nature.

At Point E, the speed of drying diminishes at a much faster rate until arriving at Point D, where product humidity equilibrium arrives at zero. During the drying process of some products, area CE often does not exist or constitutes the totality of a product's period of decreasing velocity.

The following expressions relate to the constant and decreasing speed of product drying and include Fick's Law of Mass Transference.

Dehydration for a Period at Constant Speed is determined as:

$$\frac{dx}{d\theta} = \frac{h_c A(T_a - T_s)}{\Delta H_V} = A(X_s - X_a)Kg$$

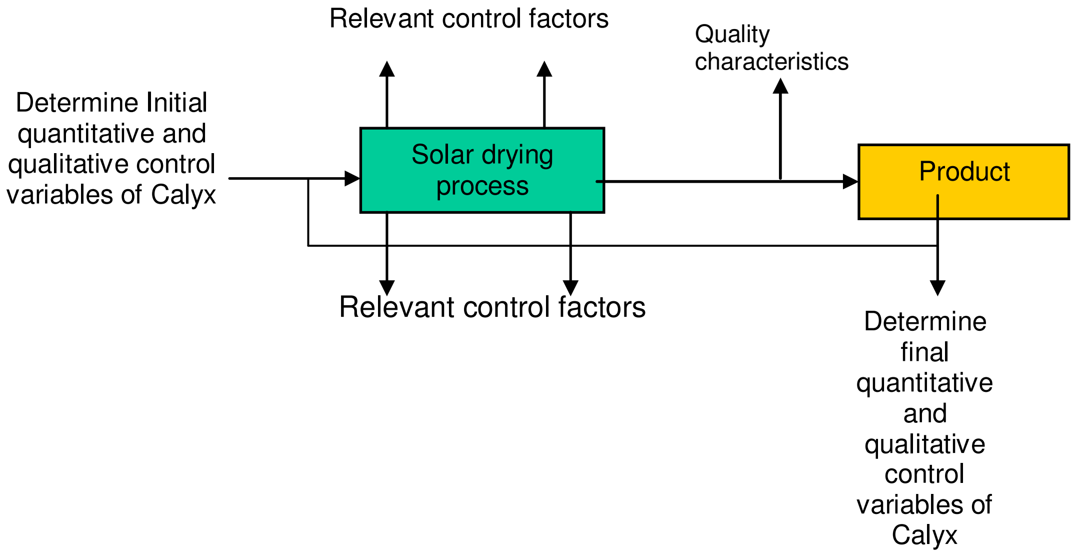


**Figure 5.** Procedure for Jamaican dehydration process using solar energy.

$$\frac{dx}{d\theta} = \frac{h_c(T_a - T_s)}{\rho_s d\Delta H_V} = \frac{Kg \ of \ Water}{Kg \ dry \ Solid}$$

Where, $\rho_s$= density of dry solid (Kg/m$^3$), d = Thickness of the bed (m)

Decreasing Speed Period as

$$\frac{X - X_e}{X_0 - X_e} = \frac{8}{\pi^2}\left[\sum_{n=0}^{n=\infty} \frac{1}{(2n+1)} e^{-(2n+1)^2 D_1 \theta (\pi/2d)^2}\right]$$

With $D_1$= Liquid Diffusivity (m$^2$/s), d = Thickness of the bed (m)

Dehydration for a Period at Decreasing Speed:

For $\beta$ >0.1

The series is truncated in the first term as:

$$\theta = \frac{4d^2}{\pi^2 D_1} \ln\left[\frac{8}{\pi^2} \frac{(X_0 - X_e)}{(X - X_e}\right]$$

$$-\frac{dx}{d\theta} = \left(\frac{\pi}{2}\right)^2 \frac{D_1}{d_2}(X - X_e)$$

Fick's Law of Mass Transference:

$J_A$=- $D_{AB}$ $\frac{dc_A}{dx}$ = *Flow; mol/Area x Time*

With
*$D_{AB}$= diffusivity of A in the A-B mixes; M$^2$/s*

*$C_A$ = Concentration of A; Mol/Volume*
*X = Distance; m*

**Design, analysis, and proposal of solar drying system**

Four stages were defined in the design and analysis of the proposed solar drying system (Figure 5):

1. Determine the basic properties of Roselle in order to establish various control variables.
2. Design and construct a solar dryer prototype based on the established control variables.
3. Analyze the test results obtained using the first prototype.
4. Design and propose a solar thermodynamic drying system based on the prototype analysis.

## Stage one – Establish control variables

The first stage included determining several control variables based on the basic properties of Jamaica. These control variables were categorized as either qualitative or quantitative:

• Qualitative Variables: color, flavor, texture, purity, homogeneity, and aroma
• Quantitative Variables: product weight, product humidity, product drying temperature, and ascorbic acid content

Initially, the variables for Jamaica were defined before any testing began. Next, 10 g of calyx was processed over thirty test runs in a thermobalance machine (Figure 6) to simulate the traditional drying process. Finally, the product variables were measured after testing. The initial and final results were as follows:

Qualitative Variables (determined through sensory observation):

Figure 6. Determining Roselle drying properties using Thermobalance.

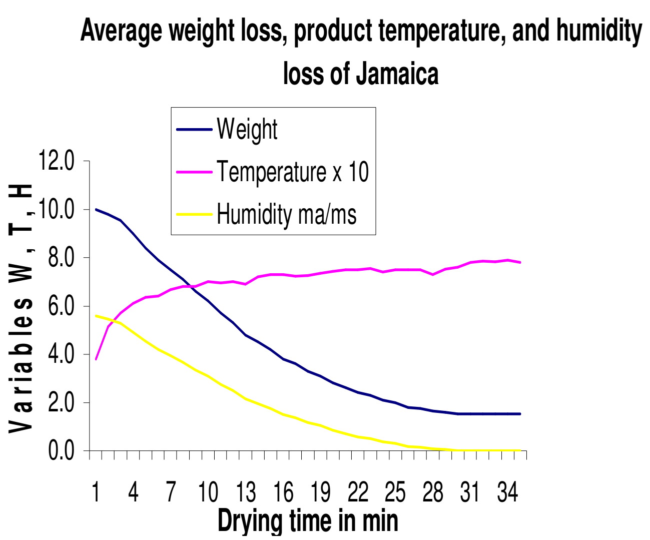


**Figure 7.** Average weight loss, product temperature, and humidity loss over time determined by Thermobalance.

- Color = Initial: dark red Final: deeper, darker red
- Flavor = Initial: acidic Final: unchanged
- Texture = Initial: moist & resilient Final: less moist & fragile
- Purity = Initial: some surface dust Final: some impurities from drying process
- Homogeneity = Homogeneous size after drying
- Aroma = Sweet smelling

Quantitative Variables (the three variables determined using thermobalance):

- Weight (Initial) = 1.0 kg of fresh product

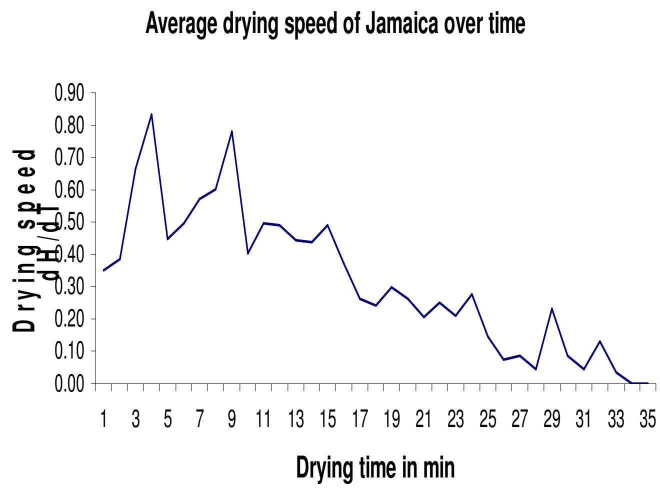


**Figure 8.** Determination of average drying speed of Roselle over time about thermobalance.

- Weight (Final) = 0.152 kg of dry solid
- Humidity (Initial) = 0.848 kg of water per 1.0 kg of fresh product
- Humidity (Final) = 0.143 kg of water per 0.152 kg of dry solid
- Drying Temperature = 48 to 68ºC

Figures 7 and 8 show the average drying properties of the thirty calyx samples tested. Figure 7 illustrates Jamaica's average weight loss over time (blue curve), average humidity loss (yellow curve), and average product temperature (pink curve). Figure 8 shows the average drying speed of Jamaica using the thermo-balance.

### Stage two – Design and construct prototype

After establishing weight, humidity, and drying temperature temperature affords better control in the preservation of Jamaica's basic properties during the dehydration process; managing air humidity enables better control over the speed of drying. The prototype was first constructed with a flat glass to obtain Jamaica's temperature and drying time profiles (Figure 9). Later, the prototype was modified with a pyramid-shaped glass cover (Figure 10) to improve the temperature performance of the prototype. The temperature profiles for the modified version were obtained in the same way as the flat glass model.

### Stage three – Analyze prototype results

The third stage included analyzing test results obtained using the original and modified prototypes. Figure 11a (original prototype) and Figure 11b (modified prototype) show the distribution of temperature during one complete

**Figure 9.** Prototype with flat glass cover.

**Figure 10.** Prototype with modified pyramid-shaped glass cover.

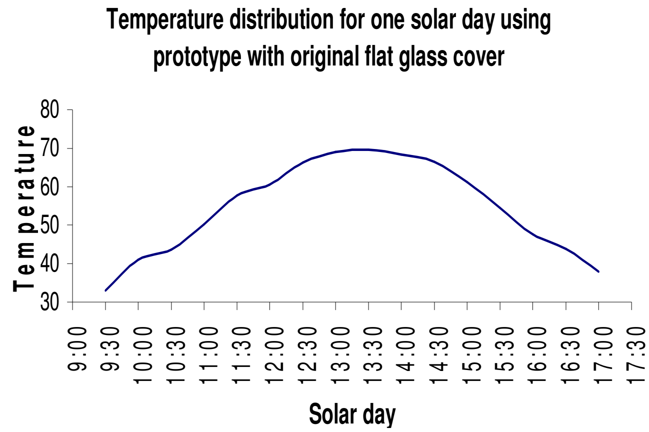


**Figure 11a.** Temperature distribution for one day of solar incidence using prototype with original flat glass cover.

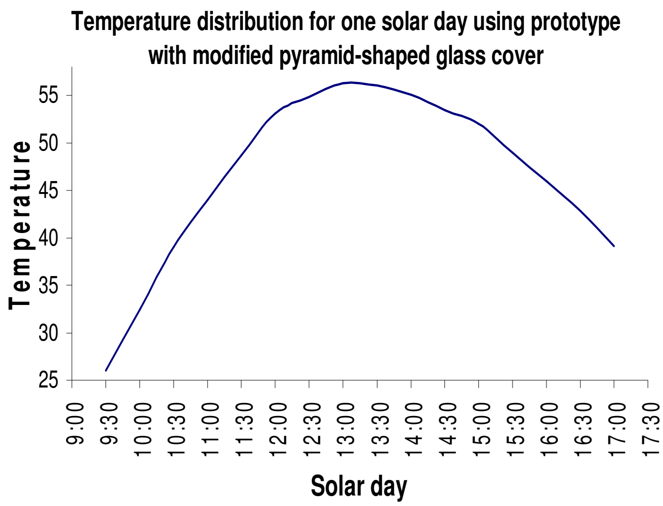


**Figure 11b.** Temperature distribution for one day of solar incidence using prototype with modified pyramid-shaped glass cover.

day of solar incidence from 9 am to 6 pm. Peak temperature times correlate with peak sun exposure, with the highest dryer temperatures being recorded between 1 and 3 pm.

Figures 12 and 13 illustrate the environmental conditions related to humidity (*H*) and dry bulb temperature ($T_{db}$). As the dry bulb temperature (or ambient air temperature) increases during the course of the day, air humidity diminishes and solar drying conditions are at their most favorable. This is to say, as air humidity decreases, there is less outside humidity available for product absorption and product humidification does not increase. On the contrary, the surrounding, unsaturated air actually absorbs the product humidity, furthering the dehydration of Jamaica.

Figures 14a and 14b demonstrate the drying kinetic process characteristics of Jamaica using ten grams of calyx over ten sample runs. Two different tests were conducted utilizing the original prototype: the first under a vacuum pressure of 60 mmHg (Figure 14a) and the second under atmospheric pressure using an air ventilaor as an extractor (Figure 14b). The vacuum pressure test exhibited a drying kinetic period at constant speed followed by a period of decreasing speed. The atmospheric pressure test only displayed a drying period at decreasing speed.

The kinetic drying speed of Jamaica was calculated using the following formula:

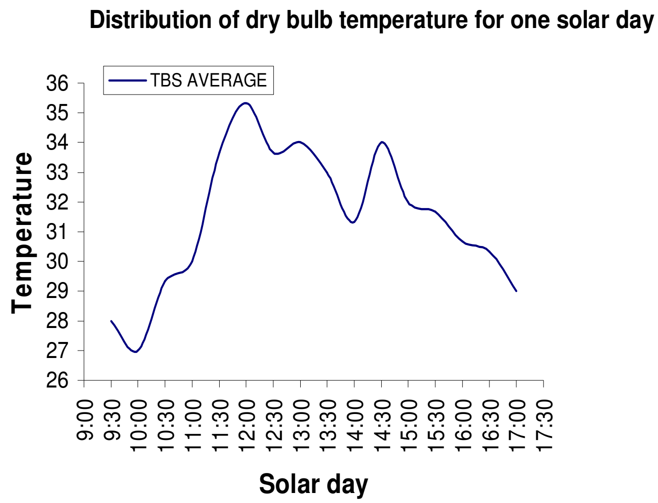


**Figure 12.** Distribution of dry bulb temperature for one day of solar incidence.

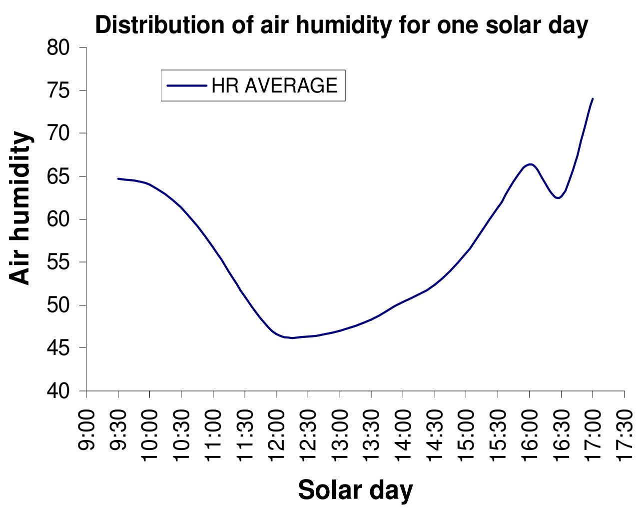


**Figure 13.** Distribution of air humidity for one day of solar incidence.

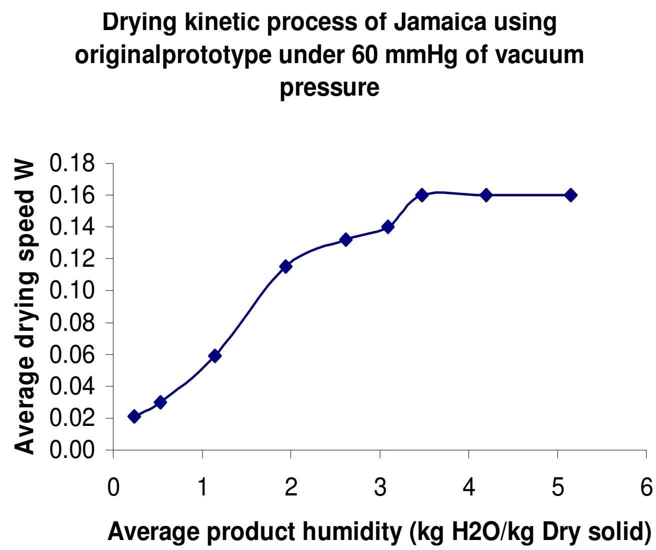


**Figure 14a.** Drying kinetic process results obtained of Jamaica under 60 mmHg of vacuum pressure.

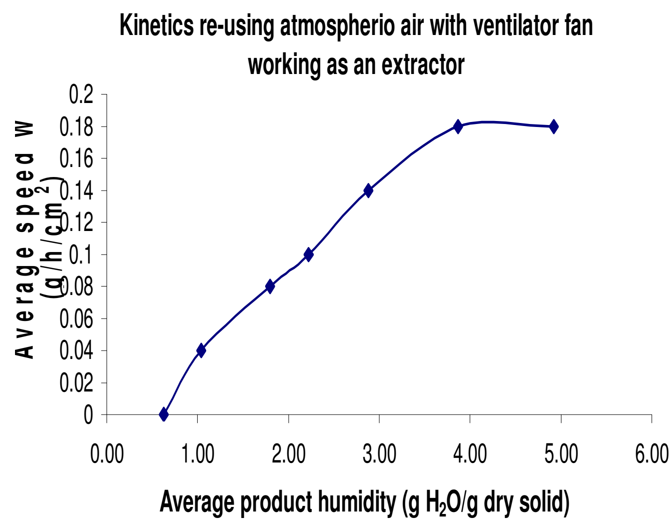


**Figure 14b.** Drying kinetic process results obtained of Jamaica under atmospheric pressure using air ventilator as an extractor.

*W = S/A (-dx/dt)*

With W = Kinetic drying speed, S = Weight of dry solid, A = Area of exposed surface.

## Stage four – Design and propose solar drying system

The fourth and final stage is proposing the design of an autonomous, low-cost and robust solar thermodynamic drying system for the dehydration of Jamaica and other agro-industrial products. This system is sponsored by the other products. The proposed design works under the subsequent requirements:

1. The mechanism needs solar energy to function.
2. Solar energy through forced convection warms the air used in the drying process.
3. The mechanism has to be intelligent enough to respond to the temperature and band-speed requirements during the drying process.
4. The drying system will serve as Fundación Produce Colima A. C., and it will be used to investigate the dehydration processes of Jamaica and he basis for the creation of other viable systems working with solar energy.
5. The mechanism must keep the product free of contaminants, unlike traditional drying methods.
6. The dehydration system must be economically feasible, allowing for the fast recovery of a purchaser's.

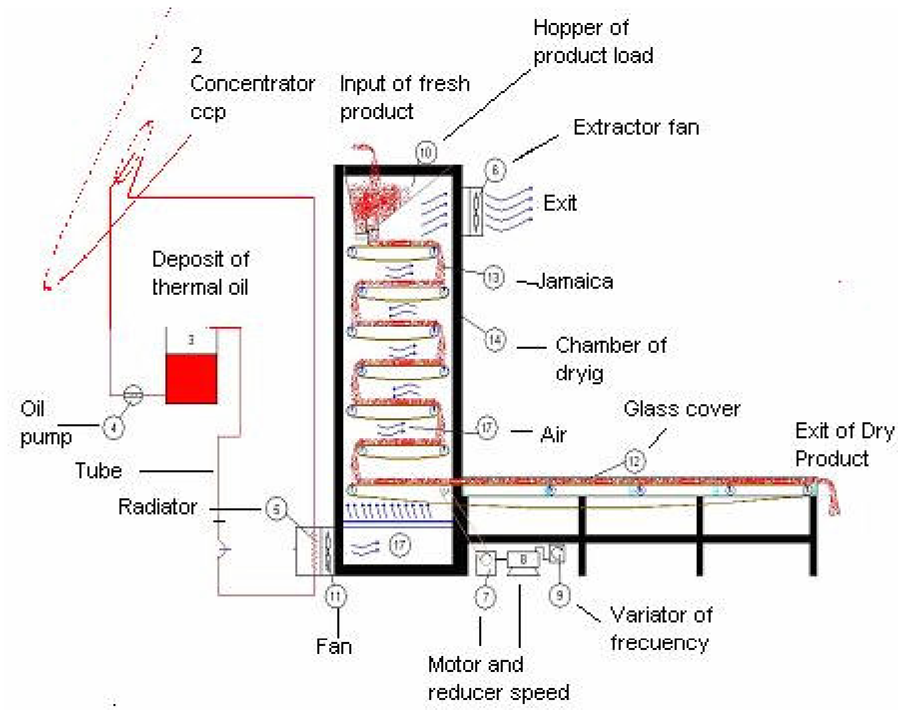


**Figure 15.** Proposed solar thermodynamic drying system for Jamaica and other products.

investment in the acquisition of the system.

## Description of proposed solar drying system

The proposed solar dryer consists of seventeen elements as seen in Figure 15. Surrounding air is introduced to a drying pre-chamber (17) via a ventilator (11). After being heated, the air rises cross-currently in the drying chamber (14) and dehydrates the product (13) as it moves along on transporting bands. The band speed is controlled by a frequency variator (9) which controls the speed of the engine motor (8). The motor is connected to the transmission by a speed reducer (7) which decreases the speed by a 30:1 relationship.

The system has a cylindrical parabolic solar energy collector (2) which warms fluid (i.e. water or thermal oil) fed to it by a pump (4) from a thermally isolated container (3). The heated fluid then passes through a tube (16) to a radiator (5), where the heat is transferred via forced convection to surrounding air introduced by a ventilator (11). The heated air, along with product humidity, is expelled from the drying chamber (14) to the environment by another ventilator (6).

The product is fed to the drying system via a stainless steel hopper (10) or funnel located at the top of the mechanism. After passing through the drying system and along the final band (12), the product is then collected in a glass-protected chamber (1), where its final humidity is measured for quality assurance purposes by a humidity sensor. The product is then ready for packaging and shipment.

## Conclusion

The proposed solar drying system for Jamaica was designed to decrease product dehydration time substantially and diminish pollutants acquired during the traditional drying process. System versatility allows for the adjustment of various process factors such as temperature and humidity. The product control variables were quantified and defined as: Initial weight (1.0 kg of fresh product), final weight (0.152 kg of dry solid), initial humidity (84.8%), final humidity (14.3%) and dry temperature (48 to 68º C).

Based on these control variables, the proposed system operates a continuously moving band at a constant speed. This process flexibility makes it possible for the system to be used with other agro-industrial products and affords better control over end-product quality by maintaining material content. Because the system uses solar energy (designed for this system), it is not dependent on electricity or other costly forms of energy, providing further adaptability in the workplace. The manufacturing cost of the proposed system would be lower compared to most non-solar dehydration systems found on the market. The solar thermodynamic system provides several benefits over traditional and alternative drying methods. This system provides environmentally advantages to agro-producers from Colima, Mexico and around the world.

**REFERENCES**

Aristeo Barrios (2000). Jamaica Asociada con Maíz, Alternativa Para la Costa del Pacifico Sur; 500 Tecnologías Llave en Mano INIFAP-Produce; pp. 261-263.

Geankoplis CJ (1999). Proceso de Transporte y Operaciones Unitarias, 3[a] Edición de CECSA, Cap. 9, pp. 579-649.

Drying Food University of Illinois at Urbana 1227: Champaign College of Agriculture, Cooperative, Extension Service Circular

Food Science (2000). FOSC 305 Lectures and Notes, Spring Semester

Irudayaraj J, Wu Y (1999). Heat and Mass Transfer Coefficients in Drying of Starch-Based Food Systems; Engineering/Processing; Journal of Food Science; March/April; Vol. 64; No. 2; pp. 323-327.

López Martínez, López de Alba (1999). XXIII Semana Nacional ANES;; Memoria p. 615.

López Martínez, Salunke DK (1999). Control de calidad de frutos deshidratados con energía solar; XXIII Semana Nacional ANES;; Memoria. pp. 615-618.

Mimeo Aquino Díaz Yolanda (1997). Efecto Protector de la *Hibiscus sabdariffa* en Hiperlipidemias; Instituto Politécnico Nacional; Escuela Nacional de Ciencias Biológicas; Sistema de Investigadores Benito Juárez; CONACYT; Edición 200; septiembre Salunke D.K., Bolin H.R., y Reddy N.R., Storage, Processing and Nutritional Quality of fruit and Vegetables; 2a.,ed.,

Nonhebel G, Moss AAH (1979). El Secado de Sólidos en la Industria Química; Edición Reverte S. A. España; Cap. 2;

Ong, KS (1995). Thermal performance of solar air heater: Matehematical model and solution procedure. Solar Energy, 55 (2): 93-109.

Palaniappa (1993). Solar heating for tea processing: Case study, energy perspectives in plantation industry. In: Proceedings of the first Int. Workshop, Connor, India from February 10-12; Madurai, India: Planters Energy Network and M.K: University; pp. 134-144.