CHEMICAL ENGINEERING TRANSACTIONS
VOL. 57, 2017

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Sauro Pierucci, Jiří Jaromír Klemeš, Laura Piazza, Serafim Bakalis

ISBN 978-88-95608- 48-8; **ISSN** 2283-9216

DOI: 10.3303/CET1757040

Design of an Apparatus for Solar Drying of Farm Products

Gustavo Sanmartin[a], Jordy Buj[a], Jose Marin[a], Luis Cortes[b], Luis Bossa[b], Juliana Puello*[a]

[a]Chemical Engineering Department, Universidad de San Buenaventura, Cartagena, Colombia
[b]Environmental Engineering Department, Fundación Universitaria Tecnológico Comfenalco, Cartagena, Colombia
jpuello@usbctg.edu.co; julianapuello@hotmail.com

A large part of crops is discarded due to their high production volume, and the small local market covered. Besides, commercialization of some crops is seasonal. Crops with a high content of water are perishable in a short time, so it is necessary to implement technological alternatives in order to preserve these products. One way to make better use of crops with high water content is by getting dehydrated products. The conversion of solar radiation into thermal energy for dehydration of crops is a widely known practice in agroindustry. Tropical regions receiving high solar radiation intensity are appropriate for the dehydration of crops in solar dryers. This process has proven effective for the upgrading of farm crops, and diversification of final products that may be destined for local and international market.
The present work is developed as a response to the priority needs for small local farm crops that are not financially supported by government royalties, in a tropical country located in South America. The solar dehydrator described here is a modular unit to be used in non electrically interconnected zones (NIZ), and built with local materials, that makes use of convective heat to remove the moisture of previously sliced farm products. This way, this study covers the development of a simple agroindustrial process focused on the upgrading of crops, the broadening of marketing alternatives and the use of renewable energy sources. Two crops are considered as case studies for the solar dehydration: mangoes and tomatoes. Data required for the design calculations (density, moisture, solar radiation, temperature and humidity of air) were obtained experimentally, and from databases developed by governmental institutions. Microbiological analysis (total coliforms, fecal coliforms, enumeration of aerobic mesophilic microorganisms, molds and yeasts) were carried on samples before and after dehydration tests, to evaluate the adequacy of the dried products for human consumption. The results show that the solar dehydration is a feasible approach for preserving crops with a high content of water, in the region considered for this study; however, some crops require to be pre-treated before drying, due to the tendency of bacteria growth during or after the process.

1. Introduction

Tomatoes are vegetables highly demanded by consumers, who use them as ingredients in soups, salads and as a condiment. Tomatoes, and especially the *Lycopersicon esculentum Mill.* variety have become one of the main items that are consumed fresh. They are also used in industry for processing, which has increased the demand of this product. Tomatoes are grown for commercialization, either as fresh fruit or to produce ketchup sauce, pasta, canned tomatoes and more recently, in the form of dehydrated product. On the other hand, mango is a fruit that grows in the intertropical zone, that has a fleshy pulp with threads. The worldwide area destined to the cultivation of mangoes is growing each year because of its great capacity for root development in any type of soil (Zuluaga et al., 2010). Due to the high water content of tomatoes and mangoes (more than 90% in tomatoes and around 85% in mangoes), it makes very perishable products in a short term. This causes the need to seek technological alternatives to try to conserve the products over time. One of the methods of conservation that can be applied to crops, is the suppression of water, which is a dehydration process. One of the most important potential applications for drying food is by using solar energy, since losses of fruits and vegetables in developing countries are estimated to be 30-40% of production, and with solar dryers, this losses could be reduced drastically. Efforts are made to know the behavior of crops and to

Please cite this article as: Sanmartin G., Buj J., Marin-Batista J., Cortes Ocana L.G., Bossa L., Puello J.M., 2017, Design of an apparatus for solar drying of farm products, Chemical Engineering Transactions, 57, 235-240 DOI: 10.3303/CET1757040

propose technologies that allow the growers to obtain the highest production, and also to preserve the products, according to the quality standards of regional and international markets. This work pretends to illustrate the conceptual design of a simple apparatus for the drying of farm crops (specifically tomatoes and mangoes) in a direct solar dryer. The variables considered as a start point are the moisture content in the product, the desired final moisture, and the weather conditions (temperature of the air, humidity of the air, global horizontal radiation). The basic characteristics of the solar dryer are estimated and described, and microbiological analysis complement the information related to the drying process.

1.1 Solar drying of farm products

Drying or dehydration is a common technology in the agroindustry sector. It consists in removing a high percentage of the water content of the product. The evaporation of the water is done through a stream of hot air, which transfers the latent heat of evaporation to the product. This drying process is in order to minimize the internal biochemical activity and the action of microorganisms. This way, the product is preserved for longer times in storage. Dehydration also allows for lower transport, packaging and storage costs, as well as meeting the needs of dry ingredients for other products, and the development of new products (Reyes et al., 2015). The dehydration process is generally carried out by means of thermal drying, and technologies like drying with air, sun drying, vacuum drying, microwaves and freeze-drying offer a variety of choices for specific needs, related to the organoleptic properties of the dehydrated product (Hii et al., 2012). This work focuses on solar drying, due to the importance of the renewable energies for sustainable agroindustry activities. There is also a wide variety of devices for solar drying of crops. Solar dryers are broadly classified into direct, indirect and hybrid solar dryers, according to the working principle for collecting the solar energy and converting it to thermal energy. The water content after dehydration is related to the final product that is required, i.e., the final content water in grains and cereals is around 12%, while in fruits it is around 8-15%, and in nuts and seeds it is 3-5%. An efficient drying process is by heated air running in tunnel or cabinets where the product is put. This technology is recommended when a strict control of temperature, air velocity and distribution of the product is needed. In tomatoes and mangoes, a water content of 10-15% is desirable, since these values are associated to low water activity. In dehydrated tomatoes, a 15% of water content is associated to 0.80-0.95 water activity, and dehydrated mangoes with a 10-15% water content is associated to 0.45-0.60 water activity. At these levels, molds, yeasts and bacteria (i.e. *E. coli*) are inhibited. Mites and insects growth is also prevented. It has been reported that, after dehydration, the product keeps its quality up to 60 days, at temperatures of 7-20°C (Ronceros et al., 2008).

1.2 Evaluation of the potential of solar energy

The use of solar radiation as a resource, contributes to the development of areas that have no access to the transport and energy system in developing countries. To assess the potential of solar energy in a particular region, the horizontal global radiation is estimated. The horizontal global radiation is the sum of the direct and diffuse radiation components. The magnitude of this instantaneous radiation parameter is expressed in units of power per unit area (i.e. energy/time·area), and is measured in watts per square meter (W/m^2). The amounts of radiation, expressed in terms of irradiance are generally integrated over time, and the units are kWh/m^2/day (if the irradiance is integrated over one day), or kWh/m^2/year (if the irradiance is integrated over one year). Other commonly used units are MJ/m^2/day or MJ/m^2/year. In the Caribbean coast of South America, high radiation levels are reached (4.5-5.0 kWh/m^2/day in average, which is equivalent to 1640-1830 kWh/m^2/year). For this study, the local conditions at a north coast location in a Southamerican country were considered, and the data were consulted from the data bases of a governmental institution.

2. Experimental

The samples used in this study were mangoes (Tommy Atkins variety) and tomatoes (*Lycopersicon Esculentum Mill.*). The information gathered for this study consisted in measuring density, initial moisture and microbiological analysis (total coliforms, fecal coliforms, enumeration of aerobic mesophilic microorganisms, molds and yeasts). For the tomatoes sample, drying curves were obtained using a tray drying oven. For this measurement, 505 g of sliced tomatoes were put in a tray drying oven (the area of the sample distributed in 4 trays being 310 cm^2). The drying process took 6 h 45 min to get 100 g of dried tomatoes (this corresponds to a final moisture of 13,74%). The temperature of the air at the entrance of the oven was 57±2°C, and the temperature at the exit was 55±2°C. This information was to compare the time needed for drying, using electric and solar energy.

Three experiments for mangoes and three experiments for tomatoes in a direct solar dryer were done, where the change of the air temperature inside of the dryer was registered during the experiment. Initial and final mass for each sample were determined, in order to estimate the mass loss. For each experiment, microbiological tests were done in each final (dried) sample, to compare with the initial results. Microbiological analysis made it possible to evaluate whether dry products are fit for human consumption.

3. Results and Discussion

The moisture content of ripe mangoes and tomatoes was determined by drying samples in an oven, at 117°C. The density and moisture content of mangoes and tomatoes (with standard deviation SD) are in Table 1. Table 2 shows the basic description for each experiment (time spent for the solar-drying experiment, temperature and mass loss). The mass loss is considered as evaporated water.

Table 1: Moisture content (MC) of tomatoes and mangoes before dehydration in oven

	MC (%)	SD	Density (g/cm^3)	SD
Mangoes	87.11	0.34	0.9999	0.02
Tomatoes	93.95	0.16	0.9885	0.15

Table 2: Basic description of sun-drying experiments (direct solar dryer)

	Mangoes			Tomatoes		
Experiment	1	2	3	1	2	3
Date	Mar 2/2016	Mar 3/2016	Mar 11/2016	Feb 17/2016	Feb 19/2016	Mar 9/2016
Time (hr)	4	2.25	4	4	2.5	2.5
Average temperature (°C)	56.4	48.9	52	53	52.9	54.1
Min. temperature (°C)	32	31.1	31.1	30.6	34.2	38.1
Max. temperature (°C)	66.5	55.3	59.1	60.7	64.3	57.5
Mass loss	73.5	72.7	73.4	94.7	93.5	86.6

Comparing the time for solar drying with the results of drying curves, it is observed that the solar drying took a shorter time, even though the average temperatures of the air were lower. This suggests that the solar radiation allows for a more efficient drying, without the need of electricity. When evaluating a process involving foods, it is strongly recommended to consider the presence of microorganisms (bacteria, fungi) and how the process could allow their growth and affect the overall quality of the finished product (Marchi et al., 2015). Usually, studies on solar drying of farm products report changes in physicochemical and organoleptic properties like moisture content, water activity, pH, texture, color (Adiletta et al., 2015). This study intends to provide complementary information, specifically related to microbiological analysis, in order to evaluate if the sun-dried products can be consumed without risk of intoxication. Table 3 shows the results for microbiological analysis in mangoes and tomatoes before and after solar drying. It also shows the limit values, according to regional standards.

Table 3: Microbiological analysis of mangoes and tomatoes before and after each sun-drying experiment

		Total coliforms (NMP/g)	Fecal coliforms (NMP/g)	Aerobic mesophilic (UFC/g)	Molds and yeasts (UFC/g)
Mangoes	Before sun-drying	<3	<3	2500	140
	Experiment 1	43	<3	100	100
	Experiment 2	3.6	<3	50	40
	Experiment 3	9.1	<3	530	120
Tomatoes	Before sun-drying	43	9.1	1199	240
	Experiment 1	<3	<3	180	140
	Experiment 2	<3	<3	7900	120
	Experiment 3	<3	<3	10	10
Limit values	--	<3	<3	10000	100-300

It is observed that in the dried samples of mangoes, a high increase in total coliforms was observed, even though the fecal coliforms kept their initial value (which is in the accepted range) after drying. The result for total coliforms makes dried mangoes not fit for human consumption, and also suggests that mangoes need a pretreatment before solar drying (i.e. blanching) in order to inhibit the bacteria growth during the drying process. On the other hand, aerobic mesophilic, molds and yeasts enumeration showed a decrease after solar drying. In the case of tomatoes, comparing the microbiological results of fresh and dried samples, it is observed that fresh tomatoes are not fit for human consumption, due to the presence of coliforms, which overpasses the limits stablished in a regional standard. However, after drying, there is a decrease in total coliforms, fecal coliforms, aerobic mesophilic, molds and yeasts, to values that meet the requirements stablished in the specification. Only one of the experiments (experiment 2) showed a higher value in the aerobic mesophilic enumeration (7900 UFC/g), compared to the result for the fresh sample (1199 UFC/g), but the result is still in the range accepted for human consumption. In general, the results show that dried tomatoes are fit for human consumption with no need of a pretreatment before the solar drying process.

3.3 Design of solar dryer (study case for tomatoes)

As a study case, fresh tomatoes are considered as the sample to be dried. The equations for sizing the solar dryer are based on an initial mass (m_i) of 3.56 kg of fresh tomatoes with a moisture content (M_i) of 95% that will be dried up to a final moisture (M_f) of 15%. Table 4 shows the variables related to the drying process. The weather conditions used for this case study are those of a town in the northern Caribbean region of a country located in South America (latitude 10,1397°, longitude -75,2271°), where the annual average daily global horizontal radiation is 4-5 kWh/m^2/day, the mean temperature is 31°C and the mean relative humidity in air is 75-80%.

Table 4: Conditions related to the solar drying process

Parameter	Abbreviation/symbol	Value	Comments
Air temperature at the entrance	T_i	31°C	
Final air temperature	T_c	57°C	
Relative Air humidity at the entrance	Rh_i	80%	From psychrometric chart
Air humidity at the exit	Rh_c	40%	From psychrometric chart
Radiation intensity	G	16.2 MJ/m^2/day	
Time	t	0.3 days (25920 s)	
Height of the dryer	H	0.38 m	
Atmospheric pressure	P	101325 Pa	
Particular constant for air	R_{air}	2.9 * 10^{-2} J/kg·K	
Latent heat of vaporization of water	L_w	2.7 MJ/kg	
Collector efficiency	η	85%	

Comparing the time needed for drying in the drying curves experiments, the solar drying experiments and the time set for calculations (0.3 days), the solar dry experiments take the shortest time, which means that the equations used in the calculations need to consider phenomena that promote a faster drying. The collector is one of the main parts of the solar dryer, because it is related to the capacity of the dryer. In this study, a direct solar dryer is considered, and the collector is an aluminum sheet coated in black paint. This way, the collector absorbs and reflects radiation, and helps increasing the temperature of the air inside of the dryer (Picon et al., 2013). Figure 1 shows a diagram of the direct solar dryer, suggested for this purpose. The suggested configuration responds to the need for an easy handling, cleaning and portability. This solar dryer can also be used for other agricultural products (vegetable, herbs, fruits), to provide a continuous use of the apparatus in different seasons. Other fruits that are common in the region are pineapples, papaya, guava and bananas. The drying temperature for each product has to be determined, due to their different composition and nutrients. In the dryer showed in the Figure 1, the sliced product is distributed over the trays, which are removable for an easy handling. The sun rays cross the glass cover and heat the air, the samples, and finally reach the collector, which reflects part of the thermal energy from the sun (as it is described above, the collector is an aluminum sheet coated in black paint). In the beginning of the process, a transient heating develops, until reaching a steady state temperature. The air enters the dryer through a grid located in the bottom (see Figure 1), and then it stablishes a convective flow through the dryer, and exits at the top, through a grid. Even at high relative humidity of air (i.e. 80%) it is possible to dry farm products. This is because the air increases its temperature inside of the dryer, and then its relative humidity decreases, making it capable for holding moisture.

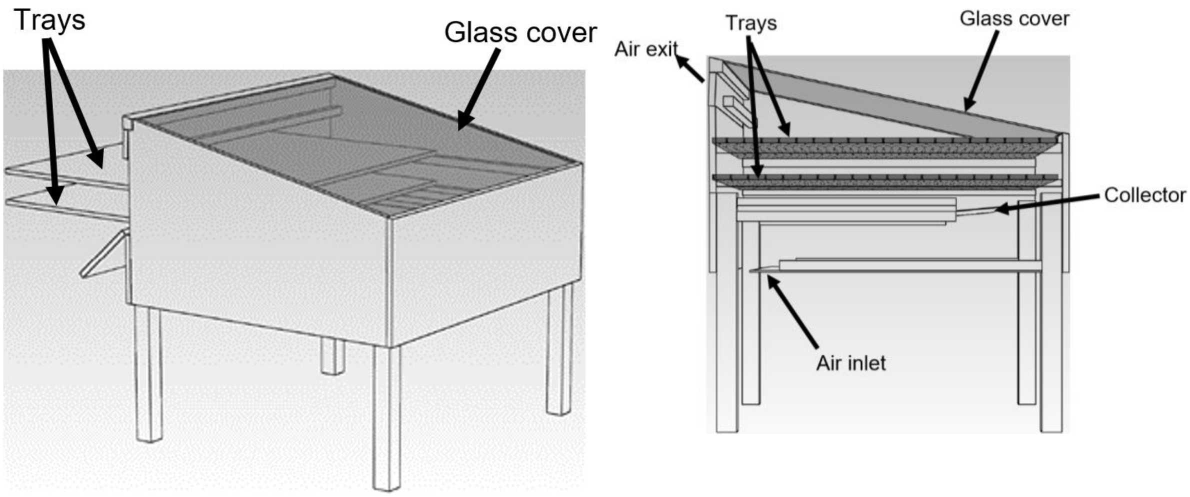

Figure 1: Schematic of the solar dryer.

However, if the air in the dryer reaches a high temperature (i.e. over 60°C), it can deteriorate the product and affect its nutritional value. To avoid this, the door located in the back of the dryer can be opened to allow a higher air flow, so the temperature inside of the dryer is kept at the desired level. A clean handling of the products before and after the process is crucial for the final quality and adequacy for human consumption. The calculations for the sizing of the collector were done according to the method described by Ayensu (1997), using the values from Table 4. The quantities calculated were: the evaporation heat required to dry the products (Q), the mass of water to be evaporated (m_w), the mass of air required to withdraw the water from the tomatoes (m_a), the mass flow of air through the dryer ($\dot{m}_a$), the change in density of air ($\Delta\rho$) and the pressure drop through the solar dryer (ΔP). The results for the calculations are summarized in Table 5, for solar drying of 3.56 kg of fresh tomatoes.

Table 5: Parameters calculated for solar drying of tomatoes

Parameter	Abbreviation/symbol	Result
Area of the collector	A	0.5033 m^2
Mass of water to be evaporated	m_w	3.35 kg
Required heat to dry 3.56 kg of tomatoes	Q	9.05 MJ
Total mass of air required to withdraw the moisture	m_a	146.8 kg
Mass flow of air during drying	$\dot{m}_a$	0.003 kg/s
Change in density of air	$\Delta\rho$	8.3×10^{-2} kg/m^2
Pressure drop through the solar dryer	ΔP	0.31 Pa

The change in the density of air ($\Delta\rho$) was calculated with Eq(1):

$$\Delta\rho = P\frac{T_i^{-1} - T_c^{-1}}{R_{air}} \quad (1)$$

The result of $\Delta\rho$ (Table 5), together with the pressure drop in the solar dryer indicates that an upward convective flow develops in the apparatus. The resulting area of the collector is 0.5033 m^2, which can be considered as an aluminum sheet 0.7622 m long and 0.6604 m wide. The panels to build the dryer are in a weather resistant wood (acacia, cedar, oak, ceiba). Instead of using glass for the cover, other alternatives are, depending upon availability, fiberglass-reinforced polyester, polycarbonate, acrylic or plastic films. The latter ones are not durable enough for solar dryer applications, but are widely used because of being inexpensive. Polyethylene is commonly found as a cover in solar dryers, but it is not durable and it falls apart more quickly than other plastic material, like polyester. Another important part in solar dryers are the screens (trays) where the food rests during the drying process. These must be made from a mesh that allows airflow. Polypropylene, fiberglass and stainless steel are recommended. Certain popular screen materials are not suitable for food applications due to their reactivity. Galvanized metal screens and wire mesh, for example, contain zinc and other metals that could oxidize and transfer themselves into the food. Aluminum screens may be suitable for many foods, but can react with acids in tomatoes.

3. Conclusions

Most of the calculations in this illustration were done for the solar drying process of tomatoes. The results can be applied to other crops with similar moisture content, and in other conditions, like ripe mangoes. Comparing the solar drying with the drying in oven (drying curves were described in the experimental section), it is observed that solar drying is more efficient, since it took less time than in the trey drying oven. After the solar drying experiments, the dried tomatoes showed to be adequate for human consumption, but dehydrated mangoes showed a high amount of total coliforms. To control the growth of microorganisms, especially in mangoes, an appropriate pre-treatment, like blanching (placing the product briefly in boiling water) is needed. Also, an analysis of the nutrients and their thermal behaviour must be considered, to estimate the temperatures where nutrients start thermal degradation. Additionally, organoleptic tests are needed to evaluate the taste quality of the dried products.

Regarding to the calculations, the experiment in the solar dryer still showed a shorter time than the estimated with the equations, so it is necessary to develop a model that describes in detail the transport phenomena involved in this process, and for this solar dryer configuration.

Finally, to provide a continuous use of this solar dryer, it is recommended to standardize this technology for the drying of other crops that are commonly found in the location, like papaya, guava and pineapples. This way, small farms can benefit from this simple process, by developing a new market for their products.

Acknowledgments

The authors would like to express their gratitude to the president of the Universidad Tecnologica del Sur UTESUR, Dr Virgilio Lopez for his contributions in the beginning of this study, and his kind invitation to implement these results in vulnerable communities in the southern regions at the Dominican Republic.

Reference

Adiletta G., Russo P., Proietti N., Capitani D., Mannina L., Crescitelli A., Di Matteo M., 2015, Characterization of Pears During Drying by Conventional Technique and Portable non Invasive NMR, Chemical Engineering Transactions, 44, 151-156, DOI: 10.3303/CET1544026

Ayensu A., 1997, Dehydration of Food Crops Using a Solar Dryer with Convective Heat Flow. Sol. Energy 59, 121-126.

Hii C.L., Jangam S.V., Ong S.P., Mujumdar A.S., Eds., 2012, Solar Drying: Fundamental, Applications and Innovations. Singapore, <http://www.arunmujumdar.com/file/Publications/books/Solar%20Drying_Fundamentals_Applications_and_Innovations.pdf > accessed 25.01.2017

Marchi L.B., Monteiro A.R., Mikcha J., Santos A., Chinelatto M., Marques D., Dacome A.S., Costa S.C., 2015, Evaluation of Antioxidant and Antimicrobial Capacity of Pomegranate Peel Extract (punica Granatuml.) Under Different Drying Temperatures, Chemical Engineering Transactions, 44, 121-126, DOI: 10.3303/CET1544021

Picón M.N., Martínez G.R., Fuentes A.L.S., 2013, Thermo-hydraulic Design of Solar Collector Networks for Industrial Applications. Chemical Engineering Transactions, 35, 457-462, DOI: 10.3303/CET1335076

Reyes A., Mahn A., Cares V., 2015, Analysis of Dried Onions in a Hybrid Solar Dryer, Freeze Dryer and Tunnel Dryer. Chemical Engineering Transactions, 43, 139-144, DOI: 10.3303/CET1543024

Ronceros B.A., Leiva J.I., Burgos E.D.C., Pardo L.D.C., 2008, Effect of the temperature and time of storage on the quality of dehydrated tomatoes, Inf. Tecnol. 19(5), 3-10 (in Spanish).

Zuluaga J.D., Cortes M., Rodríguez E., 2010, Evaluation of the characteristics of dehydrated mangoes by applying hot air drying and osmotic dehydration, Rev. Fac. Ing. UCV. 25(4), 127-135 (in Spanish).