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Analysis of Dried Onions in a Hybrid Solar Dryer, Freeze Dryer and Tunnel Dryer

Alejandro Reyes, Andrea Mahn, Verónica Cares

Department of Chemical Engineering, University of Santiago of Chile, Av. L. B. O'Higgins 3363, Santiago, Chile
alejandro.reyes@usach.cl

Onion (Allium cepa L.) belongs to the lily family, such as garlic and leeks. Dehydrated onion can be presented in powder, chunks, granules or slices. Its applications consider manufacturing of condiments, dehydrated or added to rehydrated meals.
We determined the drying curves of onion slices cut into 10 and 5 mm thickness, using a hybrid solar dryer, a tunnel dryer and a freeze-dryer. Drying kinetics adjusted adequately with a phenomenological model and with four empirical models. The best fit was obtained with Ademiluyi empirical model. Diffusivity values obtained from the constant diffusivity model fluctuated between 10^{-08} and 10^{-10} m^2/s. Finally, rehydration curves were determined and their adjustment to the simplified constant diffusivity model resulted in diffusivity values between 10^{-6} and 10^{-7} m^2/s.

1. Introduction

Drying of agro-products corresponds to the most widely used food preservation method, and its purpose is to remove moisture from the food matrix to prevent detriment of nutritional and organoleptic properties (Araya-Farias and Ratti, 2009). Owing to this there is permanent availability of seasonal agro-products, thus facilitating their storage and distribution. The convective drying is one of the most popular techniques due to reduced processing times (Doymaz, 2008, 2013). However, air heating requires large amounts of energy, with two disadvantages: the growing energy deficit and greenhouse effect. Meanwhile, the vacuum freeze-drying process corresponds to dehydration by sublimation which consists of three stages (initial freezing, primary drying or sublimation and desorption or secondary dehydration), with minimal damage to the product (Reyes et al, 2010). However it is a slow process with high economic costs (Ratti, 2001) (estimated at 4 - 6 times that of conventional tunnel drying), and then its use in industry is restricted only to high value-added products. In spite of this, the use of solar radiation as an energy source for pre-heating the drying air is a promising option, considering high energy efficiency (Reyes et al., 2013) and environmental care.
The Valencian onion (Allium cepa L.) is a lily bulb which consists of thick, fleshy layers which act as nutrient reserves, and is considered a long-lived onion, and it is one of the most important cultivars in Chile. The nutritional composition of onion varies according to the stage of maturity and variety, highlighting its high water content (close to 90 %) and the presence of important minerals such as potassium, calcium and selenium (Mota et al., 2010; El-Mesery and Mwithiga,2012; Hanif et al., 2013; Pramod et al., 2014).

2. Equipment, materials and methods

Drying kinetics curves were obtained in three dryers: hybrid solar dryer (HSD), tunnel dryer (TD) and freeze-dryer (FD). As shown Figure 1, HSD consisted of a 3 m length and 1 m width solar panel, composed by a glass sheet (5 mm thickness) and a black wavy zinc plate. The surface exposed to solar radiation was 10 m^2, including 40 zinc fins (3 cm height and 3 m length). Below this zinc plate it was placed a thermal insulating material (50 mm thickness). The air passes through the free space (50 mm height) between the glass and the zinc plate until reaching the mixing point with the recycled air. This air mixture enters the electric heating system composed by 5 kW electric resistances where the air temperature is adjusted to 60 °C. After that, the

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air enters the drying chamber (0.5 m*0.5m *1.2 m), where it distributes to pass over 10 perforated plate trays made of stainless steel (0.45m*0.5m), located in two sections of 5 trays each one. The solar energy accumulator, placed beside the solar panel, contained 14 kg of paraffin wax (PCM) distributed in 100 copper pipes (inner diameter of 14 mm) with aluminum fins in order to favor heat transfer to the drying air. The air is sucked through a 3 kW blower and directed to the electric resistances zone, although a 20 – 30 % fraction is removed from the system. The air flow rate through the trays was 0.4 ± 0.1 m/s. An advanced control system based on fuzzy logic permit to control the opening of solar panel valve and energy accumulator valve in function of solar radiation and ambient temperature(Reyes et al., 2014).

Figure 1: Hybrid solar dryer. A: Solar panel, B: Solar energy accumulator

The tunnel dryer, shown in Fig 2A, is a convective forced-circulation dryer, used with a superficial air velocity in the empty section of the dryer of 2 m/s, that possesses an air heating system composed by electrical resistances. Figure 2B shows the freeze-dryer (LABCONCO) with a 4.5 L capacity and condenser temperature of -50 °C, equipped with a vacuum pump.

Figure 2: A) Tunnel dryer; and B) Freeze-dryer

The initial moisture content of three onion samples was determined in a vacuum oven until constant weight was attained, according to AOAC 920.151. The initial mean moisture content was 89.12 ± 1.4%.The onions were peeled and cut into 5±0.1 or 10±0.1 mm sliced before dehydration in any of the three dryers.
The onion slices formed a single layer in each dryer. In the HSD and TD the temperature was set at 60 °C, and in the HSD the air recycling was set at 70 %. In FD the operating conditions were the maximum given by the equipment (0.080 [m bar] and -50 °C). Drying curves were determined by measuring the samples mass in time until reaching the final moisture content (about 2 %).
The rehydration rate was determined by immersing about 2 g of dehydrated onion samples in a water bath at 30 °C. Samples were withdrawn every 2 min, drained, wrapped in absorbent tissue, and weighed with an analytical balance. The moisture content was determined from the sample weight before and after rehydration. The assays were made in duplicate and average values were reported.

3. Results

3.1 Drying kinetics

Figures 3 and 4 shown drying kinetics for 5 and 10 [mm] onion slices. The drying curves exhibited a linear decrease of moisture content in the saturated surface period, until reaching the critical moisture content (about 0.45 ± 0.075). Then the moisture content diminished gradually until reach the final moisture content. The slowest process was freeze-drying, reaching the final moisture content in about 1200 min with no significant difference between the two thicknesses.

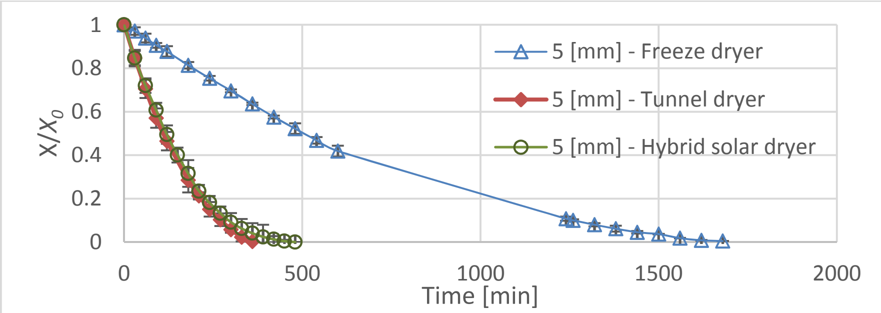

Figure 3: Drying curves for 5 mm onion slices.

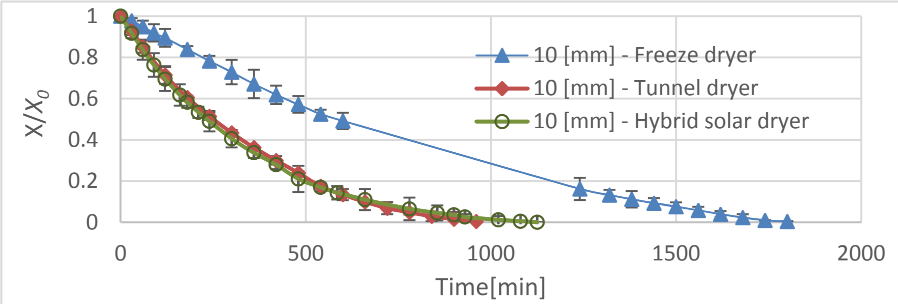

Figure 4: Drying curves for 10 mm onion slices.

Curves obtained in the tunnel dryer and in the hybrid solar were similar, although slightly higher drying times were observe in the HSD, probably because in this dryer we used air recycling, what means that the air enters with higher humidity, reducing the drying potential. In energy terms, there is less electric energy consumption in the HSD because the air is preheated in the solar panel and/or in the accumulator solar panel. The freeze dryer had the highest energy consumption, given the long drying times.

3.2 Adjustment of drying curves

The Fick's second law was integrated, considering that during drying, the air conditions and D_{eff} remain constant, and that shrinkage and external mass transfer resistance are negligible. Additionally, since equilibrium moisture content (X_{eq}) is low, it can be neglected. With these approximations, for an infinite slab of 2L thickness, the Constant Diffusivity Model (CDM) is expressed by Eq 1 (Crank, 1975).

$$MR = \frac{X_t - X^*}{X_0 - X^*} \cong \frac{X_t}{X_0} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\cdot exp\left(\frac{-(2n+1)^2\cdot\pi^2\cdot D_{eff}\cdot t}{4L^2}\right) \quad (1)$$

The adjustment to experimental data was evaluated through the correlation coefficient (R) and root mean squared error (RMSE). The diffusivity values, presented in Table 1, were lower for freeze-drying, and in all cases they were within the expected range for agro-products (10^{-8} – 10^{-11} [m^2/s]) (Revaskar et al., 2014).

Table 1: D_{eff} estimated by Eq(1)

Dryer	Thickness [mm]	$D_{eff}[m^2/s]$	RMSE*	R^2
Hybrid solar	5	$6.0283\cdot10^{-8}$	0.0894	0.9987
	10	$6.6824\cdot10^{-9}$	0.0794	0.9989
Tunnel	5	$6.4689\cdot10^{-8}$	0.0996	0.9988
	10	$6.7268\cdot10^{-9}$	0.0916	0.9997
Freeze	5	$1.3514\cdot10^{-8}$	0.0877	0.9998
	10	$3.1512\cdot10^{-9}$	0.0764	0.9997

* $RMSE = \sqrt{\frac{\sum_{j=1}^{n}(MR_{exp}-MR_{teo})^2}{n}}$

On the other hand, the drying kinetics of agro-products can be described also by empirical models (Bessadok, 2013; Revaskar et al., 2014), some of which are shown in Table 2

Table 2: Empirical models

Model	Equation	
Newton	$MR = Exp(-k \cdot t)$	(2)
Henderson-Pabis	$MR = a \cdot Exp(-k \cdot t)$	(3)
Page	$MR = Exp(-k \cdot t^n)$	(4)
Ademiluyi	$MR = a \cdot Exp(-(k \cdot t^n))$	(5)

In Table 3, the parameters of the empirical models are presented, which were adjusted through minimizing the mean squared error with respect to the experimental values, using the solver of Microsoft Office ®. The Ademiluyi model shown the best adjustment.

3.3 Rehydration curves

Figures 5 and 6 show the rehydration curves of dried onion slices (5mm and 10 mm thickness) at 30 ºC. In all cases it was observed a high rehydration rate during the first ten minutes, and after that an asymptotic increase happened during the next 50 min. From this point onwards the moisture content remained constant. The diffusion path through the dry pores of the onion slices allowed a fast re-absorption of water during the first 10 minutes of rehydration, but as the pores became filled, rehydration became slower.
The final water content after rehydration was higher for freeze-dried samples, because the particle does not shrink and its pores remain open. In tunnel and hybrid solar dryer, 5mm onion slices showed a higher rehydration level, attributed to a short diffusion water path, compared with 10 mm slices. This owes to a minor structural damage during the drying process (Melquíades et al., 2009). Besides, as in the case of the drying curves, rehydration curves were adjusted to the CDM (Equation 1), resulting in the values presented in Table 4. The values of effective diffusivity, were higher than those obtained in the drying process, because the structure of dehydrated onion is already damaged, facilitating water diffusion (Melquíades et al., 2009).

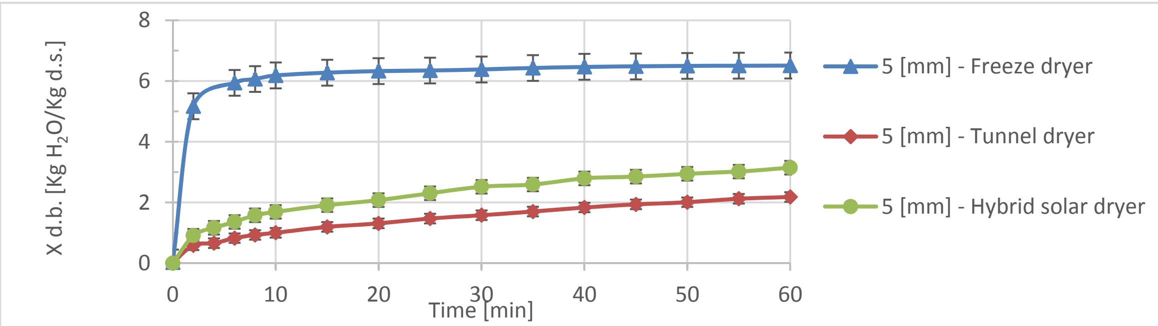

Figure 5: Rehydration curves for 5 mm onion slices.

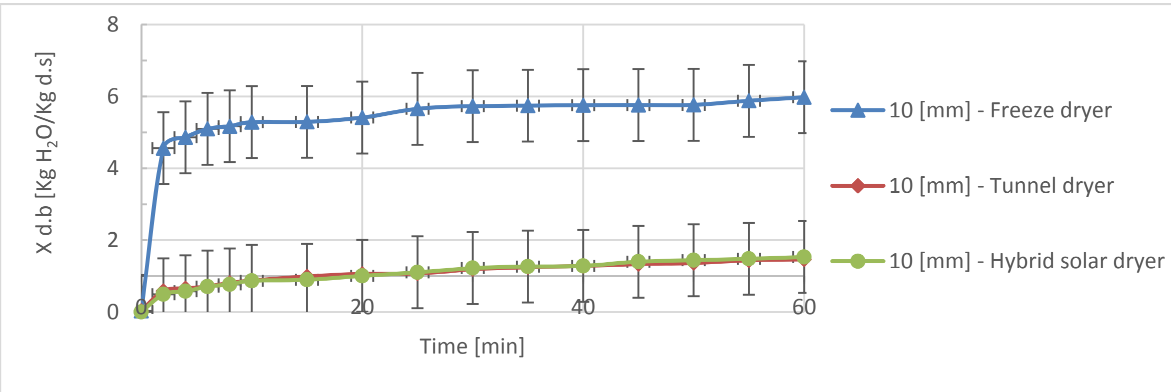

Figure 6: Rehydration curves for 10 mm onion slices.

Table 3: Parameters of empirical models.

Model	Thickness mm	Dryer	Parameters			RMSE	R^2
			k $(s^{-1})*10^4$	n	a		
Newton	5	Hybrid Solar	1.123			0.0397	0.996
		Tunnel	1.121			0.0456	0.995
		Freeze	0.258			0.0498	0.999
	10	Hybrid Solar	0.523			0.0181	0.999
		Tunnel	0.510			0.0323	0.997
		Freeze	0.233			0.0475	0.998
Henderson -Pabis	5	Hybrid Solar	1.178		1.05	0.0355	0.995
		Tunnel	1.270		1.05	0.0409	0.994
		Freeze	0.322		1.22	0.0277	0.995
	10	Hybrid Solar	0.537		1.02	0.0167	0.999
		Tunnel	0.527		1.03	0.0299	0.997
		Freeze	0.301		1.32	0.0238	0.995
Page	5	Hybrid Solar	0.285	1.26		0.0150	0.999
		Tunnel	0.300	1.27		0.0197	0.998
		Freeze	0.285	1.34		0.0122	0.999
	10	Hybrid Solar	0.320	1.08		0.0115	0.999
		Tunnel	0.183	1.17		0.0194	0.998
		Freeze	0.245	1.33		0.0158	0.998
Ademiluyi	5	Hybrid Solar	0.220	1.31	0.98	0.0136	0.999
		Tunnel	0.247	1.31	0.98	0.0189	0.999
		Freeze	0.153	1.49	0.92	0.0122	0.999
	10	Hybrid Solar	0.268	1.11	0.98	0.0108	0.999
		Tunnel	1.338	1.22	0.98	0.0181	0.999
		Freeze	0.245	1.64	0.85	0.0129	0.998

Table 4: Effective diffusivities in rehydration.

Dryer	Thickness [mm]	$\mathbf{D_{eff}}[\mathbf{m^2}/s]$	RMSE	$\mathbf{R^2}$
Hybrid solar	5	$5.3665\cdot10^{-7}$	0.0547	0.9808
	10	$1.3398\cdot10^{-7}$	0.0616	0.9730
Tunnel	5	$4.3852\cdot10^{-7}$	0.0540	0.9859
	10	$1.5880\cdot10^{-7}$	0.0688	0.9648
	5	$6.8012\cdot10^{-6}$	0.0574	0.9912
Freeze	10	$1.0760\cdot10^{-6}$	0.0824	0.9611

4. Conclusions

Drying curves showed similar shape in both hybrid solar dryer and the tunnel dryer, with longer drying times for the 10 mm slices. Drying kinetics adjusted adequately to the Constant Diffusivity Model and Ademiluyi's empirical model. Freeze-drying times were considerably longer, although resulting in better quality products. The final moisture content after rehydration was higher for freeze-dried samples. In tunnel and hybrid solar dryer, 5mm onion slices showed a higher rehydration due to a shorter diffusion water path, compared with 10 mm slices. The hybrid solar dryer seems promising because of its lower energy consumption.

Acknowledgements

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