Kinetics modeling of the drying of Opuntia ficus indica with solar energy


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Opuntia ficus indica, commonly known as nopal, is an endemic cactus plant of America. In this work the drying of nopal cladodes, using a solar dryer with natural convection was studied. The drying process was monitored daily from 9:00 to 18:00 hours, during the months of April, May, and June, 2007. The experiment took place with two kinds of nopal cladodes, one with thorns and one without 30 % of the cuticle that protects the cladodes on both sides. The nopal without thorns was dried in 46 hours in June, while in April it took 75 hours. For the complete product these drying times were 150 and 300 hours, respectively. The numerical model that best described the drying process was the double logarithm.

Keywords: Drying curve; solar energy modeling; Opuntia ficus indica.

In this work we studied the drying of nopal in natural convection, using a solar drier. We analyzed the influence of solar radiation, in the air temperature and mass flow to attain complete drying of the product [10]. Thus, alternative drying processes, such as those based on solar energy may represent important savings and effective profits, if these drying times can be cut off with the corresponding benefits in the product quality.

Several solar devices for food drying have been constructed and evaluated; for instance, a cabin type dryer has recently been used to dry vegetables such as zucchini, green pepper, beans and onion [11], at 46°C, using up to 90 effective sun hours for beans. Corn was also dried in a similar drier, requiring 75 hours of sun to dry 10 kg of product at 42°C [11]. The drying of pineapple has also been studied using a combined biomass-solar system [12]. Such device uses the alternate source of energy (biomass) to cover the night periods in order to have a continuous drying system. The product temperature was kept constant at 65°C, requiring 39 hours for total drying.

In this work we studied the drying of nopal in natural convection, using a solar drier. We analyzed the influence of solar radiation, in the air temperature and mass flow to attain the desired dryness of the product (98 %). Two types of nopal samples were studied: one with thorns and another...
without thorns, which was denuded of approximately 30% of the cuticle that protects both sides of the nopal.

2. Materials and methods

2.1. Equipment

The equipment used in this work is presented in Fig. 1. The chimney-type solar collector operated in natural convection. The capture surface was 3 m wide and 5 m long. The porous medium made from steel turnings scraps, was 0.20 m thick. The drying chamber dimensions were 0.60 m × 0.60 m × 1.00 m, with three trays for products, separated 0.15 m between them. Product samples were set in a 0.45 m × 0.45 cm tray crossed by hot air. It had a 0.005 m-thick crystal cover, separated 0.06 m from the porous media. The trapping surface inclination was 40° with respect to the horizontal plane and was oriented south-north to capture the maximum solar energy.

Air and product-surface temperatures within the drying chamber were measured using 3 calibrated K-type thermocouples with reading accuracy of ± 0.1°C, located at the entrance of the chamber and another 3, located at the exit. Relative humidity of the environment was determined using an EA25 EXTECH digital hygro-thermometer, with a reading accuracy of ± 0.1%, which was located outside the solar dryer. An AN200 EXTECH Thermo-anemometer, with a reading accuracy of ± 0.01 m/s, was used to measure the velocity of air, at the exit of the dryer’s chimney. The product mass was continuously quantified using a BL1505 SARTORIUS scale, with an accuracy of ± 0.01 g, which was located on top of the drying chamber.

The total solar radiation was measured with a 8-48 EP-PLEY pyranometer with a reading accuracy of ± 1 W/m², located on top of the solar collector and therefore, with the same inclination. All these variables were registered using the Lab-view software in 10 minutes intervals.

2.2. Experimental procedure

Nopal samples were acquired from the largest production region in Mexico, known as Milpa Alta. Nopal samples were tested in two fashions, one using the complete cladode and the other without thorns and 30% less of its protective cuticle. Both tests were done simultaneously and with identical thermal conditions. We selected those between 45 and 60 days old, which had an average mass of 180 g and had physical dimensions of 0.15 m-wide, 0.25 m-long and 0.016 m-thick. Three sets of two complete cladodes and two without thorns and 30% less cuticle samples (an approximate mass charge of 2.16 kg) were deposited in the drying trays of the chamber (Fig. 1).

The daily measuring period was from 9:00 to 18:00 hours. The following hours the solar collector was totally covered with a canvas to prevent nightly heat loss. During this period nopal was kept inside a sealed plastic bag within an isolated deposit to preserve its humidity. The following morning experimentation continued, taking care to maintain the same conditions as in the previous day.

2.3. Drying kinetics of nopal

In the drying process of vegetable products it is important to determine the model that describes such process, which is obtained from experimental data [13-19]. Several models that describe the moisture relationship ($MR$) of a product as a function of time have been developed. The moisture relationship ($MR$) is defined as,

$$MR = \frac{M - M_e}{M_0 - M_e}$$

where $M$ is the moisture content at time $t$, $M_0$ in the initial and $M_e$ is the equilibrium moisture content, whose value depends on the environmental relative humidity. This hygroscopic balance of *Opuntia* cladodes is presented by Lahsasni

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**Table I.** Mathematical models used to determine the moisture contents of agricultural products during drying processes.

<table>
<thead>
<tr>
<th>Model</th>
<th>Equation</th>
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<tbody>
<tr>
<td>Page [13]</td>
<td>$MR = \exp (-kt^n)$</td>
</tr>
<tr>
<td>Newton [14]</td>
<td>$MR = \exp (-kt)$</td>
</tr>
<tr>
<td>Modified Page [15]</td>
<td>$MR = \exp (-kt^n)$</td>
</tr>
<tr>
<td>Henderson [16]</td>
<td>$MR = a \exp (-kt)$</td>
</tr>
<tr>
<td>Logarithmic [17]</td>
<td>$MR = a \exp (-kt) + c$</td>
</tr>
<tr>
<td>Two terms [17]</td>
<td>$MR = a \exp (-K_0t) + b \exp (-K_1t)$</td>
</tr>
<tr>
<td>Verna [18]</td>
<td>$MR = a \exp (-Kt) + (1-a) \exp (-Kt)$</td>
</tr>
<tr>
<td>Wang and Singh [19]</td>
<td>$MR = I + at + bt^2$</td>
</tr>
</tbody>
</table>
et al., [20], and is useful to predict the contents of water in relative to the humidity present in air. They presented the sorption curves, necessary to determine the drying kinetics of the product, as well as the conditions of storage of the product. The most used numerical models are presented in Table I. The criteria used to select the most appropriate model was that the correlation coefficient $r$ tended to the unit and that the square chi ($\chi^2$) tended to zero. In these equations the values of constants vary for each product and each experimental condition.

3. Results and discussion

Solar collector was only used to warm up the air that was used in the drying chamber. The average solar radiation curve as a function of time registered for the month of May, 2007 and its representative equation are presented in Fig. 2. The maximum average radiation, 987.4 W/m$^2$ was observed approximately at 14:00 hours. The corresponding total energy over the collector surface was 6.40 kW/m$^2$ h. The maximal solar radiation, 1052.45 W/m$^2$ was registered in the month of June and the minimal radiation, 887.45 W/m$^2$, occurred in April. The energy over the collector values were 7.23 kW/m$^2$ h and 5.55 kW/m$^2$ h, respectively, these are relevant data, since they influence the observed temperature and the mass flow of air.

The average temperatures versus the time of the day are presented in Fig. 3. The highest temperature at the entrance of the drying chamber was 66.3°C; the temperature measured at the product was 63.5°C, and at the outlet of the chamber, 58.4°C. These values were registered at 14:00 hours and coincided with the value of highest solar radiation. The environmental temperature at the time was 26.8°C, which was also the highest value registered during the period of experimentation. The difference in temperature between the inlet and the outlet of the chamber was not constant through the day, early in the morning the difference was a minimum of 1.4°C. The highest gradient was registered around 15:00 hours, as
8.7°C. The temperature at the outlet of the chamber at the end of experimentation was 32.2°C.

The average mass flow of air registered at the drying chamber is presented in Fig. 4. The larger value of mass flow was 0.0312 kg/s and occurred in June, in May it was 0.0276 kg/s and in April it was only 0.0228 kg/s. All of these measures corresponded to a time close to 14:00 hours. This flow follows the drying chamber because of the convective draft chimney effect.

The results of the drying experiment of nopal without thorns, for which 30% of the cuticle was cut off as well, for April, May, and June 2007, are presented in Fig. 5. The graph shows the moisture content versus drying time. At the beginning of the process it was 19 kg water/kg of dry mass (d. m.) and at the end it was approximately 0.135 kg water/kg d. m. The drying time was directly dependent on the solar radiation captured on the cover of the drier. The longest drying time was registered for April as 75 hours and the shortest time was observed in June, as 46 hours. The time in May was 55 hours.

<table>
<thead>
<tr>
<th>Month</th>
<th>Nopal thorns</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>without</td>
<td>$MR=0.594\exp(-0.125t)+0.550\exp(-0.0.19t)$</td>
</tr>
<tr>
<td></td>
<td>with</td>
<td>$r = 0.998, \chi^2 = 0.00001$</td>
</tr>
<tr>
<td>May</td>
<td>without</td>
<td>$MR=0.521\exp(-0.016t)+0.521 \exp(-0.016t)$</td>
</tr>
<tr>
<td></td>
<td>with</td>
<td>$r = 0.996, \chi^2 = 0.00001$</td>
</tr>
<tr>
<td>June</td>
<td>without</td>
<td>$MR=0.364\exp(-0.172t)+0.793 \exp(-0.031t)$</td>
</tr>
<tr>
<td></td>
<td>with</td>
<td>$r = 0.995, \chi^2 = 0.00001$</td>
</tr>
<tr>
<td></td>
<td>without</td>
<td>$MR=0.515\exp(-0.018t)-0.515 \exp(-0.018t)$</td>
</tr>
<tr>
<td></td>
<td>with</td>
<td>$r = 0.997, \chi^2 = 0.00001$</td>
</tr>
</tbody>
</table>

For the complete product (Fig. 6) the drying times were considerably longer: 300 hours of sun drying in April, 225 hours in May, and 150 hours in June, which corresponded respectively to 300 %, 310 %, and 226 % longer than for the product with the cuticle removed. This was undoubtedly due to the protection exerted by the cuticle in the complete product. These results are direct consequence of the average solar radiation observed in the months evaluated. If its value is higher, so are the temperatures and flow mass.

It is relevant to notice that this technology results attractive for the drying of the product without thorns (46 to 75 hours) when comparing it to the open-air drying process that takes from 35 to 40 days [10]. However, the process is less effective and almost comparable to the open-air drying of the complete product.

Experimental data were fed to each of the numerical models presented in Table I. The double logarithmic model described the best performance of the drying process, in agreement with the two imposed criteria. The graph of the numeric model obtained for the month of May is presented in Fig. 7. The equations of the numerical model for the six experiments performed are presented in Table II, in all cases this model was the better result for the imposed conditions.

4. Conclusions

The hot air used in the drying of nopal was attained in a solar device packed with a porous medium to increment the storage of energy. The physical variables necessary to energetically evaluate the drying process were monitored daily from 9:00 to 18:00 hours, during the months of April, May, and June, 2007. The maximum air temperature at the inlet of the drying chamber was 69°C in June and 60°C in April. The nopal samples were studied in two fashions: complete and without 30 % of its protective cuticle and no thorns; this was rele-
vant to the results, because for the second type of sample the drying time diminished considerably.

The shortest drying times were observed in June, and the longest, in April, due to the intensity of the solar radiation falling over the surface of the collector. The nopal without thorns was dried in 46 hours in June, while in April it took 75 hours. For the complete product these drying times were 150 and 300 hours, respectively. The drying of the nopal without thorns (46 to 75 hours) can be competitively performed using this solar drying device, when comparing it to the open-air drying process that takes from 35 to 40 days. Nevertheless, for the complete product the process is less effective and almost comparable to the open-air drying method. The numerical model that best described the drying process with solar energy was the double logarithmical model. The criteria used to select the most appropriate model were that the correlation coefficient $r$ tended to the unit and that the square chi ($\chi^2$) tended to zero. These results could be used to design solar dryers to process largest amount of products.

**Nomenclature**

- $a, b, c, n$: dimensionless drying constants in drying models
- **d.m.**: dry mass
- $k$: drying velocity constant in drying models (1/h)
- $MR$: moisture rate, (kg water/kg dm)
- $M$: wet mass in time $t$, (kg water/kg dm)
- $M_e$: equilibrium mass, (kg water/kg dm)
- $M_0$: initial mass, (kg water/kg dm)
- $t$: time, (h)