DRYING KINETICS AND DETERMINATION OF THERMAL PROPERTIES OF OKARA

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Abstract. *Okara pellets with 75% of moisture content (w.b.) were dehydrated firstly in a pneumatic tube until 64% (w.b.) and afterwards in a rotational drum until 3% (w.b.). Time, temperature and drum rotation were correlated. The drying temperatures used were 130°C, 150°C, and 170°C in the pneumatic tube and 50°C, 60°C, and 70°C in the drum dryer. The drum rotations used were 27 rpm and 47 rpm. During the first drying level, okara presented fast moisture decreasing and during the second one the drying rates were lower due to the lower temperatures used. The combination with 150°C in the pneumatic tube and 70°C in the rotational drum provided the highest drying rate and acceptable darkening level. After okara's thermal properties were obtained versus time and temperature. Thermal properties are very important to simulate heat transfer during thermal treatment of foods. The okara's thermal properties obtained were density, specific heat, thermal conductivity, thermal diffusivity, and mass transfer coefficient from analysis of its centesimal composition, furthermore, heat transfer coefficient also was calculated,. The results show that it is possible to estimate the thermal properties using the experimental temperature and moisture content history and the centesimal composition of the food with good precision.*

Keywords*: thermal properties, drying kinetics, okara, heat transfer, mass transfer*

1. INTRODUCTION

Okara is the residue from the soy milk production process. It contains around 75% (w.b.) of moisture content and approximately 95% of the soy grain solid components. This indicates that the okara´s nutritional value is very high and that large quantities of it are produced (Smith and Circle, 1978). According to Jackson et al. (2001), about a third part of the soy isoflavone content is transferred to okara. It contains mostly crude fiber, about 25% protein and 10 to 15% oil. It is a suitable dietary additive in biscuits and snacks because it reduces calorie intake and increases dietary fiber. The high-quality protein fraction has good water holding and emulsifying qualities and contains a peptide with anti-hypertension effects (Travaglini et al., 1980; Wang, 1989; O'Toole, 1999). The okara oil component can also be applied in the cosmetical and pharmaceutical industries (Quitain, 2005).

The large quantities of okara produced annually pose a significant disposal problem due to its high biological value. This can be avoided by using okara wet, dried or as a paste in several food products. Some uses of okara already studied are related to the processing of French breads (Bowles and Demiate, 2006), sandwich loaf (Silva et al., 2006), cheese breads, which are a product from Brazil (Aplevicz and Demiate, 2007), sweet biscuits (Larosa et al., 2003) and candies (nougat) (Genta et al., 2002). For all the studies quoted the results of the sensorial tests showed satisfactory acceptance levels. Using okara as a substrate for fermentation, Fan et al. (2001) produced eicosapentaenoic and docosahexaenoic acids and Khare et al. (1995) produced citric acid. Beyond of the previous works quoted, there are in literature other works on the specific okara drying: Wachiraphansakul and Devahastin (2005) and Coronel and Tobinaga (2004) used a spouted bed, Taruna and Jindal (2002) used a continuous vortex-like moving bed of inert particles, and Tatsumi et al. (2005) applied the eletrohydrodynamic technique.

From that literature revision, one can note that there are some studies about the uses of okara, however a very small quantity of this subproduct is being used in the food industry today. According to Perera (2005) and Chua et al. (2000), color is a major quality parameter in dried food products. The drying process proposed in this study uses okara extruded on the shape of spherical pellets, with 78% (w.b.) of moisture content, which are pre-dried in a pneumatic tube with temperatures of 130°C, 150°C, and 170°C until the loss of their superficial adhesion and then the pellets are dried in a rotational drum using 50°C, 60°C, and 70°C until they achieve the moisture content of 3% (w.b.).

2. MATERIAL AND METHODS

In this study, several drying tests were accomplished and the operation temperature was studied in order to find the drying condition which allows obtaining dehydrated okara pellets with the lightest color possible and in the shortest time. The drying method proposed in this study uses okara on the shape of spherical pellets with diameter 5 mm, making the heat and mass transfer easier. The extrusion of okara was accomplished in an extruder, brand WEG, model 22STI. In order to promote the drying tests, two drying equipments were adapted and built. Firstly an adaptation in a spray-dryer (brand Lab Plant, model SD-05) was made in order to simulate the pneumatic tube. A cylinder with 12 cm diameter that fits in the air exit was built. At the end of the tube a structure which consists in a 5 cm height cylinder was encased. This structure has its upper part opened to permit the air flow and its lower part is a drilled net, which accommodates the okara pellets that are being dried, as Fig. 1a shows. Such equipment is called in this study of

pneumatic tube. Afterwards, a cylinder with 15 cm diameter with intern wings to revolve the pellets was built in order to play the role of the drum. This cylinder was incased to an engine that permits the cylinder rotation. The rotational drum dryer built can be seen at Fig. 1b. The hot air supply derives from the spray-dryer, as presented in Fig. 1c.

(a) (b) (c)

Figure 1. (a) Spray-dryer adapted: pneumatic tube; (b) Rotational drum dryer built; (c) Air supply for the rotational drum derived from the spray-dryer.

3. EXPERIMENTAL RESULTS AND ANALYSIS

Each drying test was performed in triplicate. The air temperature in each experiment in the pneumatic tube was fixed at 170ºC, 150ºC and 130ºC, the highest temperatures that could be used experimentally in order to obtain high drying rates, while in the rotational drum the air temperature was fixed at 70ºC, 60ºC and 50ºC, temperatures that did not cause high darkening rates. The drum rotations tested were 27 rpm and 47 rpm, rotations that could be used experimentally without causing damages to the dryer adapted at laboratory. The influence of these parameters on the drying time is evaluated as follows.

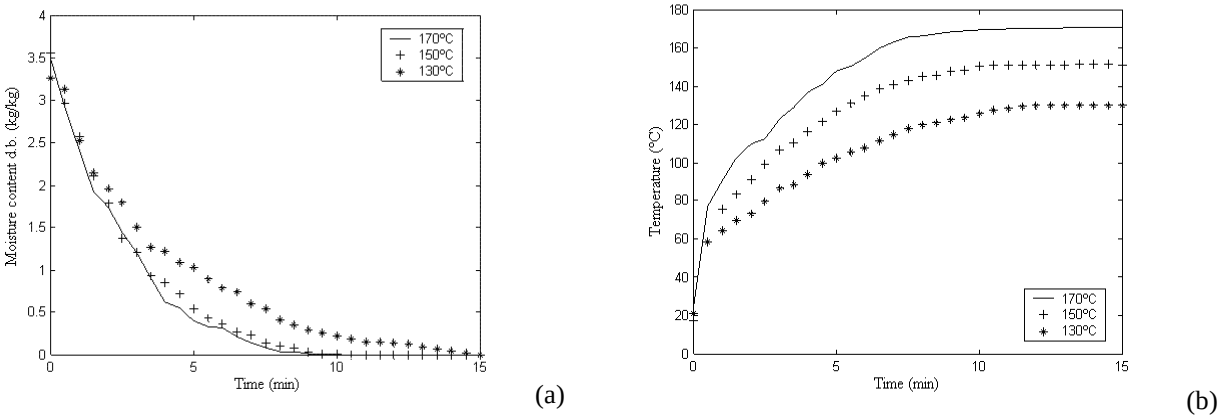
3.1 Experimental results for the okara drying in the pneumatic tube

The air supplied by the spray-dryer has its relative humidity and velocity variable with the temperature. Relative humidity was experimentally obtained through the measurements of the air wet bulb temperature, with a thermometer, and the dry bulb temperature, which was measured with a thermometer with its extremity covered by an humid gauze, and with the use of a psychometric chart. The air velocity was measured with a hot wire anemometer (brand Testo, model 445). The results obtained are described in Table 1. One can observe that the increase on the air temperature is accompanied by a decreasing on the relative humidity, while the air velocity increases. Therefore, if it was possible to use velocities of the order of 1 m/s, as is usual in food drying processes, the drying time would decrease considerably.

The analysis of moisture content were done by the gravimetric method, which consists in submitting the sample to a convection drying in a stove at 105°C for around 8 hours. The temperature profiles were obtained through the measurement of the pellet's temperature with type T thermocouples. A data acquisition central (brand HP Agilent, model 33250A) and a computer were also used for data storage.

Figure 2a shows the moisture content versus time for each drying temperature used in the pneumatic tube. As higher is the temperature, lower is the drying time, as expected. The drying times using 170ºC, 150ºC and 130ºC were 9, 10 and 15 minutes respectively. In terms of total drying time, the curves for 150°C and 170°C, presented in Fig. 2a, did not differ significantly. Until 4 minutes of drying the curves are very similar, and the drying process using the higher temperature reached the final moisture content only one minute earlier. However, both these curves (150°C and 170°C) differ significantly of the drying process using 130°C, in terms of drying time, which lasted 5 and 6 minutes more than them, respectively. This is because the thermophysical properties are dependent of the temperature. Although the relative humidity and the velocity of the air are very similar for the temperatures used, varying from 1,17% to 0,38% and 0,044 to 0,073 m/s, as described in Table 1, the apparent mass diffusivity (D_{ap}), which represents the capacity of the water to migrate from inside the product to its outside, depends on the material, on its temperature and its moisture content. The values calculated for D_{ap} for this work are found in Perussello (2008) and are presented in Table 2. One can observe that although the values for D_{ap} are all in the range of 10^{-9} m^2/s, the value for 70°C is more than two times higher than the one found for 50°C, demonstrating the temperature influence on the drying time. Figure 2b shows the temperature profiles, which were measured at the center of the okara pellets for each drying temperature in the pneumatic tube. The kinetic curves presented the same tendency: at the first minute the temperature increases very

fastly, afterwards the temperature increasing becomes lower, and then temperature stabilizes around 9 minutes of drying.



(a) (b)

Figure 2. Profiles of (a) moisture content and (b) temperature versus time during okara drying in pneumatic tube.

Table 1. Air drying conditions and parameters of the products used in the pneumatic tube.

T (ºC)	RH (%)	v (m/s)
130	1.17	0.044
150	0.77	0.051
170	0.38	0.073

Table 2. Apparent mass diffusivity for okara at different drying temperatures.

T (ºC)	$D_{ap}\times10^{9}$ (m^2/s)
50	1.0
60	1.5
70	2.2
130	4.1
150	6.2
170	7.4

According to Singh and Heldman (1993), the water activity (a_w) of a food must be decreased until approximately 0.3 in order to avoid the microbiological and enzymatic degradation reactions. For this reason, the moisture content equivalent to this value of a_w was obtained by the water activity measurements of okara samples with different known moisture contents with equipment called Aqualab (model CX-2). The results obtained for the water activity are illustrated in Fig. 3 and are expressed by the Eq. (1), which has a regression coefficient (R^2) of 0.9960.

$$Aa = 1744.1X^5 - 3812.9X^4 + 2984.6X^3 - 955.07X^2 + 112.01X - 0.0087\,, \tag{1}$$

where a_w is the water activity and X is the moisture content (% w.b.).

According to Eq. (1), it is necessary to dehydrate okara until a moisture content of 3.02% (w.b.) or 0.031 kg/kg (d.b.). The drying tests using temperatures of 170ºC, 150ºC and 130ºC will last half a minute less than if the pellets were dried until they achieve the equilibrium moisture content, that is, they will last 8.5, 9.5 and 14.5 minutes, respectively.

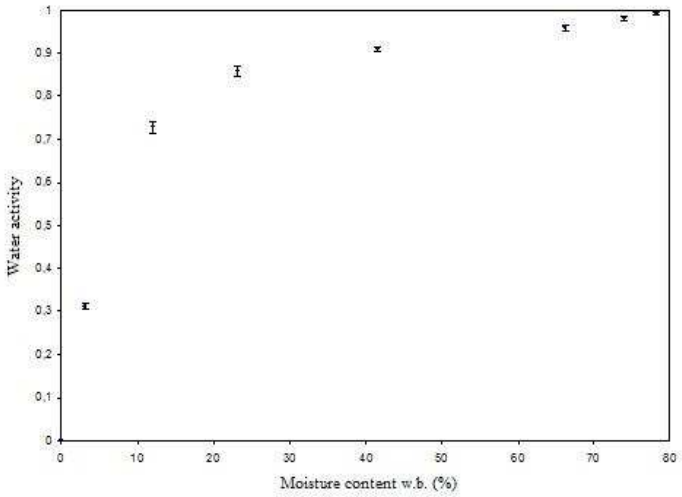


Figure 3. Okara moisture content in function of water activity.

The transition for the second dryer equipment must happen when the pre-dehydrated pellets have the adhesion and consistency sufficient for being dried in the rotational drum without sticking into its walls. For determining the transition instant, okara samples with different known moisture contents were submitted to the rotational movement inside the drum with a rotation velocity of 47 rpm. Four samples dried in the pneumatic tube with temperature of 170ºC, from 0 minute until 1.5 minutes, with an interval of 30 seconds, were used. The moisture content in wet basis of these samples was respectively, 76.71%, 73.24%, 68.97% and 63.96%, from the initial drying time. The pellets of these samples were all well structured and separated one of each other.

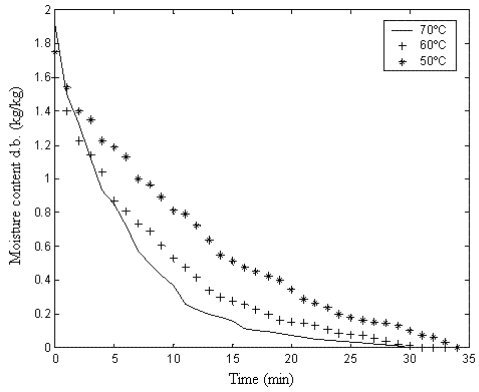
The first sample, which was not dried, was used as a control sample. The pellets of this sample stuck to the drum walls, forming united mass, and did not come off even with the equipment rotation. The second and the third samples also stuck into the equipment, in despite of their lower superficial adhesion. However, the pellets of the next sample, equivalent to 1.5 minutes of drying, left the process intact and separated. This way, independently of the air temperature and velocity of the first drying level, the pellets will be transferred to the second drying equipment when they reach the moisture content of approximately 64 % w.b, with an error of around 1% (w.b.).

3.2 Experimental results for okara drying in the rotational drum

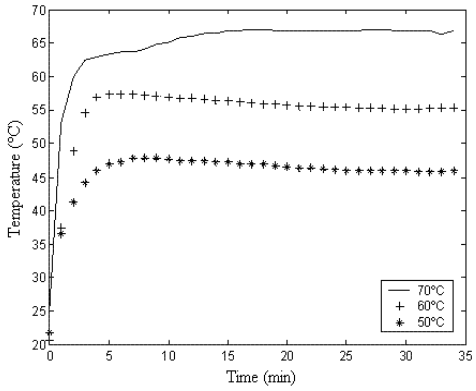
In the rotational drum, three different drying temperatures were used, 50ºC, 60ºC and 70ºC, and two different rotations, 27 and 47 rpm. The velocity and the relative humidity equivalent to each drying tests are presented in Table 3. The air velocity obtained experimentally was also much smaller than the desired one, but it was almost ten times higher than the velocities of the first drying level. This can be explained by the difference on the pipeline diameter, which carried the same air quantity from the spray-dryer to the rotational drum. The pneumatic tube diameter is 15 cm and the pipeline that supplies the air for the drum dryer has a diameter of 6.5 cm.

The preliminary tests indicated that the total time for drying in the rotational drum is approximately 30 minutes. Submitting the product to drying with the same air temperature and varying only the drum rotation, there were no significant difference on the moisture loss, that is, the process times were the same. This manner, on the next analyses, only the drying processes with the lowest rotation, 27 rpm, was used.

In Fig. 4a the profiles of moisture content using the second drying equipment are presented again, this time using only the rotation of 27 rpm. To achieve the equilibrium moisture content, the process uses 30, 31 and 34 minutes using air temperatures of 70ºC, 60ºC and 50ºC, respectively. In all drying curves there are two drying periods: until half of the process the moisture content is fastly reduced and in the rest of it the drying velocity decreases. For the pellets to reach the water activity of 0.3, the process time economy for the drying in rotational drum will be higher than in the first one: 1, 2.5 and 5 minutes using temperatures of 50ºC, 60ºC and 70ºC. Then, the processes will last 33, 28.5 and 25 minutes, respectively. The temperature profiles in function of time, using the second drying equipment, are presented in Fig. 4b. One must note that in 5 minutes of drying the temperature of the okara pellets reach its maximum value and it remains practically constant until the end of the drying process.



(a)



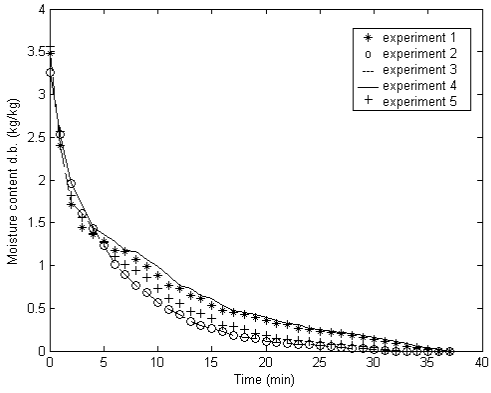
(b)

Figure 4. Profiles of (a) moisture content and (b) temperature versus time during okara drying in rotational drum.

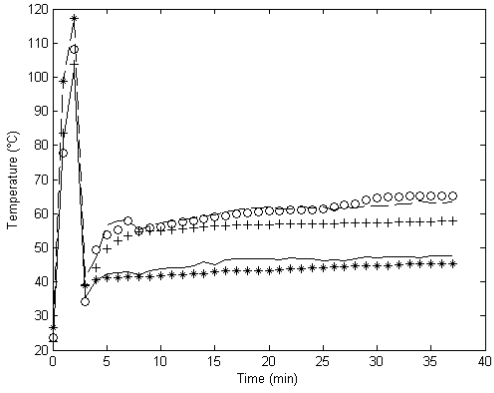
3.3 Experimental results for the complete drying process

In order to investigate the operation temperature influence on the process time, some combinations between the first and the second drying levels, performed in the pneumatic tube and in the rotational drum, respectively, were tested. With this purpose, a complete $2^{(2-0)}$ factorial experimental design was used (with 2 factors, which are the temperature of the first drying level and the temperature of the second one, two levels and one central point). Replications of the experiments were done, generating 5 experiments.

The profiles of moisture content and temperature versus time of the okara pellets for the five experiments are presented in Figs. 5a and 5b, respectively. Fig. 5a shows that the experiments 2 and 3 present the shortest drying time, followed by the 5, 1 and 4. The drying times for the okara to reach the moisture content of 3% w.b. by the combined drying processes are presented in Table 3. Considering that the combined drying process is discontinuous, that is, the pellets must be transported from the spray-dryer to the drum dryer when they achieve the transition point of moisture content (63% w.b.), there is a discontinuity on the pellet's temperature. As they leave a process where the air temperature is high and enter in the drum dryer, where the temperature is lower, the temperature of the pellets suffer a considerable decrease, as can be seen in Fig. 5b.



(a)



(b)

Figure 5. Profiles of (a) moisture content and (b) temperature versus time for each experiment of okara drying.

Table 3 – Okara's drying time for each experiment

Experiment	Temperature for the first drying level (°C)	Temperature for the second drying level (°C)	Drying time (min)
1	170	50	34,5
2	130	70	28,0
3	170	70	28,0
4	130	50	35,5
5	150	60	30,5

The statistical analysis was calculated by the program Statistica 7.0. The estimation of effects at 90% confidence intervals as well as the regression coefficient, t and p values are given in Table 4. The p-values show that only the second stage temperature is positively significant (p-value < 0.1). The results show that the second drying stage temperature has a negative effect on the drying time, increasing the temperature the time of drying decreases. The first

drying level does not influence on the drying time. This way, considering that the factor that controls the total drying time is the temperature used in the drum dryer, the lowest temperature tested for the first drying level (130°C) must be used for energy economy.The coefficient of determination R^2 shows that 98.81% of the total variation can be explained by the model.

Table 4. Estimation of variables effects for the temperature process on okara drying.

	Effect	Std.Err.	t(1)	p	-90,% Cnf level	+90,% Cnf level	Coeff.	Std.Err.
Mean/Interc.	31.3000	0.400000	78.25000	0.008135	28.7745	33.82550	31.30000	0.400000
(1)T_1	-0.5000	0.894427	-0.55902	0.675490	-6.14720	5.147190	-0.25000	0.447214
(2)T_2	-7.0000	0.894427	-7.82624	0.080906	-12.6472	-1.35281	-3.50000	0.447214
1 by 2	0.50000	0.894427	0.559020	0.675490	-5.14720	6.147190	0.250000	0.447214

3.4 Obtaining thermal properties for okara

The centesimal composition of okara was analyzed at laboratory according to standard techniques, which can be found in Matissek et al., (1998). The analysis of moisture content was made with samples of 3.0±0.5 g, which were conditioned in porcelain capsules by direct heating of the sample in stove regulated at 105ºC. The protein analysis was accomplished by the Kjeldahl digestion method, the fat evaluation was made by the continuum extraction in Soxhlet type equipment and the ashes analysis or fixed mineral residue was made by the mass loss through the incineration of the sample in a mufla stove at 550ºC. The total carbohydrates were calculated by difference, by subtracting from 100 the values found for moisture content, protein, lipids and ashes. In wet and dry basis the analysis provided the results presented in Table 5.

Table 5. Centesimal composition of okara.

Component	% (wet basis)	% (dry basis)
Water	76.49	56.57
Carbohydrates	13.30	2.47
Fats	0.58	38.93
Proteins	9.15	2.03
Ashes	0.48	

In order to calculate the okara centesimal composition including the air presence inside the pellets, the okara's porosity was also measured. The porosity was obtained in laboratory by picnometry and the experiment, accomplished in triplicate, provided the result of 23.68%. In a picnometer of 25 mL the measurement of two sample's density was made, one of them containing air from the extrusion and the other one homogenized in order to remove all the air from its interior. The results of those measurements are found in Table 6 and the final result for porosity was calculated by the Eq. 2.

Table 6. Results for the porosity analysis of okara by picnometry.

Triplicate	Density of the sample without air (g/cm³)	Density of the sample with air (g/cm³)	Porosity (%)
1	0.632	0.833	24.09
2	0.636	0.839	24.20
3	0.645	0.835	22.75

$$\varepsilon_{pellet} = \left(1 - \frac{\rho_a}{\rho_b}\right) \times 100 \tag{2}$$

where ρ_a is the density of the sample without air (g/cm³) and ρ_b is the density of the sample with air (g/cm³).

Porosity is a key property that influences on the food thermophysical properties. Its effect on specific heat is negligible, but its effect on density and thermal conductivity can be very absolutely meaningful (Mannaperuma and Singh, 1988). Thus, if the porosity is not considered inside the product, the heat transfer numerical analyses and, in consequence, the mass transfer during drying can be erroneously obtained.

Density and thermal conductivity were obtained from the centesimal composition considering the porosity (ε). Density is multiplied by a factor (1-ε) in order to account the porosity effect. This adjust on density corrects also the thermal conductivity, which is calculated using density. In order to obtain density, specific heat and thermal

conductivity, each okara pure component properties (water, carbohydrates, fats, proteins, ashes) obtained in Singh and Heldman (1993) were used, in proportion of its respective mass fraction, as described in Eqs. 3 to 6.

$$\rho = \frac{1-\varepsilon}{\Sigma(\frac{x_j}{\rho_j})}, \tag{3}$$

$$Cp = \Sigma(x_j \times Cp_j), \tag{4}$$

$$k = \frac{1}{2}\left[\Sigma x_{vj} \times k_j + \frac{1}{\Sigma(\frac{x_{vj}}{k_j})}\right], \tag{5}$$

$$x_{vj} = \frac{\frac{x_j}{\rho_j}}{\Sigma\frac{x_j}{\rho_j}}, \tag{6}$$

where ρ is density (kg/m^3), ε the porosity, x_j is each pure component mass fraction, c_p is the specific heat (J/kg·K), x_{vj} is each pure component volumetric fraction and k is the thermal conductivity (W/m·K).

In Fig. 6 the values of the okara thermophysical properties are presented, in function of the process time. One can observe that the okara density increases with time, while the specific heat and thermal conductivity decrease with time.

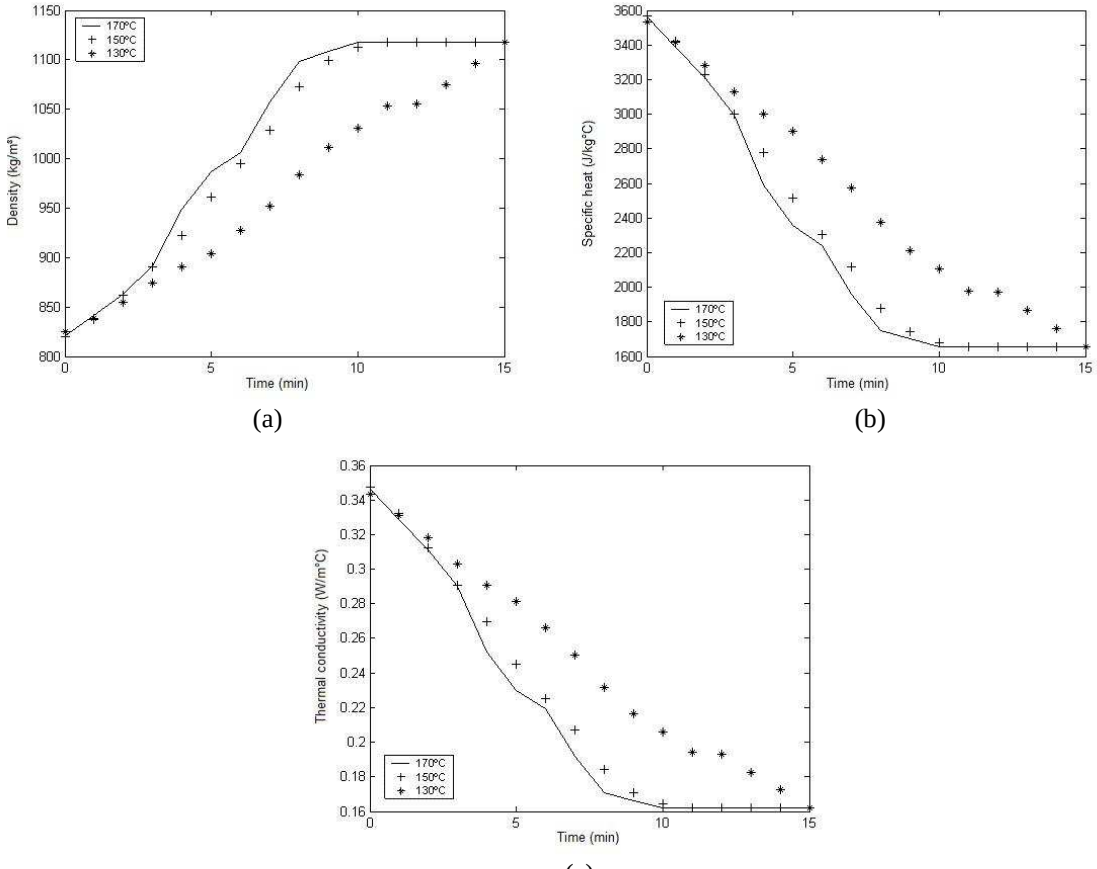


Figure 6. Okara thermophysical properties during drying versus process time (a) Density, (b) Specific heat and (c) Thermal conductivity.

Density increases with time because the solid fraction of okara presents a larger density than water does. However, the solid fraction of okara has specific heat, thermal conductivity and thermal conductivity smaller than the water does. This means that as the moisture is removed from the product, the heat transfer turns more difficult. The values found for density are between 825 kg/m³ and 1125 kg/m³ and the specific heat place between 1500 J/kg·K and 3500 J/kg·K, for the drying air temperatures range used in this work. The values found for thermal conductivity are between 0.2 W/m·K

and 0.45 W/m·K. This property depends on factors such as composition, temperature and food structure. The thermal diffusivity, by its turn, represents the speed of the product's temperature response in function of the drying air temperature and the values found for it place between 0.95×10^{-7} m^2/s and 1.3×10^{-7} m^2/s. The values obtained for these thermophysical properties of okara are coherent with the values found in ASHRAE (2002) for food products with centesimal composition alike.

4. CONCLUSIONS

In this study, the profiles of moisture content for okara (with an initial value of approximately 75% (w.b.)) was measured during drying in a pneumatic tube, in a rotational drum, and in both these equipments. The air drying temperatures used in the pneumatic tube were 130°C, 150°C and 170°C, while in the rotational drum they were 50°C, 60°C and 70°C. Combined drying processes were also used. In the beginning of these processes the drying was performed in the pneumatic tube reducing the okara moisture content until 64% (w.b.), when the product still presented a light color. Afterwards, okara pellets were removed to the rotational drum and were dried until they reach the moisture content of 3% (w.b.). The results showed that the first drying level temperature does not influence on the total drying time. This way, considering that the factor that controls the total drying time is the temperature used in the drum dryer, the lowest temperature tested for the first drying level (130°C) must be used for energy economy, together with the temperature of 70°C in the rotational drum provided the highest drying rate and thus the lower drying time. The coefficient of determination R^2 shows that 98.81% of the total variation can be explained by the model. In order to decrease drying time obtaining reduced darkening levels, higher air velocities could be used, since the range of velocities used experimentally in this study is limited (0.044 to 0.073 m/s). However, even using low air velocities, the combined drying process developed in this study provided satisfactory results, showing that the nutritional value and the market potential of okara can be explored further. The values obtained for thermophysical properties of okara are coherent with the values found in literature for food products with centesimal composition alike.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

The authors Camila Augusto Perussello, Álvaro César Camargo do Amarante and Viviana Cocco Mariani are the only responsible for the printed material included in this paper.