Effect of Temperature on Okra (*Abelmoschusesculentus)* Fruit Slices Dehydrated Using a RefractanceWindow^{TM} Dryer

Akinjide A. Akinola, Samuel O. Adehounand Stanley N. Ezeorah
Chemical and Petroleum Engineering, Department, University of Lagos, Nigeria

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ABSTRACT- This paper presents the effect of temperature on the drying kinetics of the okra fruit slices using a Refractance Window^{TM} dryer. Okra fruit slices, 3 mm thick were dried at three temperatures. The slices were dehydrated at separate times at temperatures of 75°C, 85°C, and 95°C. Themoisture content of the slices was determined periodically during the drying process. The experimental data obtained were fitted tothin-layerdrying models commonly used in the dehydration kinetics of fruit and vegetables. Observations indicated that the slices dried to a moisture content below 0.11 g-water/g-solid (dry basis) in about 90 - 110 minutes for the process conditions studied. For the nine models considered, the regression results suggested that the Haghi and Ghanadzadeh thin-layer model best describes the drying kinetics for the 3 mm thick slices for the temperatures 75°C, 85°C, and 95°C; the coefficient of determination (R^2) values were 0.9992, 9973, 9993 for the respectively. The benefit of the work done here will aid in understanding the design, analysis, and optimization of the Refractance Window^{TM} equipment in the drying of food

Keywords: *Refractance Window^{TM} drying; Dehydration curves; Thin-layer dying models; Dehydrating Okra Fruit, Refractanc Window^{TM} e.*

المستخلص: يعرض هذا البحث تأثير درجة الحرارة على حركية التجفيف لشرائح ثمرة البامية باستخدام المجفف حيث أننا قمنا بتجفيف شرائح ثمرة البامية، ذات سماكة 3 مم،باستخدام ثلاث درجات حرارة، كما أنه تم تجفيف الشرائح في أوقات منفصلة بدرجات الحرارة 75°C ، و85°C، و95°C، وتم تحديد مستوى الرطوبة في الشرائح بشكل دوري أثناء عملية التجفيف.وقد تم تطبيق المعطيات التجريبية التي تم استخلاصها على نماذج تجفيف الطبقة الرقيقة التي تستخدم عادة في حركيات تجفيف الفواكه والخضار. وأشارت الملاحظات إلى أن الشرائح جففت إلى مستوى رطوبة أقل من 0.11 غ- المياه / غ- مادة صلبة (قاعدة التجفيف) خلال 90-110 دقيقة تقريباً، وذلك طبقاً لظروف العملية المدروسة.بالنسبة للنماذج التسعة التي تمت دراستها، أشارت نتائج الانحدار إلى أن نموذج الطبقة الرقيقة Haghi وGhanadzadeh يصف بأفضل شكل حركات تجفيف الشرائح بسماكة 3 مم باستخدام درجات الحرارة 75°C ، و85°C ، و95°C؛ كانت قيم معامل التحديد (R2) 0.9992, 9973, 9993 على التوالي.

INTRODUCTION

The flowering plant, okra (*AbelmoschusesculentusMoench),*of the botanical family *Malvaceae* has fruits with seedswhich are an excellent source of edible oil and flour[1]. Okra seeds contain about 20 to 40% oil[2] and its yield is comparable to most oil-seed crops except for oil palm and soybean which have a higher yield[3]. Moreover, okra seed oil has the potential of lowering cholesterol levels in the blood. The aforementioned creates a high potential for widespread cultivation of okra for edible oil as well as for cake[3].Dehydrated okra seeds can be used to make vegetable curds. The seeds can also be roasted and ground, and used as a used as coffee additive or substitute [4]. Flour produced from the okra seeds could also be used to fortify cereal flour[5]. Maize ogi with okra meal increases the protein, ash, oil and fiber content[6]. In Egypt, corn flour is supplemented with okra seed flour to make a better quality dough [3].

The okra fruit contains many nutrients; it is high in Potassium, Vitamin A, Vitamin B, Vitamin C, Folate, DFE, and Calcium. Okra is low in calories and has a high dietary fiber content. The okra fruit has a water content of 89.58g-water/ 100g of solid[7].The nutritional value of okra per 100 g is Vitamin A - RAE, 36 µg, Vitamin IU, 716 IU, Vitamin C, 23 mg, Vitamin K, 31.3 µg. Okra also contains Calcium, 82 mg, Magnesium, 57 mg, Phosphorus, 61 mg, Potassium, 299 mg, and Folate - DFE 60 µg[7].

The okra fruit has many health benefit, both folkloric and proven medicinal. The benefits includetre at ment of the inflammation of a mucous membrane, urinary problems, fever, headache, and arthritis. Okra juice is used to treat sore throats associated with coughing, diarrhea with fever and related abdominal pains. They are also used to treat skin itchiness and alsoas a skin moisturizer[8]. However, proven health and medicinal benefits of okra include its anti-diabetic applications, antibacterial uses;it uses as an antioxidant and as a pharmaceutical adjuvant[9, 10, 11].

Cultivated worldwide, is six million tonnes of the okra fruit, 500,000 to 600,000 tonnes per year is estimated to be grown in West Africa [12]. Nigeria has a peak season and a lean season when okra is available. In the peak season, more okra than can be consumed and utilized is produced [13]. Therefore, a need exists to preserve okra for use in the lean season, when the fruits are scarce and expensive. Proper processing, preservation, and utilization of okra are necessary to minimize the wastage experienced during the peak season.

There are many preservation methods, such as refrigeration, salting, pickling, and drying. However, sun-drying is a favored method in Nigeria due to the unreliable public electric power supply in the country. This study focuses on the investigation of the Refractance Window™ drying method to dryokra fruit.In Nigeria, Refractance Window™ drying technique is feasible since it can be accomplished without reliable electric power supply. The Refractance Window™ (RW) drying technology is a novel drying method patented by R. EMagoon in 1986[14]and developed by MCD Technology Inc., Tacoma, WA, USA.

Previous researchers work on the Refractance Window™ drying technique indicate that the method is relatively inexpensive and straightforward[15]. Some researchers suggest that the process is energy efficient[15, 16], and has an excellent capacity for microbial reduction when dehydration food products [[17].

Akinola*et al.*[18, 19]used the Refractance Window™ drying technique to dehydrate 3.0 mm thick slices of yams, cassava, potatoes, and carrots, at a water temperature of 60°C in the dryer. Their studies indicated that the slices could be dehydratedto a moisture content of about 10%(wet basis) in less than 180 minutes. However, theydid not examine the effect of temperature on the drying kinetics of any of the products used in the investigations. This reportaims to show and quantify the effect of temperature on the dehydration characteristics of okra slices using a Refractance Window™ dryer. This information will be useful in the design and optimization of such a dryer.

METHODS AND MATERIAL

Sample preparation

Fresh mature okra fruits gathered from a local farm were washed to remove the sand and grit from the fruit. Absorbent paper was used to remove the surface water. The okra fruitswere cut into 3.0 mm thick slices using a Mandolin Slicer. Although the okra fruit slices have a pentagonal cross-section, the dimension across of the okra slices used in this study was between 15 mm and 25 mm. The initial moisture content of okra fruit slices was determined to be 8.54 g-water/g-solid, 89% wet basis, using an OHAUS moisture analyzer [20].

Drying Apparatus

Presented in Figure1 is a schematic diagram of the equipment used in this study. The apparatus consists of a water bath covered with a 0.15 mm thick transparent polyethylene terephthalate (PET)Mylar plastic film. The film remained secured in place with metal brackets, and it was always in contact with the heated water. The film length was one (1) meter with awidth0.5 meters. The temperature of the heated water in the bath was maintained using a temperature controller and a 2.5 kW electric immersion heater. The dryer had a hood above it from which the moist air that might inhibit the drying process was extracted.

Drying Procedure

Okra fruit slices, 3.0 mm thick, were placed on the transparent Mylar sheet on the dryer, and at 10-minute intervals, some slices were removed and their moisture content determined using an MB45 OHAUS moisture analyzer[20].Three (3) sets of experiments were performed with the water temperatures in the Refractance Window™ dryer at 75°C, 85°C, and 95°C. Each experiment was performed three times and the average value of the moisture content determined.

Thin-Layer Drying Models

Literature has more than a score of thin layer drying models [19, 21, 22]. However, in this study, the experimental data were fitted to 9 theoretical, semi-theoretical and empirical thin-layer drying models most frequently used in the dehydration of fruits and vegetables. Equations 1 – 9 show the moisture ratio and time relationships for the thin-layer drying models.

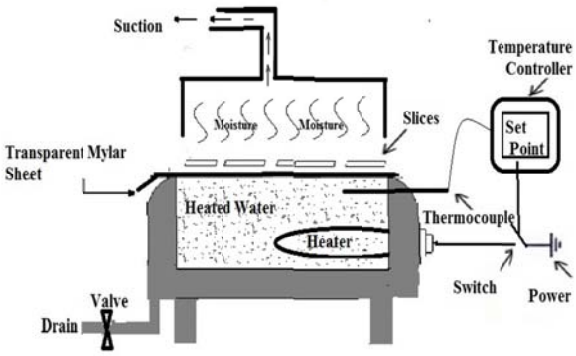


Figure 1: A Schematic Diagram of a Laboratory scale Refractance Window Dryer

$$MR = ae^{-bt^c} + dt^2 + et + f \qquad (1)$$

Haghi and Ghanadzehmodel [23]

$$MR = ae^{-kt^n} + bt \qquad (2)$$

Midilli and Kucuk Model [24]

$$MR = ae^{-kt} + bt \qquad (3)$$

Midilli*et al.* Model [25]

$$MR = ae^{-kt} + be^{-gt} + ae^{-ht} \qquad (4)$$

Modified Henderson and Pabis Model [26]

$$MR = ae^{-k_0 t} + be^{k_1 t} \qquad (5)$$

Two Term Model[27]

$$MR = ae^{-kt} + c \qquad (6)$$

Logarithmic Model [28]

$$MR = ae^{-kt} + (1-a)e^{-kbt} \qquad (7)$$

Diffusion Approach Model [29]

$$MR = e^{-kt^n} \qquad (8)$$

Page Model [30]

$$MR = e^{-(kt)^n} \qquad (9)$$

Modified Page II Model [31]

Where, MR is the moisture ratio,t is the drying time and, a, b, c, d, e, f, k, k_0, k_1, k_2 and n are all constant determined by regression analysis.The moisture ratio was determined using:

$$MR=MC_t-MC_e/MC_i-MC_e \qquad (10)$$

Where, MC_t is the moisture content of the sample after drying for time t, MC_e is the equilibrium moisture content of the sample and MC_i is the initial moisture content of the fresh sample, all in the unit of grams of water removed/grams of solids.In this analysis, MC_e, the equilibrium moisture content of the sample is assumed to be very small. Therefore, \the moisture ratio in Equation 10 was simplified to Equation 11 as recommended by many researchers [32, 33,34].

$$MR=MC_t/MC_i \qquad (11)$$

Statistical Analysis

The experimental drying data were fitted to the equations 1 – 9 to determine the thin-layer drying model that best describes the drying kinetics of the okra slices. Criteria such as the coefficient of determination (R^2), the sum of square-error (SSE), and the root-mean-square-error (RMSE) were used to determine which model best describes the drying kinetics of the okra slices. For quality fit, R^2 should be closest to unity while SSE and RMSE should closest to zero. The method of estimating R^2, SSE and RMSE are discussed extensively in the literature [35, 36] and have been used in work on drying kinetics of fruits, roots, and vegetables [21, 37]. The Polymath 6.1 software was used to perform the statistical analysis [38, 39].

After obtaining the best thin-layer drying model, that fit the drying data, the drying curves (moisture content vs. time plots), the drying rate curves (drying rate vs. time plots), and the Krischer curves (drying rate vs. moisture content plots) were drawn.

Determining the Drying Rates

The drying rate is determined by measuring the rate of change of the moisture content. This is done using the model that best fits the experimental data and obtaining predicted values every second. Numerical differentiation is then performed according to Equation 12.

$$\text{Drying rate} = \frac{MC_i - MC_{i-1}}{t_i - t_{i-1}} \qquad (12)$$

Where, t_i is the time at the i^{th} second and MC_i, is the moisture content at time t_i.

RESULTS AND DISCUSSIONS

Three sets of experiments were performed with water temperatures of 75°C, 85°C, and 95°C in the dryer. The okra fruit slices with an initial moisture content of 8.54 g-water/ g-solid, were dried to about 0.11 g-water/ g-solid. The moisture content data, on a dry basis, obtained during the drying experiments were converted into the moisture ratio (MR) and fitted to 9 thin-layer drying models.

TABLE 1: STATISTICAL PARAMETERS OF THE MODELS FITTED TO THE EXPERIMENTAL DATA AT 75°C

Serial Number	Temperature (°C)	75°C		
	Model	R^2	SSE	RSME
1	Haghi and Ghanadzeh model [23]	0.9992	0.0009	0.0101
2	Midilli and Kucuk model[24]	0.9973	0.0029	0.0163
3	Midilli*et al*.model[25]	0.9960	0.0044	0.0192
4	Modified Henderson and Pabis model[26]	0.9959	0.0045	0.0222
5	Two Term model[27]	0.9959	0.0045	0.0201
6	Logarithmicmodel[28]	0.9959	0.0045	0.0194
7	Diffusion Approach model[29]	0.9957	0.0047	0.0197
8	Page model[30]	0.9950	0.0055	0.0206
9	Modified Page II model[31]	0.9950	0.0055	0.0206

TABLE 2: STATISTICAL PARAMETERS OF THE MODELS FITTED TO THE EXPERIMENTAL DATA AT 85°C

Serial Number	Temperature (°C)	85°C		
	Model	R^2	SSE	RSME
1	Haghi and Ghanadzehmodel[23]	0.9973	0.0029	0.0178
2	Midilli and Kucuk model[24]	0.9966	0.0036	0.0181
3	Midilli*et al*.model[25]	0.9966	0.0036	0.0173
4	Diffusion Approach model[29]	0.9965	0.0036	0.0174
5	Logarithmic model[28]	0.9965	0.0037	0.0176
6	Two Term model[27]	0.9957	0.0045	0.0202
7	Modified Henderson and Pabis model[26]	0.9957	0.0045	0.0224
8	Page model[30]	0.9956	0.0047	0.0190
9	Modified Page II model[31]	0.9956	0.0047	0.0190

TABLE 3: STATISTICAL PARAMETERS OF THE MODELS FITTED TO THE EXPERIMENTAL DATA AT 95°C

Serial Number	Temperature (°C)	95oC		
	Model	R^2	SSE	RSME
1	Haghi and Ghanadzeh model [23]	0.9993	0.0007	0.0091
2	Midilli and Kucukmodel[24]	0.9991	0.0009	0.0091
3	Midilli*et al*model.[25]	0.9990	0.0010	0.0093
4	Logarithmicmodel[28]	0.9988	0.0012	0.0101
5	Modified Henderson and Pabismodel[26]	0.9987	0.0014	0.0124
6	Two Term model[27]	0.9982	0.0018	0.0130
7	Diffusion Approach model[29]	0.9982	0.0018	0.0124
8	Modified Page II model[31]	0.9982	0.0019	0.0119
9	Page model[30]	0.9982	0.0019	0.0119

TABLE 4: CONSTANTS OBTAINED BY FITTING EXPERIMENTAL DATA TO THIN-LAYER MODELS

Model	75°C	85°C	95°C
Haghi and Ghanadzeh model [23]	a = 0.8549	a = 1.532	a = 1.124
	b = 0.02335	b = 0.06092	b = 0.06493
	c = 1.415	c = 0.8721	c = 0.973

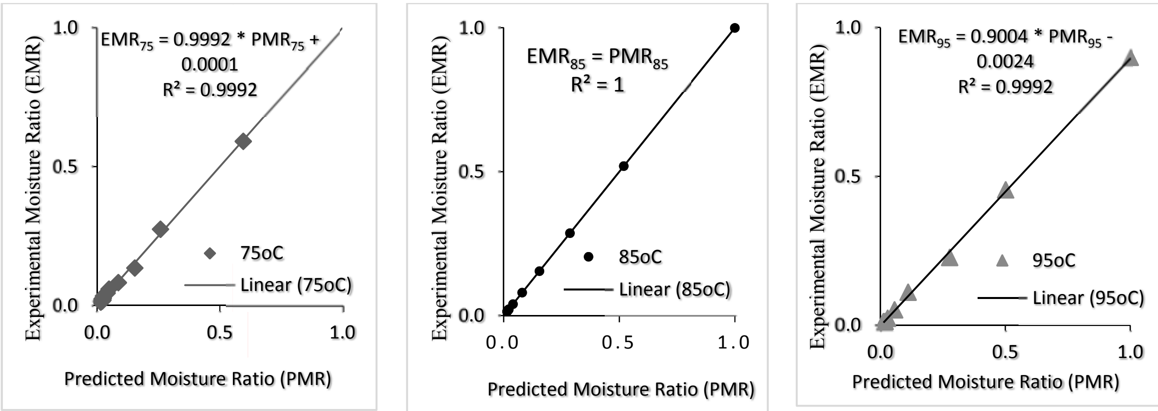
TABLE 4: CONSTANTS OBTAINED BY FITTING EXPERIMENTAL DATA TO THIN-LAYER MODELS

Model	75°C	85°C	95°C
	d = 9.733e-06	d = -3.22e-05	d = -1.008e-05
	e = -0.002285	e = 0.008233	e = 0.002366
	f = 0.1461	f = -0.533	f = -0.1248
Midilli and Kucuk model[24]	a = 1.004	a = 0.9973	a = 0.9988
	b = 0.0001692	b = 0.0001133	b = 0.0001019
	k = 0.04129	k = 0.06556	k = 0.06148
	n = 1.134	n = 0.9924	n = 1.038
Midilli*et al.*model[25]	a =1.014	a = 0.9966	a = 1.002
	b = 0.0001309	b =0.0001157	b = 9.256e-05
	k = 0.06189	k = 0.06404	k = 0.06892
Modified Henderson and Pabis model[26]	a = 0.6893	a = 1.538	a = 24.02
	b = 0.006962	b =33.79	b = -24.37
	c = 0.3178	c = -34.33	c =1.347
	g = -0.006351	g = 1.711	g = 0.5442
	h = 0.06261	h =0.5141	h = 0.07969
	k = 0.06254	k = 0.07815	k = 1.673
Two Term model[27]	a = 0.007115	a = 0.06458	a = 1.094
	b = 1.007	b = 0.9354	b = -0.09524
	k_0 = -0.006135	k_0 = 1.7	k_0 = 0.07073
	k_1 =0.06259	k_1 = 0.05963	k_1= 0.1146
Logarithmic model[28]	a = 1.001	a = 0.9861	a = 0.9939
	c = 0.01334	c = 0.01152	c = 0.00835
	k = 0.06337	k = 0.06542	k = 0.06994
Diffusion Approach model [29]	a =0.9941	a = 0.9953	a = -0.08055
	b = -0.1228	b = -0.1363	b = 0.5962
	k = 0.06164	k = 0.06463	k = 0.1182
Page model[30]	k =0.04669	k = 0.07223	k = 0.06606
	n = 1.084	n = 0.9565	n = 1.01
Modified Page II model [31]	k = 0.05926	k = 0.06409	k = 0.0679
	n = 1.084	n = 0.9565	n = 1.01

The model chosen to best fits the drying kinetics of the okra slices is the one that meets the following three criteria, R^2 is closest to unity, and SSE and RSME are closest to zero. The Haghi and Ghanadzadeh thin-layer drying model [23], is observed to best fit the experimental data in all 3 cases. The R^2, SSE, and RSME values are 0.9992, 0.0009, 0.0101when the bath water was 75°C, 0.9973, 0.0029 and 0.0178 when the bath water was 85°C, and 0.9993, 0.0007 and 0.0091 when the bath water was 95°C. The constants obtained for each model are presented in Table 4.

Further validation that the Haghi and Ghanadzadeh thin-layer drying modelbest fit the drying kinetics was done by plotting the values of experimental and predicted moisture contents (Figure2). The linesobtained, had a slope of 0.9992, 1.000 and 0.9003, and R^2 values of 0.9992. 1.0000 and 0.9992 for the 75°C, 85°C, and 95°C respectively. The implication is that the experimentally determined moisture content of the 3.0 mm thick okrafruit slices agrees with the predicted data.

For the three sets of drying experiments performed, the initial moisture content of okra fruit slices was 8.54 g-water/ g-solid. When the moisture content of the okra fruitwas about 0.11 g-water/ g-solid, the experiments were stopped. The total drying times taken for okra samples, using the Refractance Window™ dyer, to reach a moisture content of approximately 0.11 g-water/ g-solid with water bath temperatures ranging from 75°C to 95°C was 90 to 110 minutes. The drying times for the 3.0 mm okra fruit slices is observed to decrease when the water temperature in the dryer was increased. The dehydration times mentioned above are considerably shorter times than both the 4 – 8 hours experienced for drying okra using the Excalibur Dehydrator designed by Discount Juicers [40]and the maximum of 7 hours, experienced for okra fruit slices, using the dryer developed by Owolarafe*et al.*[41].



(a) (b) (c)

Figure 2: Experimental and predicted moisture ratio of 3 mm Okra slices at (a) 75°C, (b) 85°C and (c) 95°C.

The drying curves, (moisture content versus drying time) are shown in Figure 3. The drying curves show that moisture content decreases continuously with drying time. At bath water temperatures of 75°C, 85°C, and 95°C, the total drying times taken to reach a moisture content of approximately 0.11 g-water/ g-solid was 110, 97, and 90 minutes respectively.

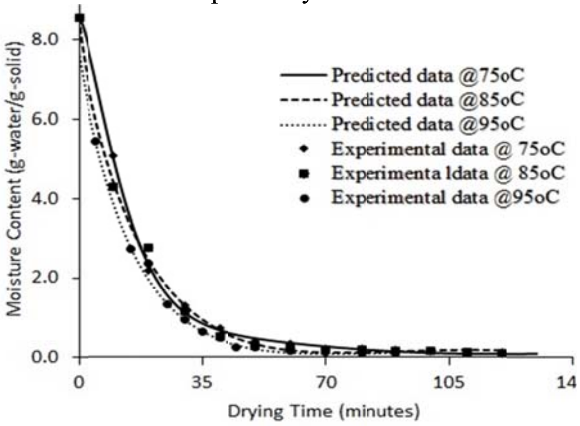


Figure 3: Experimental and predicted moisture content changes with drying time at different temperatures

An increase in the water temperature in the Refractance Window™ dryer causes a decrease the drying time of the okra slices. This reduction in drying time as dryer water temperature rises is expected, as the rate at which moisture moves through in spaces of the okra slices structure increases.Plots of the drying rate curves, i.e., drying rate vs. drying time plots for the 3.0 mm thick okra slices with water temperatures of 75°C, 85°C, and 95°C in the Refractance Window™ dryer is shown in Figure 4.

The drying rates were obtained according to Equation 3. Figure 4 shows that when the okra slices are dried at a 75°C dryer temperature, the drying rate rises initially; reaches a peak value and then starts to fall. The peak drying rate occurs at about the 6th minute. When the okra slices are dried at 85°C and 95°C dryer temperature, the drying rate appears to fall from a peak value after the first minute. This is because the peak drying rate is reached in the first minute almost immediately after the okra slices are placed in the dryer. In all situations, the falling dry rates appear to have two stages, a first stage, which has a steeper gradient than the second stage. The first stage is when the unbound moisture leaves the sample, while in the second stage the moisture has to move through the interspace of the sample structure. As observed in Figure 4, most of the dehydration occurs in the falling rate period.

Figure 5 shows the Krischer curves, (i.e., the drying rate vs. moisture content plots) for the okra fruit slices. The curves are a combination of the drying curves and the drying rate curves. Figure 5 shows that the drying rate (right to left) initially increases, it reaches a peak value and then drops (falling rate period).

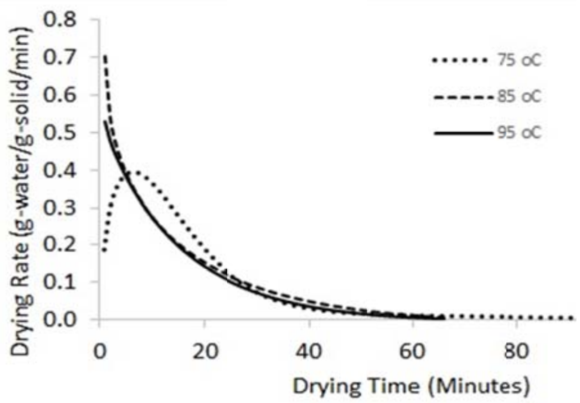


Figure 4: Drying rate changes with drying time at different temperatures

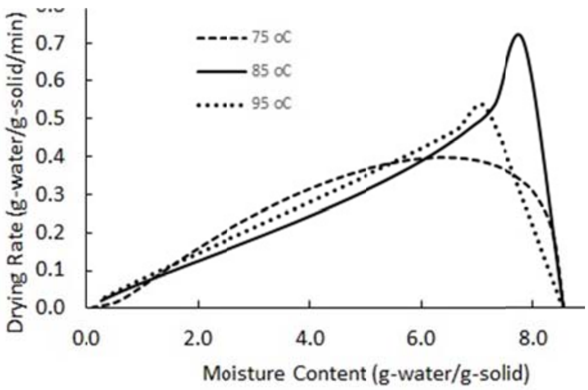


Figure 5: Drying rate changes with moisture content at different temperatures

For the okra slices dried when the dryer water temperature was 75^{o}C, the peak drying rate occurs at the 6 minutes; in this period the unbound water was gradually expelled from the sliced samples. On the other hand, when the dryer water temperature was 85^{o}C and 95^{o}C, the unbound water was removed more rapidly, and the peak drying rates occurred in the first minute. In this study, the peak drying rates were reached when the moisture content of the dehydrated slices was about 0.28, 0.75 and 1.79 g-water/g-solid/min and the dryer operated with the water temperature at 75^{o}C, 85^{o}C, and 95^{o}C respectively.

CONCLUSIONS

Okra fruit slices, 3.0 mm thick, were dehydrated from an initial moisture content of 8.54 g-water/ g-solid to a moisture content of about 0.11 g-water/g-solid using a RefractanceWindow^{TM} Dryer. The experiments were performed with the heating water temperature in the dryer at 75^{o}C, 85^{o}C, and 95^{o}C respectively. The conclusions are as follows.

1. The 3.0 mm thick okra slices dried to a moisture content of 0.11 g-water/g-solid in 90 and 110 minutes when the water temperature in the Refractance Window^{TM} dryer ranged from 75^{o}C to 95^{o}C.
2. The drying rates of the okra fruit slices increased with increase in the temperature of the water in the Refractance WindowTM dryer. An increase in drying rates was expected as heat, experienced at higher temperatures, is one of the factors known to increase the rate of water expulsion for the slices [42].
3. Okra fruit slices dehydrated with dryer water temperatures of 85 and 95oC, reached their maximum drying rates in the first minute, implying that unbound moisture in the samples was removed almost immediately they were placed on the dryers' plastic film. The okra slices dehydrated with the water temperature of 75oC, however, reached their maximum drying rates less rapidly, i.e., in about the tenth minute. This is expected as there is less energy for dehydration at 75oC than at 85 and 95oC.

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