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Full Length Research Paper

The drying of onion slices in two types of hot-air convective dryers

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Drying experiments were carried out using two types of convective hot-air dryers such that the hot air passed perpendicularly through a thin layer of onion slices in one dryer while the air passed parallel to the thin layer in the second dryer. The drying air temperatures were 50, 60 or 70°C, while air velocity was set at 0.5, 1.0 or 2.0 m/s. The drying behavior of onion slices under the aforementioned experimental parameters was fitted using Newton, Henderson and Pabis, Page and Modified Page models. The results were compared for their goodness of fit in terms of coefficient of determination (R^2) and standard error (SE). The Page model was the best in describing the drying behavior of onion slices when compared to the other models. The drying time in the case of the horizontal convective hot-air dryer in comparison with vertical convective hot-air dryer was considerably less while onion slices dried at higher temperatures generally had higher rehydration ratios.

Key words: Convective, onion, drying, modeling, rehydration.

INTRODUCTION

The onion (*Allium cepa* L.) has widely been used even in ancient time as a food seasoning and also as a natural medicine. In current times, the onion is an important vegetable that is served as an ingredient in dishes, as toppings on burgers, in seasonings and as chip coatings (Sharma et al., 2005). Onions find widespread usage in both fresh and dried forms. Dried onions are a product of considerable importance in world trade and are made in several forms that include flaked, minced, chopped and powdered onions. It is used as a flavor additive in a wide variety of food formulations such as comminuted meats, sauces, soups, salad dressings and pickle relishes (Kumar et al., 2006). Onion ranks third highest in production in the world among seven major vegetables, namely, onion, garlic, cauliflower, green peas, cabbage, tomato and green beans. Fruits and vegetables are regarded as highly perishable foods due to their high moisture content (Simal et al., 1997). In addition to the preservation of vegetable, drying is commonly practiced so as to reduce bulk handling, to facilitate transportation and to allow their use during the off-season. Drying is therefore one of the widely used methods of fruit and vegetable preservation. Longer shelf life, product diversity and substantial volume reduction are the main reasons for the popularity of dried fruits and vegetables and further improvements in drying technology will increase the current level of acceptance of dehydrated foods (Akpinar et al., 2003).

Simultaneous heat and mass transfer takes place during convective drying process where water is transferred by diffusion from inside the food material to the air-food interface. At the interface, the water is transferred to the air stream by convection. At the same time, as water is being removed, heat is transferred by conduction to the interior of the food product that is being dried. The moisture removal during drying is greatly affected by the drying air conditions as well as the characteristic dimension of the material while all other process factors have less influence (Kiranoudis et al., 1997). Mathematical models have proved to be very useful tools in design and analysis of heat and mass transfer processes. All parameters used in simulation

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models are directly related to the drying conditions. Furthermore, the drying condition can be directly related to the drying time and the energy demand (Babalis and Belessiotis, 2004). There are several studies on the drying behavior of onion. Rapusas and Driscoll (1995) used an experimental dryer to study the drying of 2 to 5 mm thick onion slices of the *Allium cew* L., cv. Southport White Globe variety at air temperatures ranging from 42.5 to 90°C and airflow velocities of 0.6 to 1.4 m/s. An Arrhenius–type relationship best represented the drying behavior and they also found that the drying rate was greatly influenced by the thickness of the slices and air temperature. In another study, a laboratory scale thin layer dryer was developed and used for the dehydration of fresh onions (cultivar - Talaja local white) by Akbari et al. (2001). They examined the effect of process parameters such as drying air temperature, air velocity and slice thickness on drying time. They also studied the effect of drying conditions on sensory quality and rehydration characteristics. They recommended that drying be done at an air temperature of 76°C and an air velocity of 27 m/min which was sufficient to get good quality dehydration of 3 mm thick slices over a drying period of 58 min. Other researchers who have studied the drying of onion include Yaldiz and Ertekin (2001) who studied the solar drying of onions and Wang (2002) who studied the far infrared drying of onions. All these studies have established that the drying conditions such as temperature and initial moisture content have a great influence on final food properties and rate of drying.

The objectives of this study are to: 1) evaluate the effectiveness of two types of hot air convective dryers with respect to drying time and rehydration; 2) examine and compare the applicability of four different thin-layer models on simulating the change in onion slices (Giza 6 variety) moisture content during the drying process.

MATERIALS AND METHODS

Experimental dryer

The schematic views of the two experimental dryers used in this study are shown in Figure 1. Each of the dryers consisted of three basic units; a fan provided the desired drying air velocity, electrical heaters that were used to control the temperature of drying air and a drying chamber. In both dryers, the drying chamber was 50 cm long, 40 cm across and 40 cm high and was made from galvanized metal sheet of 1.5 mm thickness. A single door opened on one of the side walls in order to allow the insertion or removal of the drying tray. Air was forced through the dryers using an axial flow blower and the velocity of air was controlled by use of an air control valve. The actual velocity was measured using a vane anemometer sensor with an accuracy of ± 0.1 m/s that was placed 2 cm above the drying tray. Air was heated as it passed through two spiral type electrical heaters that had a heating capacity of 1.5 kW each. These electrical heaters could also be turned off or on separately via a temperature controller in such a way that air temperature could be maintained to within ± 0.1°C of the set value. The difference between the two chambers was that in the horizontal convective (HC) air drying chamber, the hot air flowed straight through the plenum chamber to exit at the wall opposite the entry point. This allowed the hot air to flow both over the drying slices and under the drying tray. In the case of the vertical convective (VC) drying chamber, the air exited from the top of the plenum chamber thus, passing perpendicularly through the drying layer of onion slices.

Fresh onions of the Giza 6 variety (Bahnasawy et al., 2004) were used in the present investigation and were procured in bulk from the local market and then stored in a refrigerator at 4°C. To prepare the onion for the drying experiments, they were removed from refrigerated storage and allowed to equilibrate at ambient environment before being hand peeled. The onions were then cut into slices of approximately 5 ± 0.1 mm thick. The direction of cutting was perpendicular to the vertical axis of the onion bulbs and a sharp stainless steel knife was used. A micrometer was used to check the thickness and uniformity of each slice at three different locations and acceptance was based on consideration of average value and the deviation of each value from the desired thickness. A sample of about 100 g of onion slices of sizes ranging from 5 to 8 cm in diameter and at thickness of 5 ± 0.1 mm was then carefully set up as a single layer on the drying tray for use in the drying experiment.

Experimental procedure

Before inserting the drying tray into the plenum chamber, the dryer was brought up to process conditions by running it empty for about 30 min which was the duration required to achieve a steady state condition. There were two different types of convective dryer (VC and HC), three levels of air temperature (50, 60 and 70°C) and three levels of air velocity (0.5, 1.0 and 2.0 m/s), making a total of 18 runs. Each experimental run was also replicated three times and it is the average value of the three reading that was then used for further data analysis. As the 100 g onion slices were inserted into the drying chamber, a stopwatch was also activated for time recording purposes. The mass of the onions was measured using a digital electronic balance every 15 min throughout the drying experiments. In order to measure the mass of the sample during experiments, the sample along with its tray were taken out of the drying chamber and weighed on the digital top pan balance (METTLER PM30, Germany) to an accuracy of 0.01 g. The digital top pan balance was kept near the drying unit in order to ensure that the sample could be weighed and returned into the drying chamber within seconds. Drying time was defined as time required to reduce the moisture content of product to 7% (w.b.).

Analytical methods

Moisture content determination

The AOAC (1990) oven method was used to determine the initial moisture content of onion slices. A sample of approximately 20 g was placed in a pre-dried aluminum dish and placed in an air oven whose operating temperature was already set at 105°C and allowed to dry for 24 h. The sample was then taken out of the oven, and weighed using an electronic balance having sensitivity of 0.01 g. The initial mass and bone-dry mass were used to calculate the moisture content which was expressed as g_{water} / $g_{dry\ matter}$ in dry basis.

Rehydration ratio

Rehydration processes for the dehydrated onion slices were carried out by immersing the dried samples in water. Approximately, 10 g of dried sample was put in 50 ml of distilled water contained in a 100 ml beaker. The beaker was then kept in a hot water bath

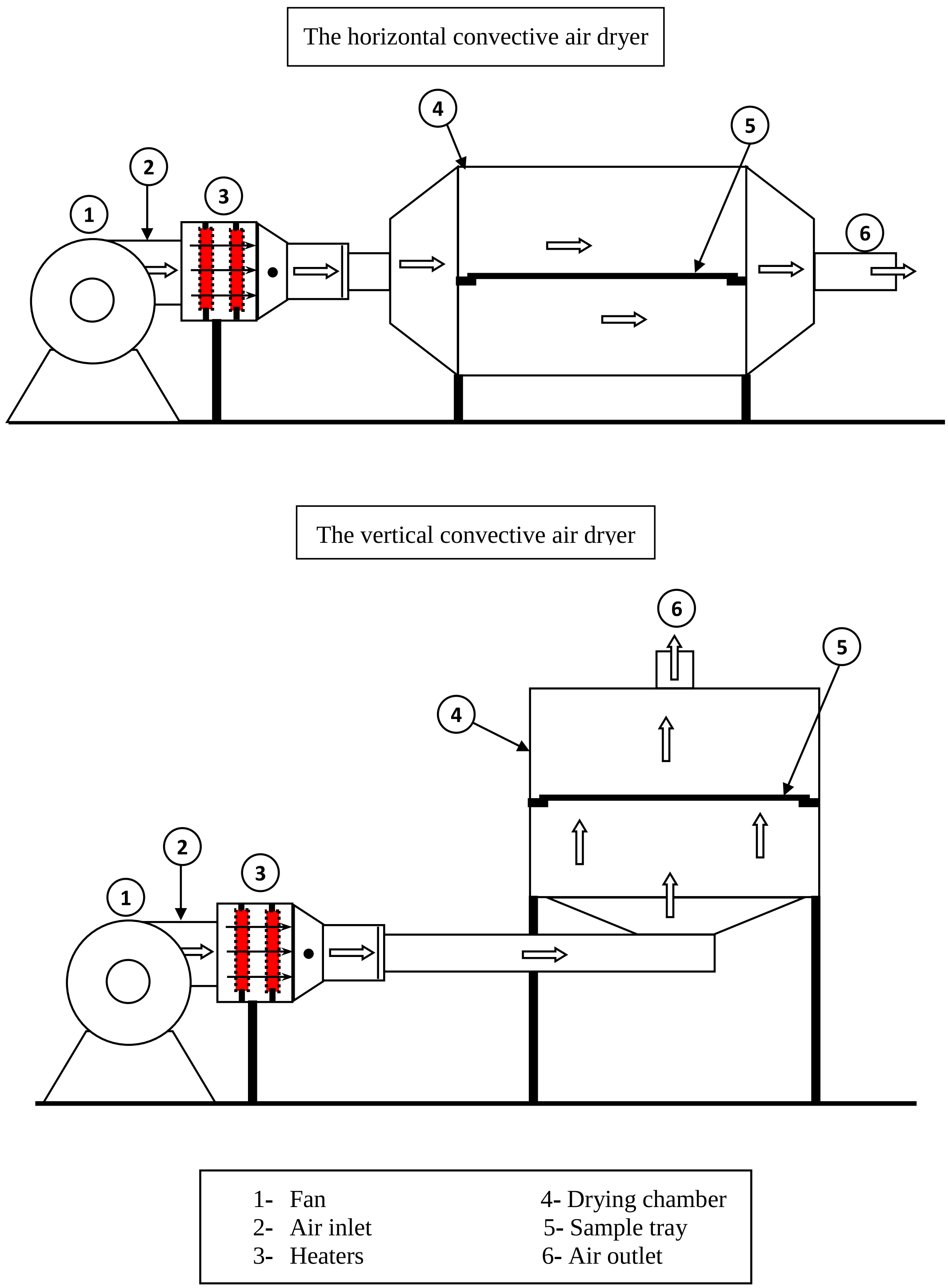

Figure 1. Schematic diagram of the experimental setup.

maintained at a water temperature of 35°C for a duration of 5 h (Kim and Toledo, 1987). At the end of the 5 h, all the water that remained in the beaker was drained and the sample was removed. The surface moisture on the sample was removed by gently wiping off the surface with a tissue paper before weighing the sample. The rehydration ratio was calculated as the ratio of mass of rehydrated sample to mass of dry sample.

Mathematical modeling of the drying curves

The experimental drying data of onions slices were fitted into four commonly used thin-layer drying models listed in Table 1 as Equations 1, 2, 3 and 4 (Ayensu, 1997; Henderson and Pabis,1961; Page, 1949; Ozdemir and Devres, 1999). In these models,the moisture ratio (MR) represents the dimensionless ratio, namely:

Table 1. Mathematical models applied to the drying curves.

S/N	Model	Equation	Reference
1	Newton	MR = exp (-Kt)	Ayensu (1997)
2	Henderson and Pabis	MR = a.exp(-Kt)	Henderson and Pabis (1961)
3	Page	MR = exp ($-Kt^n$)	Page (1949)
4	Modified Page	MR = exp [$-(Kt)^n$]	Ozdemir and Devres (1999)

MR=(M-Me)/(Mo-Me),Where M is the moisture content of the product at any time M_o is the initial moisture content and M_e is the equilibrium moisture content. The values of M_e are relatively small compared with M or M_o and can therefore be set to zero for air drying temperatures such as those used in this study (Akgun and Doymaz, 2005; Yaldiz et al., 2001; Togrul and Pehlivan, 2004). Thus, moisture ratio can be simplified to MR = M/M_o.

Correlation coefficients and standard error of analyses

The goodness of fit of the tested mathematical models to the experimental data was evaluated using the coefficient of determination, (R^2) and standard error (SE) such that the higher the R^2 values and the lower the SE, the better is the goodness of fit (Ertekin and Yaldiz, 2004).

RESULTS AND DISCUSSION

Drying parameters at varied processing condition

The initial moisture content of onions was about 7.30 to 5.99 g water/g dry matter which is equivalent to a moisture content of 85.7 to 88.0% in wet basis. This initial moisture content compares well with the initial moisture content of 7.4 g water/g dry matter reported by Sharma et al. (2005). Other researchers who have reported similar initial moisture contents included Sarsavadia et al. (1999) who reported an initial moisture content of brimmed onion slices of 86% (w.b.) and Kumar et al. (2006) who reported an initial moisture content of 85 - 90% (w.b.). The moisture ratio versus drying time for onion slices dried at different air temperature and air velocity are shown in Figures 2 and 3 for the VC and HC dryers, respectively, and it can be seen that the rate of moisture removal increased with increase of drying air temperature and air velocity in both dryers. Within the experimental range of this work, varying the drying air temperature had a greater effect on the drying process than varying the air velocity. In general, the reduction of moisture ratio with time was higher for the samples dried under the HC dryer when compared to those dried in the VC dryer for the same setting of air temperature and velocity. This is probably because the air flowing over the surface of the material has longer contact duration than air flowing perpendicularly through the thin layer. For the VC dryer, a change of the air temperature from 50 to 70°C at an air velocity of 0.5 m/s caused the drying time to decrease from 690 to 555 min while holding air velocity constant at 2.0 m/s and increasing the air temperature over the same temperature range (50 to 70°C) caused the drying time to decrease from 510 to 360 min.

For the HC, dryer changing the air temperature from 50 to 70°C at an air velocity of 0.5 m/s decreased the drying time from 675 to 525 min while changing air temperature over the same range while holding air velocity constant at 2 m/s decreased the drying time from 480 to 330 min.

Modeling of drying operation

The moisture content data obtained at different air temperatures and air velocities was converted to dimensionless moisture ratio (MR) and then fitted to the four thin-layer drying models presented in Table 1. The results of the statistical analysis described in hereafter are presented in Tables 2 and 3, for the VC and HC, respectively.

The vertical convective hot-air dryer

The statistical results for the VC dryer indicated that all four drying model considered in this study could describe the drying behavior of onion slices satisfactorily as indicated by high R^2 and low values of SE. The drying rate constant (k) and other model coefficients (n and a) also lie within the range of values obtained by other researchers (Kumar el al., 2006; EL-Mesery, 2008). The model constants in Table 2 were used to compute moisture contents values using each drying equation for similar drying conditions (drying time, air temperature and air velocity) as those used during drying experiments. These computed values for the drying of onion slices at an air flow velocity of 0.5 m/s were then plotted against the original measured values and are presented in Figure 4. It is clear from the figure that the estimated points are less scattered at the lower temperature of 50°C and that scattering increases with increase in temperature. Furthermore, estimated values for the Page model are less scattered when compared to other models. The average values of R^2 and SE for each of the models were also computed and are given in Table 2. These values show that the page model had the highest average R^2 values and lowest average SE values. Other researchers

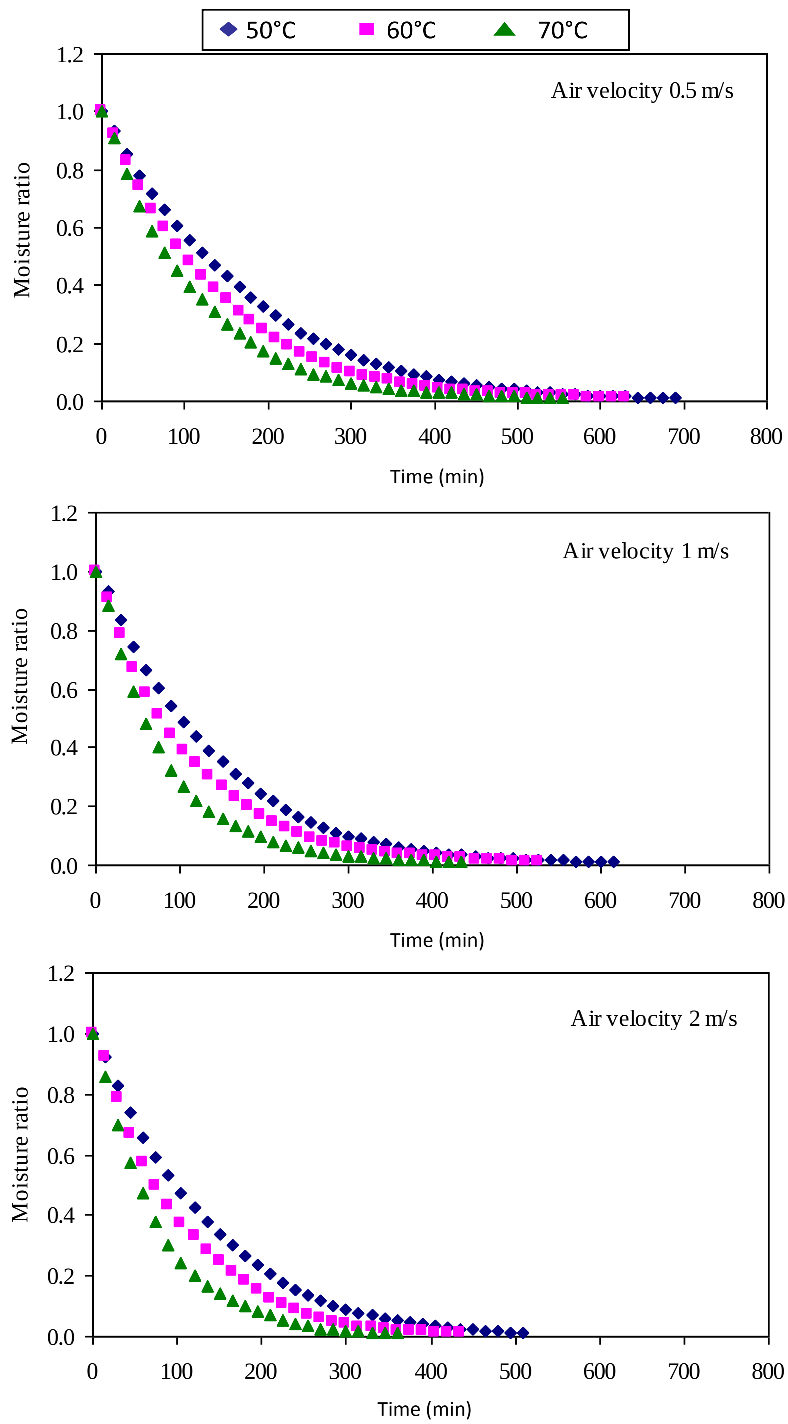

Figure 2. Variation of moisture ratio of onion slices with drying time for the vertical convective hot-air dryer at different drying air temperatures and air velocities.

representative of drying behaviour include Kumar et al. (2006) and Wang (2002). Since the Page model provided a good agreement between experimental and predicted moisture content in comparison with the other models, its drying coefficients were analyzed further.

The drying constant (k) of Page model increased with increase in air temperature and air velocity while the constant n decreased, which agrees with the work of who have found the Page model to be highly other researchers such as Togrul and Pehlivan (2003) and

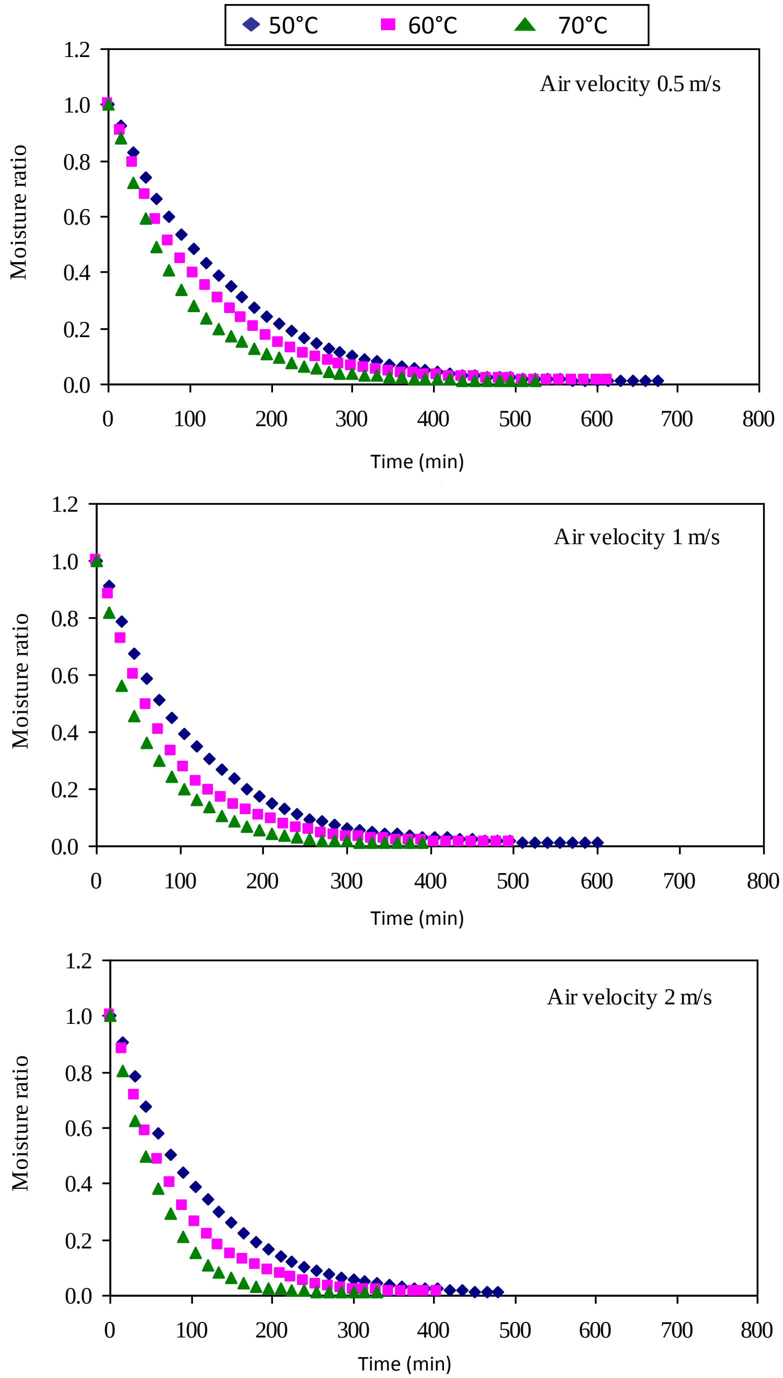

Figure 3. Variation of moisture ratio of onion slices with drying time for the horizontal convective hot-air dryer at different drying air temperatures and air velocities.

Akpinar and Bicer (2006). A simple linear regression analysis was used to relate the drying air temperature (T) and air velocity (V) to the drying constants k and n. The obtained relationships are presented in form of Equations 5 and 6:

$$k_{page} = -0.0099 + 2.7 \times 10^{-4} (T) + 3.3\times10^{-4} (V) \quad (5)$$

$$n_{page} = 1.24 - 0.0036 (T) + 0.037 (V) \quad (6)$$

Equations 5 and 6 together with the Page equation were used to estimate the moisture content of onion slices during drying over the temperature range of 50 to 70°C and the air flow range of 0.5 to 2.0 m/s. The estimated values were then plotted against the measured values

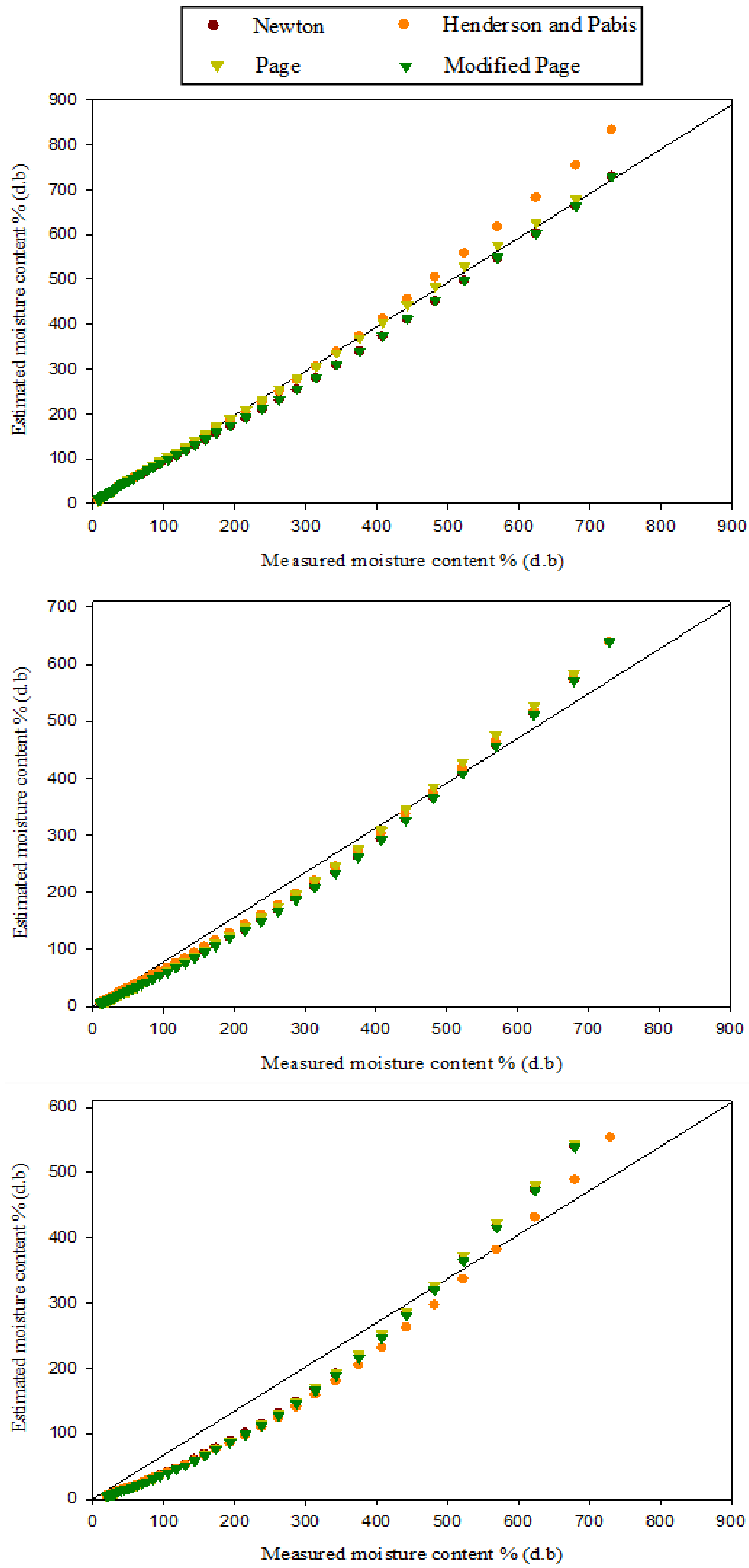

Figure 4. Measured and estimated moisture content values for onion slices dried at different air temperatures but a fixed air velocity of 0.5 m/s when using a vertical convective hot-air dryer.

Table 2. Statistical results obtained from different thin-layer models for the vertical convective hot-air dryer.

S/N	Air velocity (m/s)	Air temperature (°C)	Constants		R^2	SE
1	0.5	50	k = 0.0064		0.997	9.04
		60	k = 0.0074		0.996	5.05
		70	k = 0.0086		0.991	5.68
	1	50	k = 0.0076		0.997	7.00
		60	k = 0.0088		0.995	5.27
		70	k = 0.0111		0.994	8.11
	2	50	k = 0.0083		0.996	9.03
		60	k = 0.0105		0.994	8.51
		70	k = 0.0131		0.994	5.02
	Average				0.995	6.97
2	0.5	50	k = 0.0067	a = 1.143	0.995	9.97
		60	k = 0.0071	a = 0.999	0.997	4.88
		70	k = 0.0083	a = 0.901	0.994	6.91
	1	50	k = 0.0077	a = 1.043	0.996	8.01
		60	k = 0.0087	a = 0.943	0.990	5.48
		70	k = 0.0103	a = 0.820	0.993	9.37
	2	50	k = 0.0088	a = 1.194	0.992	8.79
		60	k = 0.0112	a = 1.158	0.994	9.68
		70	k = 0.0131	a = 1.005	0.991	5.45
	Average				0.994	7.62
3	0.5	50	k = 0.0038	n = 1.084	0.999	3.53
		60	k = 0.0051	n = 1.065	0.999	3.02
		70	k = 0.0075	n = 1.026	0.999	4.12
	1	50	k = 0.0044	n = 1.091	0.999	3.88
		60	k = 0.0072	n = 1.039	0.999	4.01
		70	k = 0.0113	n = 1.001	0.998	6.69
	2	50	k = 0.0042	n = 1.121	0.999	3.33
		60	k = 0.0047	n = 1.151	0.998	6.98
		70	k = 0.0099	n = 1.052	0.999	3.61
	Average				0.999	4.35
4	0.5	50	k = 0.0059	n = 1.084	0.997	9.50
		60	k = 0.0072	n = 1.065	0.995	5.27
		70	k = 0.0085	n = 1.026	0.992	6.40
	1	50	k = 0.0069	n = 1.091	0.998	6.57
		60	k = 0.0086	n = 1.039	0.998	6.73
		70	k = 0.0113	n = 1.001	0.994	9.01
	2	50	k = 0.0073	n = 1.121	0.996	8.18
		60	k = 0.0095	n = 1.151	0.994	9.01
		70	k = 0.0125	n = 1.052	0.995	5.71
	Average				0.995	7.38

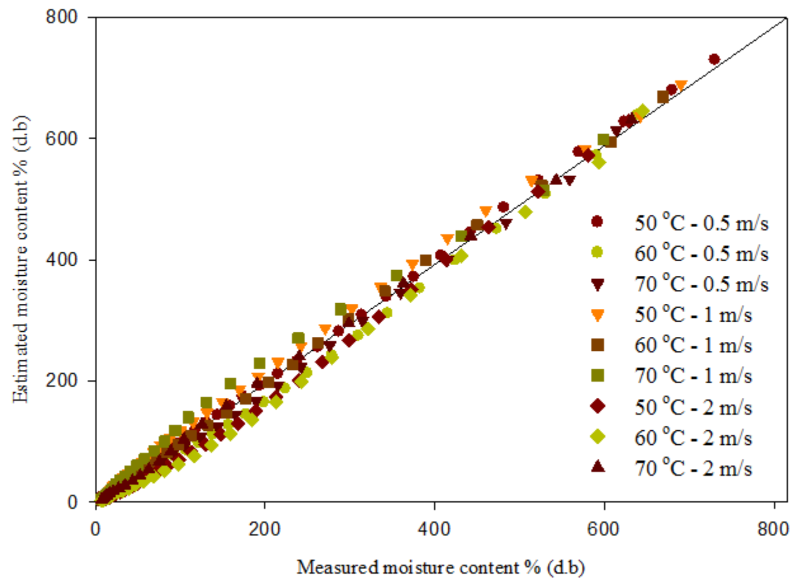

Figure 5. Measured and Page Model estimates moisture content values of onion slices that were dried in vertical convective hot-air dryer at different drying conditions of air temperature and velocity.

and are presented in Figure 5. The values were found to fit closely to 1.0 slope and there was also a high coefficient of determination of 0.993 indicating that the overall Page model could be used to predict the moisture content of onion slices with a high degree of accuracy.

The horizontal convective hot-air dryer

The statistical analysis results for the drying of onion slices using the HC dryer are presented in Table 3. As can be seen, all the studied models fitted closely to the experimental data and the drying rate constant was found to increase with increase in temperature for all models. The drying rate constant and other model constants fell within the expected range when compared to values obtained from similar research work (EL-Mesery, 2008; Krokida et al., 2004). Figure 6 presents a plot of measured moisture content values against those estimated using constants drawn from Table 3 for all four models and for a drying air flow velocity of 0.5 m/s and similar results (though not presented here) were obtained at other drying air velocities. As it can be seen from the figure, all four models could successfully describe the drying behavior of onion slices and this is also supported by the high coefficients of determination and low SE as presented in Table 3. However, the goodness of fit appear to decrease with increase in temperature because the moisture content values in Figure 6 are more scattered in the case of 70°C than those at 60°C while those at 60°C are also more scattered than the ones at 50°C.

As was the case for the VC dryer, the Page model was considered the best model for describing the drying behavior of onions slices and estimating the change in moisture content because of its high average values of R^2 and low values of SE when compared to other models. Therefore, a simple regression analysis was conducted in order to relate the drying air temperature (T) and air velocity (V) to the drying constants k and n of the Page model. The obtained relationships are presented in form of Equations 7 and 8:

$$k_{page} = -0.022 + 5.5 \times 10^{-4}\ (T) + 2 \times 10^{-4}\ (V) \quad (7)$$

$$n_{Page} = 1.23 - 0.0045\ (T) + 0.034\ (V) \quad (8)$$

Figure 7 is a plot of measured values of moisture content while drying onion slices in an HC dryer against values estimated using Equation 7 and 8 coupled with The Page model. The model could estimate the drying behaviour of onion slices with good accuracy over the entire temperature and velocity range.

Rehydration ratio

The rehydration ratio was considered to be one of the important quality attribute for the dried slices in the present study. The rehydration ratio was found to

Table 3. Statistical results obtained from different thin-layer models for the horizontal convective hot-air dryer.

S/N	Air velocity (m/s)	Air temperature (°C)	Constants		R^2	SE
1	0.5	50	k = 0.0073		0.997	5.41
		60	k = 0.0082		0.995	9.09
		70	k = 0.0099		0.991	9.18
	1	50	k = 0.0083		0.997	8.63
		60	k = 0.0104		0.993	8.20
		70	k = 0.0133		0.984	9.97
	2	50	k = 0.0094		0.993	4.98
		60	k = 0.0121		0.991	6.73
		70	k = 0.0161		0.992	9.31
	Average				0.993	7.94
2	0.5	50	k = 0.0073	a = 0.963	0.998	5.20
		60	k = 0.0078	a = 0.819	0.993	8.28
		70	k = 0.0089	a = 0.706	0.981	9.91
	1	50	k = 0.0078	a = 0.836	0.994	8.95
		60	k = 0.0096	a = 0.762	0.986	9.81
		70	k = 0.0121	a = 0.708	0.974	9.74
	2	50	k = 0.0095	a = 1.033	0.998	5.32
		60	k = 0.0119	a = 0.931	0.994	6.94
		70	k = 0.0153	a = 0.777	0.995	7.12
	Average				0.990	7.92
3	0.5	50	k = 0.0053	n = 1.057	0.999	3.91
		60	k = 0.0083	n = 1.004	0.999	5.04
		70	k = 0.0136	n = 0.954	0.998	7.66
	1	50	k = 0.0082	n = 1.007	0.999	5.09
		60	k = 0.0124	n = 0.978	0.998	6.45
		70	k = 0.0236	n = 0.903	0.998	5.02
	2	50	k = 0.0063	n = 1.072	0.999	4.51
		60	k = 0.0094	n = 1.049	0.998	5.31
		70	k = 0.0157	n = 1.011	0.999	6.11
	Average				0.998	5.46
4	0.5	50	k = 0.0082	n = 1.057	0.993	8.44
		60	k = 0.0096	n = 1.004	0.997	9.58
		70	k = 0.0129	n = 0.954	0.991	7.62
	1	50	k = 0.0065	n = 1.007	0.981	8.63
		60	k = 0.0084	n = 0.978	0.969	9.32
		70	k = 0.0101	n = 0.903	0.934	9.95
	2	50	k = 0.0088	n = 1.072	0.999	7.65
		60	k = 0.0124	n = 1.049	0.997	8.65
		70	k = 0.0167	n = 1.012	0.998	7.22
	Average				0.984	8.56

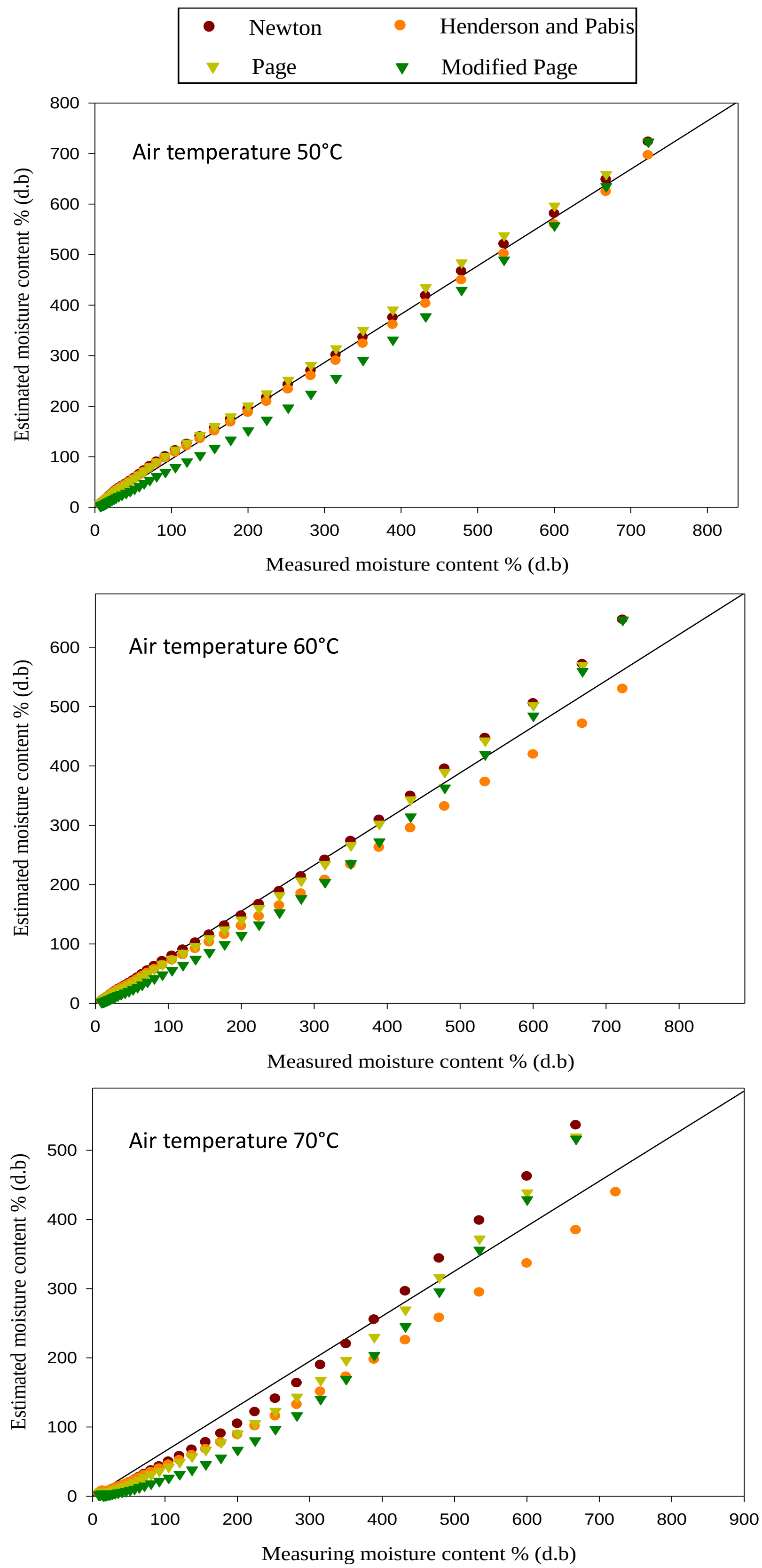

Figure 6. Measured and estimated moisture content values for onion slices dried at different air temperatures but a fixed air velocity of 0.5 m/s when using the horizontal convective hot-air dryer.

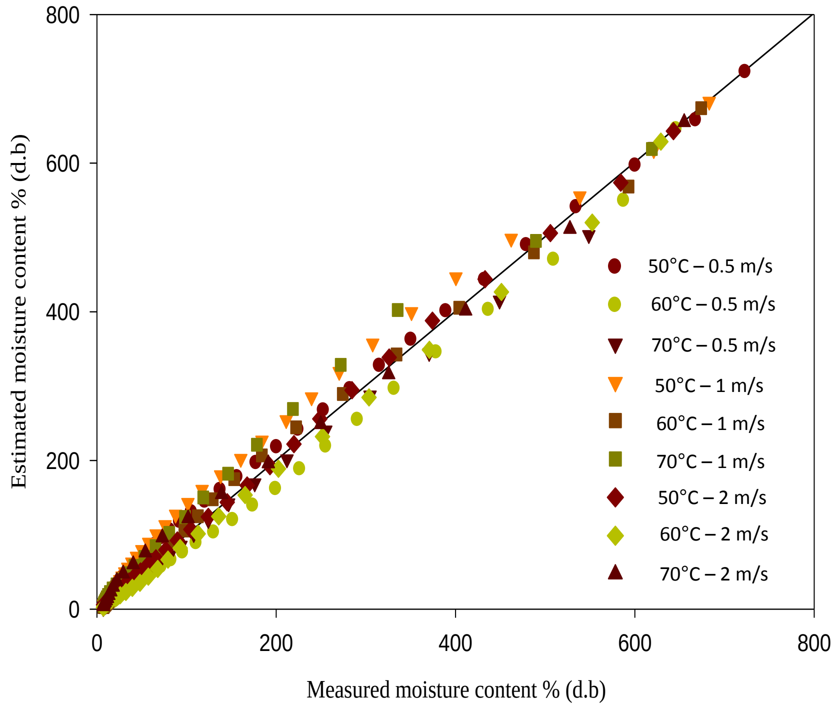

Figure 7. Measured and Page Model estimates of the moisture content of onion slices dried under different drying conditions inside a horizontal convective hot-air dryer.

increase with increase in drying air temperature and velocity in both the VC and HC dryers. EL-Mesery (2008) also observed an increase in rehydration ratio with increase in drying air temperature and velocity when using a hot-air convective dryer. Increasing the air temperature from 50 to 70°C while holding an air velocity constant at 0.5 m/s in the VC dryer caused the rehydration ratio to increase from 1.81 to 2.11. On the other hand, at an air velocity of 2 m/s, the rehydration ratio increased from 2.02 to 2.34 over the same temperature range for onions slices previously dried using the VC dryer. Onion slices dried using the HC dryer over the air temperature range of 50 to 70°C and a fixed air velocity of 0.5 m/s had an increase in rehydration ratio of 1.98 to 2.23, while at an air velocity of 2 m/s, the rehydration ratio increased from 2.29 to 2.46.

This trend was in agreement with that observed by Sharma et al. (2005). Thus, the rehydration ratio for slices dried using the HC dryer were higher than those for the VC dyer for similar settings of air temperature and velocity.

Conclusions

The drying behavior of the onion slices was investigated using two types of convective hot-air dryers (vertical and horizontal air-flow) at three levels of air temperature and three levels air velocity. Drying air temperature and air velocity greatly affected the drying rate and drying time with drying rate increasing with increase in both air temperature and velocity while drying time decreasing with increase in temperature and velocity. The Page model could be used to predict the moisture content of the product at any time of the drying process with high accuracy within the drying air temperature range of 50 to 70°C and air velocity range of 0.5 to 2.0 m/s for both types of convective hot-air dryer. The horizontal dryer was found to be more efficient in drying onion slices when compared to vertical dryer and it also had a higher rehydration ratio.

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