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Development of an intermittent drying process of onion

Essohouna Takougnadi1, Tcha-Esso Tchamye Boroze1 and Ouézou Yaovi Azouma1,2*

Abstract: This study was carried out to develop an intermittent energy-saving drying process that best preserves the quality attributes of the onion. Onion slices, 5 mm thick were dried at 45, 55 and 65°C under air flow rates of 20, 24 and 28 dm³/s. The first critical drying time determined was between 0.75 and 3.5 h while the second was between 3.25 and 14 h. The most energy-efficient couple (temperature; air flow) was (65°C; 24 dm³/s). An intermittent drying process (step-down) was developed and these critical drying times and the most energy-efficient couple were put into consideration. This step-down process was compared to the most energy saving continuous drying at 65°C under the air flow of 24 dm³/s. The results showed an improvement on the energy efficiency of 12.70% of the intermittent process compared with continuous drying and the nutritional quality, particularly the fat content (166.04%), the vitamin C (53.85%) and proteins (2.50%) were significantly maintained. The modeling of drying kinetics (by ten empirical models) showed that the model Two term exponential and the model of Midilli described both the continuous drying and the developed intermittent process.

Subjects: Food Engineering; Material Science; Technology

Keywords: onion; critical drying time; energy efficiency; intermittent drying; continuous drying; food value

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Engineer in agricultural mechanization, DEA in Material Sciences, PhD in Industrial Engineering, Postdoc in Logistics engineering, Associate Professor Ouézou Yaovi Azouma is in charge of the Research Team on Agricultural Mechanization and Process Engineering (ERMAP) at “Ecole supérieure d’agronomie” of “Université de Lomé” in Togo (West Africa). This paper is related to our research project which goal is to carry out “Energy and quality saving in tropical high value crops drying”.

PUBLIC INTEREST STATEMENT

The loss of crops is greater in developing countries where 30–40% of fruits and vegetables are wasted. Drying process can help solve this problem but it is a high energy consuming operation in agro-industrial process. Besides, poor food quality can lead to diseases and nutritional deficiencies. In order to provide a solution to this problem, our research team designed a pilot dryer which makes it possible to dry products under various temperature and air flow. So, this work has developed an intermittent energy-saving drying process that best preserves the quality attributes of the onion, a high value crop in West Africa. Finally, the mastery of kinetics and energy performances of drying processes will help to design best dryers for tropical crops.
1. Introduction
Drying is an important method widely used in the processing of agricultural products (Koyuncu, Tosun, & Pınar, 2007). Due to lack of timely and appropriate treatment, approximately one third of global agricultural production is lost each year (Gustavsson, Cederberg, & Sonesson, 2011). This loss is even greater in developing countries where 30 to 40% of fruits and vegetables are wasted (Karim & Hawlader, 2005a, 2005b). Drying is probably the most energy consuming operation of the agroindustrial process (Hany & Gikuru, 2014; Kudra, 2004) and accounts for up to 15% of all industrial energy use (Chua, Mujumdar, Hawlader, Chou, & Ho, 2001a). In an energy-consumption industry such as the drying industry, improving energy efficiency by 1% could result in a 10% increase in its profit (Beedie, 1995). Therefore, any small improvement in energy efficiency in the drying process of agricultural products would contribute to sustainable development (Kumar, Karim, & Joardder, 2014).

The drying air conditions have a great effect on the quality attributes of the dried product.

The desire to reduce the energy consumption of the drying process and to improve the quality of the dry product has led to the development of several drying processes (Hany & Gikuru, 2014) including the intermittent process which consists in varying the conditions of the drying air over time. This process has in many cases reduced energy consumption and significantly maintained product quality attributes. However, the variation in air conditions in relation to the specificity of the product has not been established.

The drying kinetics of agricultural products have three phases, mainly one phase at constant speed and one decay phase (Dissa, Desmorieux, Bathiebo, & Koulidiati, 2011). Knowledge of the drying kinetics of a product and the determination of critical water contents (or critical times) would allow better regulation of the variation of the drying conditions during the different phases for a better energy efficiency and a good quality of the dried product. The modeling of the kinetics would make it possible to say whether the developed process can be described by a known empirical model.

Onion (Allium cépa-L) is a product containing a significant amount of bioactive components such as organo-sulfur compounds, vitamins and flavonoids (Belarbi-Ouarkoub, Allaf, & Hamdi, 2008). It is widely used to flavor dishes but also for its nutritional and medicinal quality. Onion serves as a good medicinal compound for cataract, cardiovascular diseases and cancer thanks to its hypocholesterolemic, thrombolytic and antioxidant effects (Goudra, Ramachandra, & Udaykumar, 2014). Its conservation poses enormous difficulties and the losses recorded during storage, despite the different methods used, reach 22% (Currah & Proctor, 1990).

Dried onions, being increasingly incorporated in eating habits have become a standard ingredient used as an aromatic additive in many agro-industrial products such as sauces, soups, sausages, meats, fries, biscuits, etc., (Alam & Islam, 2014; Kaymak-Ertekin & Gedik, 2005; Mazza & Lemaguer, 1980).

This work aims to develop an energy-saving drying process that preserves the nutritional quality of the dry product. It is based on the couple (temperature; air flow) which brought best energy efficiency (quantity of water evaporated compared to provided energy) at the constant speed drying phase and on critical times for the various tested conditions.

2. Materials and methods

2.1. Materials

2.1.1. Sample collection
The plant material consisted of onions of the variety “violet de galmi”. These onions were purchased at the big market of Lomé in Togo.
2.1.2. Experimental device and measuring devices
The device used (Figure 1) was a convective pilot dryer comprising a drying chamber coupled to an air heating chamber connected to each other by a centrifugal fan. It is a dryer newly designed by our research team to experiment drying processes in the laboratory. It permits to dry products under various temperature and air flow (Figure 2).

The drying chamber comprised three superimposed trays of 0.34 m long and 0.32 m wide. The heating chamber equipped with a burner supplied with butane gas made it possible to raise the temperature of the drying air which could reach 115°C. The centrifugal fan (type HCAS 520-2 MONO) with a power (P) of 0.55 kW, with flow rates (D) up to 42.3 dm³/s sucked hot air from the heating enclosure and pushed it back into the drying chamber. It was linked with a frequency converter to regulate the flow of drying air. Aeration air duct homogenizing the flow of incoming air facilitated the measurement of the air drying air velocity.

The various measuring instruments used during the experiments are presented in Table 1.

2.2. Methods

2.2.1. Preparation of samples
The fresh onion was weighed and measured; then peeled, washed and cut into washer thickness 5 mm using a TOPAZ 195 slicer. The thickness of 5 mm has been also used by Sarsavadia (2007) which was based on the average thickness commonly used in the onion flake industries. A part of sample was taken, weighed and placed in an oven at 105°C for 24 h to determine the dry mass and then the initial water content (AFNOR, 1974). The empty trays were weighed after the drying chamber has been warmed up and the air flow has been adjusted. The onion slices were then regularly placed on the trays. These loaded trays were weighed and then introduced into the drying chamber. The drying time measurement was then switched on.
2.2.2. Experimental procedure

Firstly, onion slices, 5 mm thick were dried at temperatures of 65, 55 and 45°C and combined with air flow rates of 28, 24 and 20 dm³/s. The aim was to determine the critical times (times corresponding to the critical water contents), deduce the different drying phases and the most energy-saving drying condition (temperature, flow) during the drying phase at constant speed where drying is governed mainly by external conditions (Dissa et al., 2011). The selected temperatures were related to the maximum drying temperature of the onion reported in the literature as 55°C (Boroze, Meot, Azouma, Desmorieux, & Napo, 2013).

Secondly, onion slices of the same thickness were dried in continuous at a temperature of 65°C and a flow rate of 24 dm³/s (couple, temperature and flow rate most energy efficient during the phase of drying at constant speed) and then in intermittent by varying the temperature as follows:

- first phase: 65°C for 2 h (drying phase at constant speed);
- second phase: 55°C for 5 h (first part of the deceleration phase);
- third phase: 45°C until equilibrium (second part of the phase of decrease).

The increase in temperature during the drying step at constant speed above the maximum drying temperature of the onion was explained by the fact that during this phase the product remained at the humid air temperature. The flow rate was kept constant and equal to 24 dm³/s because the influence of the flow rate on the drying kinetics was small and even negligible beyond the first critical time (Edoun, Boroze, Kuitche, & Giroux, 2013).

2.2.3. Drying curve

During the drying process, the trays charged with products were removed and weighed every 15 min for 3 h, then every 30 min until the equilibrium was established. The characteristics of the air (temperature, velocity and humidity) were recorded every 5 min using an Almemo 2980 station. The masses obtained through weighing were used to determine the reduced water content and draw the curve of the reduced water content depending on the drying time.

2.2.4. Determination of critical water contents

2.2.4.1. First critical water and critical time. The first critical water content $X_{cr1}$ represents the transition point between the constant speed phase and the phase of decrease (Touré & Kibangu-Nkembo, 2004). This transition is explained by the change in the phenomenon governing the rate of drying. From the stage where the drying is controlled mainly by the external convective transfers to that of the control by the internal diffusive transfers (Dissa et al., 2011).

It was estimated from the tangent method at the origin (Derdour, 1998). This method consisted in plotting the tangent at the origin of the curve representing the rate of drying as a function of the average water content of the product. It assumed that the curves of drying velocity as a function of
the water content were comparable to two straight lines representing respectively the drying period at constant speed and the period of deceleration. This method is suitable only if during the period of slowing down the drying kinetics can be described by a diffusion law with a constant diffusivity (Moyne, Roques, & Wolf, 1989). The critical point was then the point of intersection between the two straight lines. The critical time was then deduced from knowledge of the critical water content (Dissa, Desmorieux, Savadogo, Segda, & Kouliadi, 2010).

2.2.4.2. Second critical water and critical time. The second critical water content represents the transition water content between the first phase of decrease and the second phase of decrease. This is the water content at which the analytical solution of Fick diffusion equation passes from one simplified form to another (Dissa et al., 2011).

The determination of this critical water content consisted in plotting the curve of the logarithm of the reduced water content as a function of the difference between the drying time \( t \) and the first critical water content \( t_{cr1} \). On this curve, a quasi-linear part could be observed, starting from the first critical water content, corresponding to the first phase of decrease. The end of this linear part marked the point of second critical water content (Dissa et al., 2010; Kibangou-Nkembo, 2013).

2.2.5. Evaluation method of mass diffusivities during the phase of decrease

The transfer of humidity during the phase of drying decrease was controlled by the internal diffusion. By assuming this unidirectional diffusion (following \( z \)), the Fick diffusion law (Equation (1)), linked the water content of the product \( (X) \), the mass diffusivity \( (D) \), the time \( (t) \) and the direction \( (z) \) used to describe the drying process for most products.

\[
\frac{\delta X}{\delta t} = D \frac{\delta^2 X}{\delta z^2}
\]  

(1)

For a uniform distribution of the initial moisture, the external negligible resistors and an isothermal process, the analytical solution of Equation (1) is Equation (2) (Fahloul & Boudra, 2009):

\[
\frac{X - X_{eq}}{X_0 - X_{eq}} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \exp \left[ -(2n - 1)^2 \frac{\pi^2 D t}{4 e^2} \right]
\]  

(2)

The solution took into account the initial water content \( (X_0) \), the water content at the equilibrium \( (X_{eq}) \) and the thickness of the sample. Equation (2) was simplified by taking the first term of the solution of the series and assuming \( X_{eq} \) equals 0:

\[
X_t = \frac{X}{X_0} = \frac{8}{\pi^2} \exp \left[ \frac{\pi^2 D t}{4 e^2} \right]
\]  

(3)

Equation (3) can be written as Equation (4):

\[
\ln(X_t) = \ln \left( \frac{8}{\pi^2} \right) - \frac{\pi^2 D t}{4 e^2}
\]  

(4)

Which is an equation of a straight line in the form \( y = b + ax \) where:

\[
b = \ln \left( \frac{8}{\pi^2} \right)
\]  

(5)
\[
\alpha = -\frac{x^2 D}{4e^2}
\]  

(6)

By plotting the experimental curve \(\ln(X) = f(t)\), the coefficient \(\alpha\) was determined and the diffusivity \(D\) of the product was deduced from the Equation (6).

2.2.6. Method for evaluating the energy efficiency of the intermittent process vs. continuous drying

The energy \(E\) of a given quantity of air at a temperature \(\theta\), containing \(Y\) kg of water vapor per kg of dry air is given by the Equation (7) (Bimbenet, Duquenoy, and Trystram, 2002):

\[
E = m_a (C_p_a + Y . C_p_v) . \theta
\]

(7)

where \(m_a\) represents the mass of dry air, \(C_p_a\) et \(C_p_v\) the mass heat at constant pressure respectively of dry air and water vapor and \(\theta\) the temperature of this air. \(Y\) is given by the Equation (8) (Bimbenet et al., 2002):

\[
Y = \frac{0.622 . P_o . \varphi}{10,132,500 - P_o . \varphi}
\]

(8)

where \(\varphi\) is the relative humidity expressed in\% and \(P_o\) is the saturated vapor pressure at a temperature \(\theta\) expressed in Pascal (Pa). For a temperature \(\theta > 45^\circ\text{C}\), this saturating vapor pressure is given by Eqn. 9 (Nadeau & Puiggali, 1995):

\[
P_o' = \exp\left(23,1964 - \frac{3816.44}{\theta + 227.05}\right)
\]

(9)

The mass of dry air was evaluated on the basis of the relation between the mass of water vapor \((m_v)\) contained in the air considered and its mass of dry air as follows Equations (10) and (11):

\[
m_v = Y.m_a
\]

(10)

\[
\frac{m_v}{M_v . M_a} = \frac{Y . m_a}{M_v . M_a}
\]

(11)

where \(M_v\) and \(M_a\) are the respective molar masses of water (water vapor) and dry air. So we have Equations (12)–(14):

\[
\frac{V_v}{M_a} = \frac{Y . V_a}{M_v}
\]

(12)

\[
V_v = Y . \frac{M_a . V_a}{M_v}
\]

(13)

\[
V_a + V_v = \left(1 + \frac{M_a}{M_v}\right) V_a
\]

(14)

But \(V_a + V_v = V = Da.t\), where \(V_a, V_v, V, Da\) and \(t\) are respectively the volume of dry air, volume of water vapor, total volume of air, air flow and the drying time. Equation (15) was then obtained:

\[
m_a = \rho_a . V_a = \frac{\rho_a . M_v . Da . t}{M_v + Y . M_a}
\]

(15)

\(\rho_a\) is the density of the dry air which results from the absolute temperature \(T\), Equation (16):

\[
\rho_a = 1,292 \frac{273.15}{T}
\]

(16)
The energy actually supplied by the air heating chamber was given by Equation (17):

\[ \Delta E = E_{\theta_s} - E_{\theta_{amb}} \]  \hspace{1cm} (17)

\( \theta_s \) and \( \theta_{amb} \) are respectively the drying temperature and the ambient temperature.

The energy saving carried out from the intermittent process compared to the continuous drying was then evaluated by the Equation (18):

\[ g = \frac{\Delta E_c - \Delta E_i}{\Delta E_c} \times 100 \]  \hspace{1cm} (18)

Where the indicators c and i respectively represent the continuous and the intermittent.

2.2.7. Mathematical modeling of drying curves
Four empirical models (Table 2) were used to model the kinetics of continuous and intermittent drying in order to determine which model best describes each process. This would allow to know whether the developed process introduces a significant change or not in the kinetics of drying.

The adjustment between the experimental data and the predicted data for these models was determined using the coefficient of determination (\( R^2 \)), the sum of squared errors (SSE) and the root mean square error (RMSE) (Equations (19)–(21)). The choice of the best model is based on the highest \( R^2 \), the lowest SSE and RMSE values.

\[ R^2 = 1 - \frac{\sum_{i=1}^{N} \left( X_{\exp,i} - X_{\text{cal},i} \right)^2}{\sum_{i=1}^{N} \left( \bar{X}_{\exp,i} - \bar{X}_{\text{cal},i} \right)^2} \]  \hspace{1cm} (19)

\[ SSE = \sum_{i=1}^{N} \left( X_{\exp,i} - X_{\text{cal},i} \right)^2 \]  \hspace{1cm} (20)

\[ RMSE = \left[ \frac{1}{N} \sum_{i=1}^{N} \left( X_{\exp,i} - X_{\text{cal},i} \right)^2 \right]^{1/2} \]  \hspace{1cm} (21)

Table 2. Empirical mathematical models of the reduced water content

<table>
<thead>
<tr>
<th>Name of the model</th>
<th>Equation of the model</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newton</td>
<td>( X = \exp(-kt) )</td>
<td>Ayensu (1997)</td>
</tr>
<tr>
<td>Page</td>
<td>( X = \exp(-kt^n) )</td>
<td>Agrawal and Singh (1977)</td>
</tr>
<tr>
<td>Page modified</td>
<td>( X = \exp(-kt^n) )</td>
<td>Ozdemir and Onur Devres (1999)</td>
</tr>
<tr>
<td>Henderson et Pabis</td>
<td>( X = a \exp(-kt) )</td>
<td>Henderson and Pabis (1961)</td>
</tr>
<tr>
<td>Logarithmique</td>
<td>( X = a \exp(-kt) + b )</td>
<td>Yagcioglu (1999)</td>
</tr>
<tr>
<td>Two term</td>
<td>( X = a \exp(-kt) + b \exp(-kt') )</td>
<td>Madamba, Driscoll, and Buckle (1996)</td>
</tr>
<tr>
<td>Two term exponentiel</td>
<td>( X = a \exp(-kt) + (1 - a) \exp(-kt) )</td>
<td>Henderson (1974)</td>
</tr>
<tr>
<td>Approximation of diffusion</td>
<td>( X = a \exp(-kt) + (1 - a) \exp(-ktb) )</td>
<td>Kassem (1998)</td>
</tr>
<tr>
<td>Wang et Singh</td>
<td>( X = a + bt + ct^2 )</td>
<td>Wang and Singh (1978)</td>
</tr>
<tr>
<td>Midilli et al.</td>
<td>( X = a \exp(-kt^n) + bt )</td>
<td>Midilli et al. (2002)</td>
</tr>
</tbody>
</table>
In the above Equations (19)–(21), \( N \) is the number of observations, while \( X_{\text{exp}} \) and \( X_{\text{cal}} \) are the experimental and predicted values for the dependent variable at any observation \( i \), respectively.

2.2.8. Methods of nutritional analysis
The water content of the fresh and dried onions was determined by drying at 105°C for 24 h (AFNOR, 1974), the lipid content by the Soxhlet method (1879) and the protein content by the method of Kjeldahl (1883). The total reducing sugars were extracted in an aqueous medium and assayed by the method of Miller (1959). Vitamin C was assayed by a chemical method with iodine (Deymié, Multon, & Simon, 1981).

3. Results and discussions

3.1. Evaluation of critical times and critical water levels
The first and second critical times as well as the first and second critical water content for the different conditions tested are shown in Table 3.

It was noted that the first critical time was between 0.75 and 3.25 h while the second critical time was between 3.5 and 14 h. These critical times decreased with increase in temperature and flow rate of the drying air, except for the flow rate of 20 dm³/s for which the first critical time was the same at 55 and at 65°C. The first reduced critical water content was between 0.56 and 0.73, it increased with air flow and was low for the temperature of 65°C. Kibangou-Nkembo (2013) found 0.71 for plantain and mango and 0.60 for cassava. Touré and Kibangu-Nkembo (2004) found 0.91 and 0.89 for sweet banana, 0.89 for mango and 0.83 for cassava. The second critical water content was between 0.095 and 0.331 and obeys no tendency. For this parameter, Kibangou-Nkembo (2013) obtained 0.12 for mango, 0.24 for plantain and 0.36 for cassava.

3.2. Calculation of mass diffusivities during the phase of decrease
Table 4 shows the mass diffusivity of the onion for different drying conditions during the deceleration phase.

During drying phase of decrease, the variations between the mass diffusivities were too small, so it can be said that this phase was influenced by the drying conditions. In the literature, similar values were reported for other food products (Dissa et al., 2010; Lewicki, Witrowa-Rajchert, & Nowak, 1998).

### Table 3. Critical times and water contents

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Air flow (dm³/s)</th>
<th>( t_{\text{cr,1}} ) (h)</th>
<th>( X_{\text{rcr,1}} )</th>
<th>( t_{\text{cr,2}} ) (h)</th>
<th>( X_{\text{rcr,2}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>20</td>
<td>3.25</td>
<td>0.64</td>
<td>14</td>
<td>0.095</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>2</td>
<td>0.7</td>
<td>12</td>
<td>0.128</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>1.5</td>
<td>0.73</td>
<td>10</td>
<td>0.131</td>
</tr>
<tr>
<td>55</td>
<td>20</td>
<td>1.5</td>
<td>0.66</td>
<td>7</td>
<td>0.202</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>2</td>
<td>0.71</td>
<td>6</td>
<td>0.237</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>1.1</td>
<td>0.72</td>
<td>4</td>
<td>0.331</td>
</tr>
<tr>
<td>65</td>
<td>20</td>
<td>1</td>
<td>0.56</td>
<td>5</td>
<td>0.206</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>0.75</td>
<td>0.72</td>
<td>3.5</td>
<td>0.271</td>
</tr>
</tbody>
</table>

*\( t_{\text{cr,1}} \): first critical drying time; \( t_{\text{cr,2}} \): second critical drying time; \( X_{\text{rcr,1}} \): first critical reduced water content; \( X_{\text{rcr,2}} \): second critical reduced water content.*
3.3. Evaluation of the energy efficiency of the intermittent process versus continuous drying

The evolution of the reduced water content during continuous drying and intermittent drying with reference to time is shown in Figure 3. It can be seen that the products dried according to these two methods reached the same water content after 6.5 h for continuous drying and 7 h for intermittent drying. From these durations, the energies provided in the two processes were calculated and the energy gain obtained with the intermittent process was deduced and presented in Table 5.

It was noted that the intermittent process developed allowed energy savings of 12.70% with an extension of the drying time of 0.5 h, i.e. 7.69%. For intermittent drying on/off and an intermittency of 0.33, Jumah (1995) obtained for the drying of grain at 80°C during 20 min of effective drying, an energy saving of 19% with an extension of drying time of 81.34% compared to continuous drying. Chin and Law (2010) obtained for the drying of Ganoderma tsugae at 40.6°C and effective drying time of 120 min an energy saving of 21% with an extension of 76.86% of drying time (Kumar et al., 2014).

3.4. Mathematical modeling

Tables 6 and 7 present the results of the modeling of the reduced water contents as a function of time for continuous drying and intermittent drying, respectively. For continuous drying the two term
exponential and Midilli, Kucuk, and Yapar (2002) models had the same coefficient of determination (0.999). The sum of squared errors (SSE) and the root mean square error (RMSE) was respectively 0.001798 and 0.009995 for two term exponential and 0.001731 and 0.0104 for Midilli et al. model. According to Hany and Gikuru (2014), the model of Midilli et al. is that one which better fit the continuous drying curve of onion.

In the case of intermittent drying, the Two-term exponential model has the highest coefficient of determination and the lowest sum of squared errors and root mean square error ($R^2$: 0.999, SSE: 0.001798, RMSE: 0.009995), followed by the Midilli et al. model ($R^2$: 0.9999, SSE: 0.0002487, RMSE: 0.003717).

It can be noted from the above analysis that the two term exponential model described very well the intermittent drying developed. The intermittent drying could therefore be described by an empirical model according to whether the process definition took into account the characteristics of the product in order to minimize changes in the drying kinetics. Two term exponential was the same one that best described continuous drying. This confirms that the changes in the drying kinetics caused by the variation of the drying conditions of the developed process were negligible.

### Table 5. Energy effectiveness of the intermittent process compared to continuous drying

<table>
<thead>
<tr>
<th>$\theta$ (°C)</th>
<th>$Y$ (kg of water/kg of dry air)</th>
<th>$t$ (h)</th>
<th>$m_a$ (kg)</th>
<th>$E_{\theta}$ (kJ)</th>
<th>$\Delta E$ (kJ)</th>
<th>$g$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous drying</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>0.02</td>
<td>6.5</td>
<td>567.21</td>
<td>38,711.83</td>
<td>20,844.83</td>
<td>12.70</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>6.5</td>
<td>17,867.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intermittent drying</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>0.02</td>
<td>2</td>
<td>175.52</td>
<td>11,899.10</td>
<td>18,197.32</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td></td>
<td>5</td>
<td>452.16</td>
<td>25,938.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>7</td>
<td>627.67</td>
<td>19,640.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 6. Results of the four best models continuous drying

<table>
<thead>
<tr>
<th>Name of the model</th>
<th>Constant of the model</th>
<th>Statistical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k$ = 0.5286</td>
<td>$R^2$: 0.9987</td>
</tr>
<tr>
<td></td>
<td>$n$ = 1.103</td>
<td>$SSE$: 0.002356</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$RMSE$: 0.01144</td>
</tr>
<tr>
<td>Two term exponential</td>
<td>$\sigma$ = 1.588</td>
<td>$R^2$: 0.999</td>
</tr>
<tr>
<td></td>
<td>$k$ = 0.71</td>
<td>$SSE$: 0.001798</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$RMSE$: 0.009995</td>
</tr>
<tr>
<td>Approximation of diffusion</td>
<td>$\sigma$ = 2.482</td>
<td>$R^2$: 0.9989</td>
</tr>
<tr>
<td></td>
<td>$b$ = 0.8036</td>
<td>$SSE$: 0.00019</td>
</tr>
<tr>
<td></td>
<td>$k$ = 0.4082</td>
<td>$RMSE$: 0.01057</td>
</tr>
<tr>
<td>Midilli et al.</td>
<td>$\sigma$ = 0.9854</td>
<td>$R^2$: 0.999</td>
</tr>
<tr>
<td></td>
<td>$b$ = −0.001645</td>
<td>$SSE$: 0.001731</td>
</tr>
<tr>
<td></td>
<td>$k$ = 0.5105</td>
<td>$RMSE$: 0.0104</td>
</tr>
<tr>
<td></td>
<td>$n$ = 1.11</td>
<td></td>
</tr>
</tbody>
</table>
3.5. Nutritional analysis results

Table 8 shows the nutritional composition of onions dried continuously and intermittently. It was noted that the intermittent process allowed a retention of 166.04% (fat), 2.50% (protein) and 53.84% (vitamin C) compared to continuous drying. Reducting sugars, on the other hand, were better retained by continuous drying with a retention of 15.60% more than intermittent drying. The developed intermittent drying process had therefore significantly maintained the nutritional composition of dried onions except for reducing sugars.

<table>
<thead>
<tr>
<th>Name of the model</th>
<th>Constant of the model</th>
<th>Statistical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Page</td>
<td>$k = 0.5108$</td>
<td>$R^2: 0.9999$</td>
</tr>
<tr>
<td></td>
<td>$n = 1.056$</td>
<td>$SSE: 0.0002901$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$RMSE: 0.003808$</td>
</tr>
<tr>
<td>Two term exponentiel</td>
<td>$\alpha = 1.48$</td>
<td>$R^2: 0.9999$</td>
</tr>
<tr>
<td></td>
<td>$k = 0.6275$</td>
<td>$SSE: 0.0001686$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$RMSE: 0.002904$</td>
</tr>
<tr>
<td>Approximation of diffusion</td>
<td>$a = 4.382$</td>
<td>$R^2: 0.9997$</td>
</tr>
<tr>
<td></td>
<td>$b = 0.9321$</td>
<td>$SSE: 0.0004974$</td>
</tr>
<tr>
<td></td>
<td>$k = 0.4172$</td>
<td>$RMSE: 0.005116$</td>
</tr>
<tr>
<td>Midilli et al.</td>
<td>$a = 0.9949$</td>
<td>$R^2: 0.9999$</td>
</tr>
<tr>
<td></td>
<td>$b = -0.0001267$</td>
<td>$SSE: 0.0002487$</td>
</tr>
<tr>
<td></td>
<td>$k = 0.5051$</td>
<td>$RMSE: 0.003717$</td>
</tr>
<tr>
<td></td>
<td>$n = 1.062$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name of the model</th>
<th>Constant of the model</th>
<th>Statistical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

4. Conclusion

This work has developed an intermittent method of onion drying based on the determination of critical water contents, critical times and diffusivity. The first critical time determined for the various conditions tested was between 0.75 and 3.25 h while the second between 3.5 and 14 h. The diffusivities during the phase of decrease were very low and vary from $8.58 \times 10^{-10}$ to $2.19 \times 10^{-9}$ m$^2$/s. The intermittent process developed showed an energy saving of 12.70%, better retention of fat, protein and vitamin C, respectively 166.04, 2.50 and 53.84%. However, an extension of the drying time of 0.5 h and a loss of reducing sugars of 16.50% in relation to the continuous drying carried out at 65°C with an air flow rate of 24 dm$^3$/s was recorded.

Nomenclature

<table>
<thead>
<tr>
<th>Symbole</th>
<th>Désignation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>Hour (h)</td>
</tr>
<tr>
<td>$X_{ms}$</td>
<td>dry matter content (kg dry matter/kg wet material)</td>
</tr>
<tr>
<td>$X_0$</td>
<td>initial moisture content (kg water/kg d.b)</td>
</tr>
</tbody>
</table>
X  moisture content at the instant t (kg water/kg d.b)
X_{eq}  equilibrium moisture content (kg water/kg d.b)
X_r  reduced moisture content
m_s  dry mass (kg)
m_h  initial mass (kg)
m  mass at time t (kg)
−\frac{dx}{dt}  Drying rate (kg water/kg d.b/h)
−\frac{\Delta X}{\Delta t}  Variation of the moisture content reported to the duration (kg water/kg d.b/h)
e  Thickness (mm)
P_o  Saturating vapor pressure (Pa)
ϕ  Relative humidity (%)
m_a  Dry air mass (kg)
m_v  Water vapor mass (kg)
M_a  Mass molar of dry air (g/mol)
M_v  Mass molar of water (g/mol)
V  Volume of drying air (m³)
V_a  Volume of dry air (m³)
V_v  Volume of water vapour (m³)
ρ_a  Density of the dry air (kg/m³)
∆E  Energy provided by the enclosure of heating (J)
E_θ  Energy of the air at the temperature θ (J)

Indice
a  dry air
v  water vapor
amb  ambient
s  drying (dry)
c  continuous
i  intermittent
exp  experimental
cal  calculated or predicted
θ  temperature
eq  équilibre
r  reduced
h  wet
ms  dry matter
vs  saturating vapor
0  initial

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Competing Interests
The authors declare no competing interest.

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