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A Modeling Study for Moisture Diffusivities and Moisture Transfer Coefficients in Drying of "*Violet de Galmi*" Onion Drying

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Abstract

In the present work, the mass transfer characteristics, namely moisture diffusivity and moisture transfer coefficient of "*Violet de Galmi*" variety of onions were evaluated using the analytical model. Onions were dried in a single layer at different temperatures (40˚C, 50˚C, 60˚C, and 70˚C) and for a relative humidity of drying air of 20%. The results showed a reasonably good agreement between the values predicted by the correlation and the experimental observations. This model computed the Biot number, effective moisture diffusivity, and mass transfer coefficient. Effective diffusion coefficient values are obtained between 0.2578×10^{-9} $m^2 \cdot s^{-1}$ and 0.5460×10^{-9} $m^2 \cdot s^{-1}$. Mass transfer coefficients of "*Violet de Galmi*" onion drying vary between 3.37×10^{-7} $m \cdot s^{-1}$ and 13.38×10^{-7} $m \cdot s^{-1}$. Numbers of mass transfer Biot are found between 0.9797 and 2.9397. The activation energy E_a is 31.73 $kJ \cdot mol^{-1}$.

Keywords

"*Violet de Galmi*" Onion, Diffusion Coefficient, Drying Coefficient, Lag Factor

1. Introduction

Onion is one of the most important crops and one of common consumer products in World. In 2012, world production was estimated to 82,851,732 tons of onion. Among these global data, production in West Africa was estimated at 2,131,600 tons [1]. Local variety of improved onion "*Violet de Galmi*" constituted 75% of the production in this African region because this is an insect and disease resistant and high-yielding cultivar [2]. "*Violet de Galmi*" variety was in an elliptical form with purple coloration. This round bulb consisted of external dark-violet color flakes and light purple trend at the level of internal flakes. Onions "*Violet de Galmi*" are a seasonal vegetable being harvested from the market garden during February-April in West Africa. Fresh onions, having relatively high moisture contents, are very sensitive to microbial spoilage during storage, even under refrigerated conditions. Therefore, within a few weeks following harvest they must either be consumed or processed into various products. Drying is the most common form for onion processing during its period of abundance. Onions can be dried for longer shelf-life by reducing the moisture content to a low level that prevents microbial spoilage and moisture-related deteriorative reactions. Since drying is an energy intensive operation, and due to the sharp increase in energy cost over the last few years, it has become the prime concern of the researchers to find the means of attaining optimum process conditions for good quality products, which leads to energy savings. Towards this goal, accurate determination of moisture transfer parameters for the drying operation of onion is essential. Moreover, decreasing the energy consumption in the drying process will decrease the environment impact in terms of pollutants and hence protect the environment.

To achieve these goals, in the literature, many experimental and theoretical studies have been conducted on the determination of onion drying profiles by many researchers [3]-[13]. Indeed, in a comprehensive review of thin-layer drying curve models, Kucuk *et al.* [3] evaluated the empirical models of onion drying considering the pretreatment of product, the drying parameters and drying methods employed on onion. In this review, Midilli-Kucuk model was found one of the best models employed for onion drying applications. Mota *et al.* [4] were obtained three empirical models (Newton, Modified Page and Logarithmic) for describing relatively well the air convective drying kinetics which was evaluated at 30˚C, 50˚C and 60˚C. For predicting moisture distribution in each layer of onion bulb, a model of multi layers onion drying was investigated in base of one dimensional partial equation. This model was useful to estimate the drying time of outer layer to the desired level [13]. In a laboratory scale infrared-convective dryer, the infrared convective drying of onion slices (6 mm thickness) was observed in a falling rate process with different values of average effective moisture diffusivity. Its values increased for air constant temperature and air constant velocity as applied radiation intensity was increased. For an air constant temperature and fixed radiation intensity, its values decreased with increase in air velocity. The drying time increased with this increase in air velocity because of the increased cooling effect at the surface of the product [5] [7] [8]. In the two convective (50˚C, 60˚C and 70˚C) and microwave (328 W, 447 W and 557 W) drying techniques of onion slices, the constant activation energies of the convective or microwave onion drying were evaluated using an exponential expression based on Arrhenius equation [9]. During the convective, vacuum, and microwave drying techniques of onion slices either dipped into 8% NaCl solution for 40 min or intact, the activation energies of pre-treated onions were lower than slices contained no salt solution under vacuum and microwave drying conditions. Brine solution had a negative effect on convective drying time but had a positive effect on both vacuum and microwave drying times [10]. The use of (60˚C, 70˚C and 80˚C for 1, 3, 5 and 10 min) blanching as a pre-treatment before drying of onions resulted in enhanced phyto-chemical content and drying efficiency [11]. For improving this drying efficiency of onion slices *i.e.* the drying time reduced and effective diffusivity increased, Albitar and al. [12] adopted the instant controlled pressure drop technique as a blanching-steaming pre-treatment of fresh onion slices before their drying. So, sensorial and nutritional attributes of dried onions could be preserved with a perfect decontaminated end product. Arslan and Özcan [6] carried out experiments of the sun, oven (50˚C and 70˚C) and microwave oven (210 and 700 W) drying of onion slices to monitor quality degradation of dried onions. The highest values of the K, Ca, Na, Mg and P mineral were measured in oven dried onions. Sun and microwave oven drying revealed better color values in the dried onions. The phenolic contents of microwave oven dried onions were the best. In addition, the thin-layer infrared radiative and convective drying modeling was carried on different varieties of onion. In this drying technique, the coefficients of drying models obtained by fitting of experimental data were expressed according drying conditions of onion [7] [14] [15] [16]. For determining the moisture transfer parameters, onion slices in thin layer were dried using different drying techniques such as infrared, convective, microwave and vacuum drying. The different transfer modes of moisture were defined in term of effective moisture coefficient. For quantifying these moisture transfers, the effective diffusion coefficients for each variety of onion was obtained by the conventional solution of Fick's second law of diffusion developed by Crank [8] [9] [10].

Although there is a large amount of studies available in the literature to determine and calculate the moisture transfer parameters such as moisture diffusivities and drying constants for the onions subjected to drying, no studies have been carried out to determine moisture diffusivities and moisture transfer coefficients using the drying process parameters in terms of *lag factor* and *drying coefficient*. This approach developed by [17] [18] is a simple but efficient tool to determine the moisture diffusivities and moisture transfer coefficients of solid objects exposed to drying. In this regard, in practice design engineers and workers prefer to use it for design and optimization of the process, which not only saves their valuable time but also helps in evaluating these parameters in a simple and accurate way without getting into complicated analysis [19]. In this model, the transient moisture diffusion process observed in the drying of solid foods is similar in form to the process of transient heat conduction in these objects. The governing Fickian equation is exactly in the form of the Fourier equation of heat transfer, in which temperature and thermal diffusivity are replaced by concentration and moisture diffusivity. The mass (moisture) transfer in drying of solid objects being in the transient form, Biot number and Fourier number of moisture transfer are defined after establishing a similarity between transient heat transfer and transient moisture transfer [20]. To show the goodness and the simplicity of this transient model, in the literature, several studies have used it to determine/estimate drying process parameters and drying moisture transfer parameters for wet solids drying. The model was shown to adequately determine the drying process parameters (e.g., drying coefficient, lag factor, and half-drying time) and moisture transfer parameters (e.g., moisture diffusivity and moisture transfer coefficient), and to calculate moisture content for drying spices (e.g. saffron stigmas [21]), fruits (e.g. lemon, bananas, passion fruit and kiwifruit [22] [23] [24] [25] [26]), vegetables (e.g. yam, broccoli, eggplant and potato [26] [27] [28] [29] [30]) and powders (e.g. lactose powder [31]). Otherwise, the graphical model for solid slabs has been developed and validated with some illustrative examples. Using this graphical methodology determination of the drying process parameters did not require solution of transcendental equations nor using an iterative solution technique [32]. An analytical technique of model was developed and verified by these illustrative examples to determine drying times of geometrically (slab, cylinder, and sphere) and irregularly shaped multi-dimensional objects by use of the geometric shape factors. The shape factors are employed and based on the reference drying time for infinite slab geometry. The irregular objects considered were approximated by representative elliptical cylinder and ellipsoid for two and three-dimensional shapes, respectively [33] [34]. In an extension of this model, a number of drying correlations, namely Bi-S, Bi-Re, Bi-G and Bi-Di were proposed to determine the moisture transfer parameters for solids drying processes. These correlations were found to adequately predict the moisture distribution profiles of some illustrative examples in its works, and were considered to be suitable for use in practical drying applications [20] [35] [36] [37].

It is in this logical approach that, using the experimental data, the aim of this study is to determine the moisture diffusivity and moisture transfer coefficients for "*Violet de Galmi*" onion subjected to convective drying using the analytical model developed by Dincer and Dost [19]. In addition, the effective moisture diffusivity as a function of air-drying temperature is also determined.

2. Materials and Methods

2.1. Materials

Fresh onion bulbs of the variety "*Violet de Galmi*" were purchased on stalls of fruits and vegetables from the central market, Ouagadougou, Burkina Faso. Fresh onions were sorted, cleaned and peeled by hand from their external layer. These onions were then stored at 4˚C in a refrigerator prior to the experiments [14].

After being stabilized at room temperature for 2 h, some homogeneous samples of onion were sliced 1 - 3 mm thick perpendiculars to the length of the largest semi-spindle of onion using an electric chain saw (model Secotom-10, Struers with precision of 1 - 3 mm). We obtained sliced samples from 30 mm to 50 mm in diameter and 1 - 3 mm thick. The sliced onions were then wrapped by using aluminum foil in an environment having average temperature of 24˚C to prevent all contact of the sample with ambient humidity. This permitted to avoid discrepancy in the composition of onion due to evaporation or to prevent the decay caused by microorganisms [38]. The mass of dry matter was determined by drying the onions at the end of the experiments in an electric oven at 70˚C for 24 h [39]. Experiments were repeated three times to get a reasonable average.

2.2. Experimental Set-Up

Thin-layer drying experiments were carried out in a wet laboratory dryer with control electronics Mincon 32 (VC0018, otsch Industrie technik Gmbh, German) (**Figure 1**). Dryer included, among other things, a console, a drying chamber, a cabinet. The relative humidity and the temperature of the drying air were controlled by the control panel and could be varied from 10% to 96% and from 10˚C to 90˚C. The speed of the air was regulated according to temperature and relative humidity determined by the panel. The drying chamber with a capacity of 190 liters was made in polished stainless steel. The maximum load of the

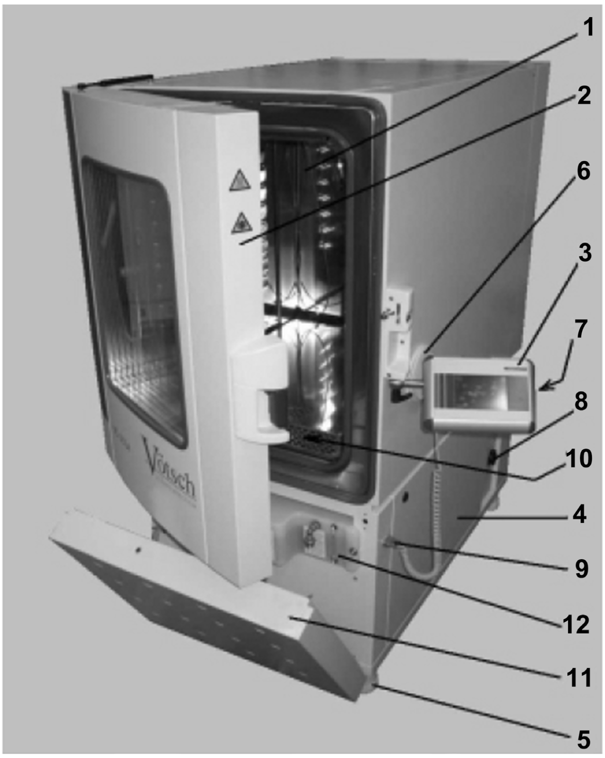

Figure 1. Description of the laboratory Dryer. 1: Drying room, 2: door, 3: command desk, 4: mechanic compartment, 5: support, 6: passage, 7: electric cabinet, 8: electric switch, 9: connexion, 10: humidity and temperature probe, 11: hood, 12: tank of water.

products by tray was 30 kg when the dryer operated in an environment of 25˚C. The fuse of the unit as well as all electrical components and control were integrated in the electrical cabinet. Measurement errors in the temperature according to time and to space in the drying chamber were respectively ±0.1 to ±0.5˚K and ±0.5 to ±1˚K. Measurement errors in the time relative humidity were ±1% to ±3% (**Figure 1**).

2.3. Experimental Protocol

A sliced sample was placed on a tray hanging from an electric balance (Model S4002, DENVER Instrument with precision of 1 - 3 g) which was located at the top of the dryer (**Figure 2**). The tray was made of nylon mesh allowing the crossing of the air on the surfaces of the sample. Balance is positioned in the center of the circular slot performed above the dryer. Minor vibrations caused by the driving forces of the fan ensuring the forced convection are eliminated by pressing tare of the balance before starting each one of the experiment. The experiments are conducted at temperatures of 40˚C, 50˚C, 60˚C and 70˚C and at 20% RH.

For each drying condition, averages of three repetitions were taken as data. At the end of each experiment, the sample was heated in an oven temperature of 70˚C during 24 h of drying in order to obtain the mass of dry onion skeletal structure [39]. Before performing experiments, dryer was turned on without a loading in order to stabilize at the instruction given by the command board. Heating and cooling rates are 0.6˚C/min and 0.3˚C/min, respectively. The dryer is therefore run for a sufficient period of time to reach the set point. The acquisition system is composed of a data logger (NI USB-6210, National Instruments), a LABview program installed in a computer.

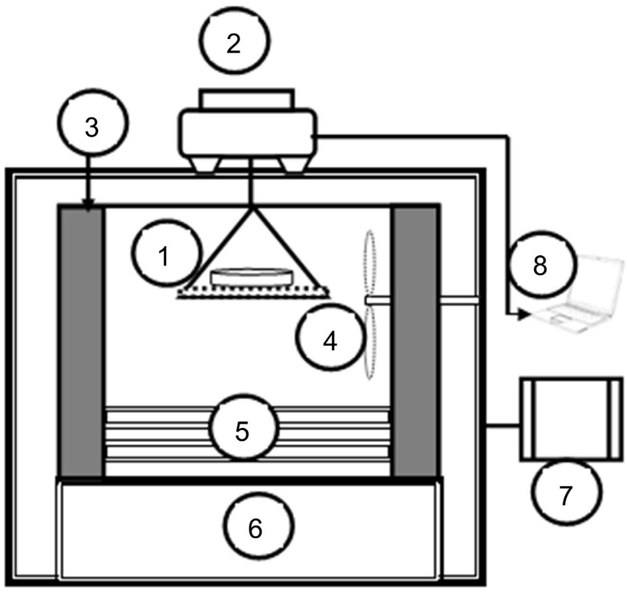

Figure 2. A schematic of the drying system. 1: Onion slices, 2: Balance, 3: Heater, 4: Fan, 5: Tray, 6: Water and electric material, 7: Panel, 8: Data logger.

2.4. Data Analysis

2.4.1. Mathematical Formulation of Drying

The transient moisture diffusion process observed in drying of solid objects is similar in form to the process of heat conduction in these objects. The governing Fickian equation is exactly in the same form of the Fourier equation of heat transfer, in which temperature and thermal diffusivity are replaced with moisture and moisture diffusivity, respectively, as following [40]:

$$\frac{\partial X}{\partial t} = D_{eff}\left(\frac{1}{y^n}\right)\left(\frac{\partial}{\partial y}\right)\left[y^n \frac{\partial X(y,t)}{\partial y}\right] \text{ with } n = \begin{cases} 0 \rightarrow \text{infinite plate} \\ 1 \rightarrow \text{infinite cylinder} \\ 2 \rightarrow \text{sphere} \end{cases}. \quad (1)$$

Consider an onion layer as an infinite slab being dried in a medium. Assume constant thermo-physical properties for the onion and for the drying medium, and the effect of heat transfer on the moisture loss is negligible. The moisture diffusion is assumed to occur in the thickness direction in the onion slab. Under these conditions, the one-dimensional transient moisture diffusion equation in rectangular coordinate can be written in the following form:

$$\frac{\partial X}{\partial t} = D_{eff}\left(\frac{\partial^2 X}{\partial y^2}\right) \quad (2)$$

This equation can be non-dimensionalized by the ratio of water content as follows

$$\frac{\partial \phi}{\partial t} = D_{eff}\left(\frac{\partial^2 \phi}{\partial y^2}\right) \quad (3)$$

$$\phi = \frac{X - X_{eq}}{X_0 - X_{eq}} \quad (4)$$

The equilibrium moisture content of onion was obtained from the Modified Henderson model of onion sorption on the respective ranges of 30˚C - 50˚C and 15% - 85%. This model was written as [41]:

$$X_{eq} = \frac{1}{100}\left[\frac{\ln(1-a_w)}{-3.6\times10^{-5}(T+10.87)}\right]^{\frac{1}{2.48}} \quad (5)$$

Equation (3) has the following boundary and initial conditions.

$$\phi(y,0) = 1 \quad (6)$$

$$\frac{\partial \phi(0,t)}{\partial y} = 0 \quad (7)$$

$$-D_{eff}\frac{\partial \phi(L,t)}{\partial y} = h_m \phi(L,t); 0.1 \le B_i \le 100 \quad (8)$$

2.4.2. Analytical Solution

The solution of the governing Equation (3) and the conditions in Equations (6)-(8) with $y = 0$ yields dimensionless center moisture distributions for the corresponding objects in the following forms [19]:

$$\phi = \sum_n^\infty A_n B_n \quad \text{for } 0.1 < B_i < 100 \text{ and } B_i > 100 \tag{9}$$

The above solution can be simplified if the values of $\mu_1^2 F_0$ > 1:2 are negligibly small. Thus, the infinite sum in Equation (9) is well approximated by the first term only, *i.e.* [32]:

$$\phi \approx A_1 B_1 \tag{10}$$

$$A_1 = \exp\left(\frac{0.2533 B_i}{1.3 + B_i}\right) \tag{11}$$

$$B_1 = \exp\left(-\mu_1^2 F_0\right) \tag{12}$$

with $B_i = \dfrac{h_m L}{D_{eff}}$ and $F_0 = \dfrac{D_{eff}}{L^2} t$.

Drying profile of onion was defined by the form similar to what has been done for the cooling profile for an object in transient heat transfer during the least squares method. This following model was proposed for the drying of onion using a dimensionless lag factor G and coefficient of drying S (s^{-1}) [36].

$$\phi = G \exp\left(-St\right) \tag{13}$$

The coefficient of drying was expressed the drying capacity of the product per unit of time and lag factor was an indication of internal resistance to mass transfer in the product during the drying process. These settings were useful for the evaluation and representation of the drying process. The values of the dimensionless moisture content can be found using the experimental moisture content measurements from Equation (4). The Equation (10) and Equation (13) permitted to put that $G = A_1$. Thus, the Biot number of moisture transfer for the onion slices was obtained as following:

$$B_i = \frac{1.3 \ln G}{0.2533 - \ln G} \tag{14}$$

The moisture diffusivity for the onion slices is given by the following equation:

$$D_{eff} = S\left(\frac{L}{\mu_1}\right)^2 \tag{15}$$

where the corresponding characteristic root μ_1 for an infinite slab object is given as [42]:

$$\mu_1 = \operatorname{atan}\left(0.640443 B_i + 0.380397\right) \tag{16}$$

Equation (15) can easily be used to determine the moisture diffusivity values for the slab onions. The equations determining the moisture transfer coefficients are given in the following form:

$$h_m = \frac{B_i D_{eff}}{L} \tag{17}$$

2.4.3. Activation Energy

The activation energy E_a was identified taking into account the variation of the effective diffusion coefficient of water in respect with the temperature following the Arrhenius relation [10].

$$D_{eff} = D_0 \exp\left(-10^3 \frac{E_a}{R\left(T + 273.15\right)}\right) \tag{18}$$

2.4.4. Fitting Parameters

The precision of data modeling was assessed using the following statistical criteria:

- The coefficient of determination (R^2)

R^2 is used in the context of statistical models whose main purpose is the prediction of future outcomes on the basis of other related information. It is the proportion of variability in a data set that is accounted for by the statistical model. It provides a measure of how well future outcomes are likely to be predicted by the model. The coefficient of determination is not likely to be 0 or 1, but rather somewhere in between these limits. The closer it is to 1, the greater relationship exists between experimental and predicted values. This value is used for the quantative comparison criteria and shows the level of agreement between measured and predicted values [43]. It was one of the first criteria used to select the appropriate model to describe the behavior of drying of fruits and vegetables [4].

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(P_{exp,i} - P_{pre,i}\right)^2}{\sum_{i=1}^{N}\left(\bar{P}_{exp} - P_{exp,i}\right)^2} \tag{19}$$

- Root Mean Square Error (*RMSE*)

Root-mean-square deviation, *RMSD*, or root-mean-square error, *RMSE*, is a frequently used measure of the differences between values predicted by a model or an estimator and the values actually observed from the thing being modeled or estimated. *RMSD* is a good measure of accuracy and serves to aggregate the residuals into a single measure of predictive power. It is required to reach zero and can be calculated as [39]:

$$RMSE = \left[\frac{\sum_{i=1}^{N}\left(P_{exp,i} - P_{pre,i}\right)^2}{N}\right]^{1/2} \tag{20}$$

- Chi-square reduced (χ^2)

It is the mean square of the deviations between experimental and predicted values for the models and used to evaluate the fitting agreement of each model. The lower the values of χ^2, the better the goodness of the fit and could be calculated as follows [43]:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(P_{exp,i} - p_{pre,i}\right)^2}{N - z} \tag{21}$$

- Sum of Squared Errors, *SSE*

SSE is the measure of the deviation of a sample from its "theoretical value". This parameter is defined as the difference between the experimental and predicted data and defined as [44]:

$$SSE = \sum_{i=1}^{N} \left(P_{exp,i} - P_{pre,i} \right)^2 \tag{22}$$

where P is the setting for drying given, $P_{exp,I}$ is the experimental value of the parameter, $P_{pre,I}$ is the value predicted by the parameter P, $\overline{P}_{exp,i}$, is the average value of the parameter P, N is the number of observations and z is the number of constants in each regression. The goodness of fit was found where R^2 was highest and lowest values of $RMSE$, χ^2 and SSE were found [39].

3. Results and Discussions

3.1. Drying Kinetics

Figure 3 shows the curves of drying for "*Violet de Galmi*" onions drying at four temperatures (40˚C, 50˚C; 60˚C and 70˚C) and at relative humidity of 20%. On Figure 3, all drying kinetics follows a drying falling-rate period. The absence of a constant drying rate period may be due to the thin layer of product that did not provide a constant supply of water for an applied period of time. Also, some resistance to water movement may exist due to shrinkage of the product on the surface, which reduces the drying rate considerably. The moisture content decreases gradually while the drying time elapsed, exhibiting a smooth downward curve. The dominating mechanism of moisture transfer during this period was moisture diffusion similar to that for most fruits and vegetables as such kiwi-fruit,

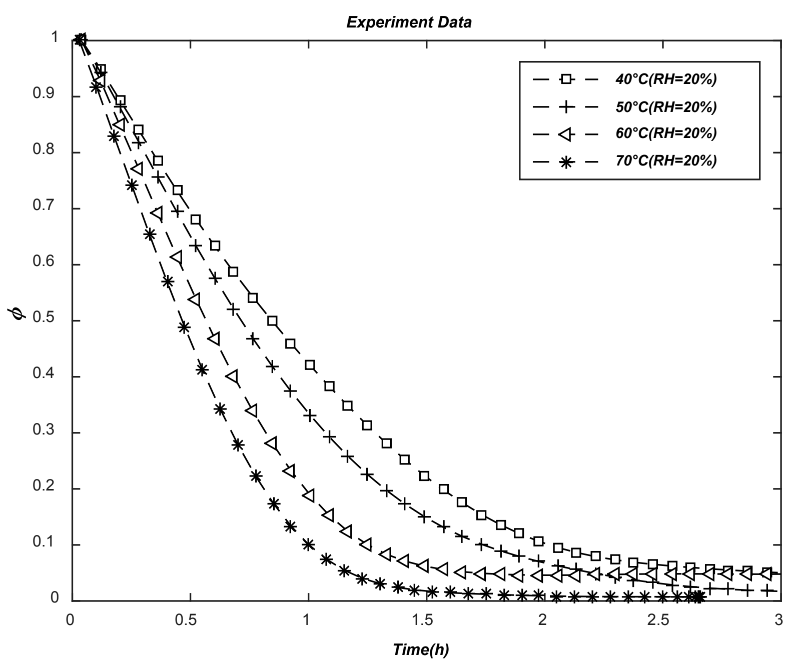

Figure 3. Curves of the onion drying in conditions of relative humidity of 20% and temperatures of 40˚C, 50˚C, 60˚C and 70˚C.

avocado, mango, cassava and banana [45] [46] [47] [48]. The drying times onions were obtained at 1.5, 2.0, 2.8 and 3.0 h at 70˚C, 60˚C, 50˚C and 40˚C, respectively. The air temperatures have a major effect on the drying kinetics. The air temperature increase from 40˚C to 70˚C leads to an increase in slope of curve describing the onion drying kinetics. By reducing the drying time of 40˚C to 70˚C, represents nearly 50% of the time of drying at air temperature of 40˚C. The drying air temperature influence water diffusion transport in onion convective drying when the air temperature increment between the different drying conditions is by at least 10˚C. The air drying running at higher air temperature and higher energy power leads to higher temperatures of onion slices implying a larger driving force for mass transfer. The mass transfer rates were higher in the beginning of the drying processes and gradually reduced through the end of the process. Thus more energy was absorbed by the water at the onion surface initially, resulting in faster drying and with the onion surface drying out subsequently, heat penetration through the dried layer decreased thus retarding the drying rates. Also the differences in drying rates caused by different air temperatures levels are higher at the beginning of drying; while by the end of the processes all drying kinetics are closer to each other. During the processes towards the end of drying, the influence of temperature on the drying kinetics is lower than at the beginning and that moisture transport is hindered more and more by internal mass resistances of onion bulb [28]. Because this temperature effect on drying, stepwise changes in temperature from one drying period to another period could be employed so as to avoid a degradation of heat-sensitive natural compounds (antioxidants, color, vitamins) of onion slices and so to save much energy of drying. Similar observations were obtained in a review from Sagar and Kumar [49] on the recent advances in the drying and the dehydration of fruits and vegetables. In literature, our results were generally in agreement with some previous findings on onion drying. It was indicated in a convective drying of *yellow* onion under drying air temperature of 30˚C to 60˚C. It was visible how the moisture (expressed in dry basis) follows an exponential decay, and how the increase in temperature accelerated this drying process. In this, at 30˚C the drying stabilized after approximately 7 hours whereas at 60˚C 2 hours were sufficient, representing a very important reduction in the drying time (more than 70%) [4]. Three levels of airflow temperature (40˚C - 50˚C - 60˚C) were applied to dry onion by a custom designed fluidized bed dryer equipped with a heat pump dehumidifier, predicting its drying behavior by regression, fuzzy logic and artificial neural network techniques [50]. Drying temperatures exerted a pronounced effect on the quality changes of sliced onion. The drying temperatures up 60˚C did not show any influence on quality changes. However, drying temperatures above 60˚C significantly influenced the color of the dried onion [51]. By using oven drying method (50˚C and 70˚C), the onion drying time up to the moisture content of approximately $X_f = 0.818$ (*dry basis*) could be shortened by 11.76% and 79.41%, when compared to sun drying, respectively. For microwave oven drying at 210 W and 700 W, the onion drying times to reach the moisture content of $X_f = 0.960$ (*dry basis*) were 10.5 min and 8.33 min, respectively. This was due to the fact that drying at higher temperature and higher energy power which led to higher temperatures implied a larger driving force for heat transfer [6]. The effect of drying temperature on drying kinetics of onion (*Allium cepa L.*) slices with convective and microwave drying showed that the drying rate increased with increasing in drying air temperature and consequently decreased the required drying time. It is a fact that the higher temperature difference between the drying air and onion slices increases the heat transfer coefficient, which influences the heat and mass transfer rate. Drying of onion slices generally occurred in falling rate period because of quick removal of moisture [52].

3.2. Drying Process Parameters

The experimental data of onion drying curves obtained at air temperatures of drying (40˚C, 50˚C, 60˚Cand 70˚C) and at relative humidity of 20%, in the form of moisture content ratio, are fitted to Equation (13). The statistical results of fitting are performed by using the MATLAB.7.12.0 (R2011a) installed on the network of the University of Lorraine (France). **Table 1** summarizes the statistics and drying parameters for modeling convective onion drying at air temperatures of 40˚C to 70˚C.

Among these established statistical results, the values of *SSE*, R^2 and *RMSE* obtained for modeling drying have been varied between 0.0288 and 0.0468, between 0.9824 and 0.9931 and between 0.0235 and 0.0370 respectively. The average values of *SSE*, R^2 and *RMSE* are 0.0415, 0.9883 and 0.0301, respectively. This average value of R^2 is very close to 1 while the average values of *SSE* and *RMSE* are close to 0. These statistic parameters of model have been satisfied for modeling drying of this onion variety. To illustrate the quality of model fitting, **Figure 4** shows the experimental data compared to those of the model obtained at drying temperatures. In this figure, the results showed a reasonably good agreement between the values predicted from the correlation and the experimental observations. Therefore, the drying parameters obtained from the model reflect the physical and thermal behavior of the process of convective drying of the "*Violet de Galmi*" onion in thin layers. Due to the fact that drying has an exponentially decreasing trend, two drying parameters like lag factor (*G*, dimensionless) and drying coefficient (*S*, s^{-1}) could be introduced for describing this drying. Drying

Table 1. Drying process and fitting parameters for drying the onion with drying air temperature.

Model	40˚C	50˚C	60˚C	70˚C
G	1.111	1.136	1.150	1.162
S (s^{-1}) × 10^4	2.856	3.322	4.794	5.056
SSE	0.0344	0.02883	0.05614	0.04681
R^2	0.9919	0.9931	0.9824	0.9858
RMSE	0.02572	0.02355	0.037	0.03421

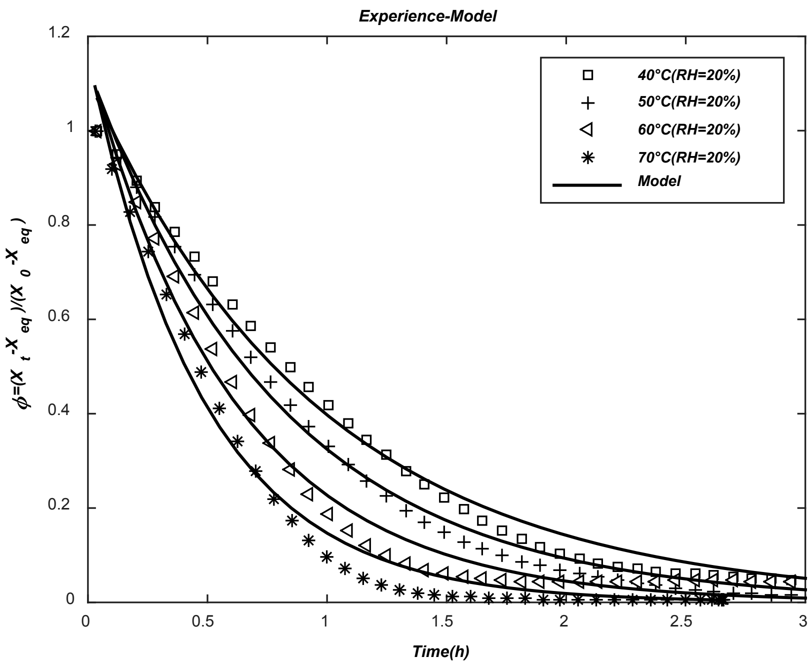

Figure 4. Modeling of onion drying curves at air temperatures of 40˚C, 50˚C, 60˚C and 70˚C.

coefficient shows the drying capability of onion slice and has a direct effect on the moisture diffusivity. In **Table 1**, the obtained drying coefficient values, *S*, were 2.856 × 10^{-4}, 3.322 × 10^{-4}, 4.794 × 10^{-4} and 5.056 × 10^{-4} s^{-1} for drying temperatures of 40˚C, 50˚C, 60˚C and 70˚C, respectively, providing an accurate indication of the drying behavior (**Figure 3**). This *S* value range was in concordance with that of other food products such as carrot (1.038 × 10^{-4} s^{-1} at 50˚C), prune (0.70 - 3 × 10^{-4} s^{-1} at 60˚C), potato (0.70 - 9 × 10^{-4} s^{-1} at 40˚C - 80˚C), starch (6 × 10^{-4} s^{-1} at 59˚C), okra (9 × 10^{-4} s^{-1} at 40˚C), broccoli (13 - 24 × 10^{-4} s^{-1} at 50˚C - 75˚C), passion fruit peel (1.83 - 2.74 × 10^{-4} s^{-1} at 50˚C - 70˚C) (**Table 2** and **Table 3**). Kaya *et al.* [53] reported the drying coefficient for some regularly shape agricultural products such as slab carrot (0.20 - 0.41 × 10^{-4} s^{-1}), slab pumpkin (0.16 - 0.33 × 10^{-4} s^{-1}) and cylindrical carrot (0.19 - 0.39 × 10^{-4} s^{-1}) dried in a convective hot air dryer at temperatures of 30 - 60˚C and constant air flow rate of 1 m·s^{-1} [53]. Torki-Harchegani *et al.* [22] were obtained drying coefficient values range 0.027 - 0.24 × 10^{-4} s^{-1} for the whole lemons. The whole lemons were dried in a convective hot air dryer at drying temperatures of 50˚C - 75˚C and a constant air velocity (1 m·s^{-1}) [22]. In infrared thin layer drying of saffron stigmas, Torki-Harchegani *et al.* [21] found the drying coefficient varied from 4.75 - 16.11 × 10^{-4} s^{-1} at the temperatures from 60˚C to 110˚C [21]. From the obtained results, the drying coefficient increased with increasing drying air temperature. This is due to the fact that an increment in drying temperature increases the heat and mass transfer between the heating media and solid object and consequently, leads to a higher drying capability of the object. Babalis *et al.* [54] reported the same results for convective hot air drying of figs in the temperature range of 55˚C - 85˚C and the air flow rate in the range of 0.5 - 3 m·s^{-1} [54].

The lag factor (G) is an indicator of the magnitude of both the internal and external resistance to moisture transfer from the product and has a direct effect on the moisture transfer coefficient as a function of the Biot number [36] [55]. The values of lag factor (1.111, 1.136, 1.150 and 1.162 for air temperatures of 40˚C, 50˚C, 60˚C and 70˚C, respectively) were more than 1 indicating moisture diffusion within the samples is controlled by both internal and external resistance. The variation in calculated values, between 1.111 and 1.162, reflects lumped system specific mass transfer properties. The obtained lag factor values in this study are consistent with reported results for the foods products (**Table 4**) such as prune (1.0016 - 1.0086) [20] [32] [35] [37], potato (1.0074 - 1.255) [20] [35] [56], broccoli (1.000 - 1.006) [28], passion fruit peel (1.020 - 1.051) [24], eggplant (1.032 - 1.117) [29], lactose powder (1.086 - 1.370) [31], lemons (1.118 - 1.158) [22], saffron (1.096 - 1.104) [21] and apples (1.108 - 1.209) [57].

3.3. Mass Transfer Biot Number

The lag factor is an indicator of magnitude of both internal and external resistances of a solid object to the heat and/or moisture transfer during drying process as a function of the Biot number (Equation (14)). There are three cases of the Biot number: $B_i < 0.1$, $0.1 < B_i < 100$ and $B_i > 100$. The case of $B_i < 0.1$ indicates that minor internal resistance and major surface resistance across the boundary layer (external resistance) to moisture transfer and moisture gradient inside the product are so small while, $B_i > 100$ means that internal resistance is much more than external resistance. The case of $0.1 < B_i < 100$ indicates the existence of both finite internal and surface resistances and is known as the most common case for the drying applications [36] [55]. The calculated Biot number values were in the range of 0.9797 - 2.9397 at drying temperature range 40˚C - 70˚C (**Table 2**), indicating the presence of the both internal and external resistances to moisture transfer, which is consistent with reported results for foods on literature (**Table 4**) such as potato (0.0851 - 1.1280, at 40˚C - 80˚C) [20] [35] [56], broccoli (0.2299 - 0.3228, at 50 - 75˚C) [28], passion fruit peel (0.1018 - 0.3199, at 50˚C - 70˚C) [24], lemon (0.361 - 2.894, at 50˚C - 75˚C) [22] and lactose powder (0.185 - 1.370, at 20˚C - 40˚C) [31]. The variation in calculated Bi numbers suggests that it was a function of the product and drying process parameters. During onion convective drying, the B_i number was found to increase

Table 2. Biot numbers and moisture transfer parameters calculated for onion drying with air temperature.

Parameters	40˚C	50˚C	60˚C	70˚C
B_i	0.9797	1.4323	1.6003	2.9397
μ_1	0.7893	0.9142	0.9523	1.1547
$D_{eff} \times 10^9$ (m^2·s^{-1})	0.2578	0.3975	0.5287	0.5460
$h_m \times 10^7$ (m·s^{-1})	3.37	5.69	8.46	13.38

with increasing temperature indicating internal mass transfer control (**Table 2**). The results are in agreement with those reported for the convective drying of lemon slices [22], broccoli [28], eggplant slices [29] [58], potato [56] [59], passion fruit peel [24], saffron [21] and banana [60]. McMinn *et al.* [56] found that the microwave and combined microwave-convective drying of potato slices and cylinders were controlled by power levers. Thus the Bi number increased with power level (slab, 0.521 and 0.650 for 90 and 650 W, respectively) [56]. This is why a number of Biot number correlations for mass transfer, namely Bi-S, Bi-Re, Bi-G and Bi-Di were proposed according the medium and product parameters for use in practical drying applications [20] [35] [36] [37].

3.4. Effective Diffusion Coefficient

Analysis of moisture transfer mechanism in the falling rate period, based on the procedure described by [61], confirmed the diffusive nature of moisture movement. The non-linear pattern of moisture ratio and time on a semi-log plot also indicated the diffusive nature of moisture transport rather than capillary. It may be attributed to shrinkage in the product, non-uniform distribution of initial moisture and temperature coupled with variation of moisture diffusivity with moisture content [62]. The mass diffusivity in the diffusion model is a fundamental property based on molecular interactions and on the physical structure of the material [63]. All of the various phenomena of mass diffusion are represented by the effective diffusion coefficient. Using the values of μ_1 and S, effective diffusion coefficient D_{eff} of "*Violet de Galmi*" onion drying is calculated from Equation (15). The calculated values of D_{eff} at onion drying conditions are found between $0.2798 \times 10^{-9}\ m^2 \cdot s^{-1}$ and $0.8121 \times 10^{-9}\ m^2 \cdot s^{-1}$ (**Table 2**). The magnitude range of these D_{eff} values is close to those proposed for air convective drying of onion obtained by the conventional solution of Fick's second law of diffusion developed by Crank (**Table 3**) such as the range 3.33 - 8.559 × $10^{-9}\ m^2 \cdot s^{-1}$, at 30˚C - 60˚C obtained by [4], the range 0.025 - 0.032 × $10^{-9}\ m^2 \cdot s^{-1}$, at 30˚C - 60˚C obtained by [5], the range 0.747 - 1.554 × $10^{-9}\ m^2 \cdot s^{-1}$, at 50˚C - 70˚C obtained by [6], the range 34.9 - 94.4 × $10^{-9}\ m^2 \cdot s^{-1}$, at 50˚C - 70˚C obtained by [9], the range 1.96 - 14 × $10^{-9}\ m^2 \cdot s^{-1}$, at 50˚C - 70˚C obtained by [10], the range 2.084 - 2.271 × $10^{-9}\ m^2 \cdot s^{-1}$, at 40˚C - 60˚C obtained by [13]. The small difference range of D_{eff} for onion convective drying are due to the diffusivities dependence of the drying characteristics (air velocities, combination of Infrared, vacuum, microwave drying techniques with convective drying) and product characteristics (thickness, pretreatment namely water blanching and blanching-steaming). Dincer and Hussain [35] explained that the variation of moisture diffusivity data of the foods was often due by structure complexity of foods [35]. Pathare and Sharma [5] noted that the diffusivities are negatively correlated with air velocity. The increase in air velocity accelerated the cooling effect, which reduced the temperature of the product and water vapor pressure [5]. Concerning the temperature parameter, the temperature level had a considerable influence on the magnitude

Table 3. The drying process parameters and moisture transfer parameters for drying of food products in literature.

Product	Drying conditions					Model coefficients			Drying coefficients	
	Shape	T_a (˚C)	RH (%)	v_a (m/s)	$CD \times 10^3$ (m)	B_i (−)	$S \times 10^4$ (1/s)	G (−)	$D_{eff} \times 10^8$ (m²/s)	$h_m \times 10^7$ (m·s⁻¹)
Carrot [32]	Slab	50	—	2.5	5	0.637	1.038	1.08	0.5189	6.6084
Prune [32]	Slab	60	15	3 - 5	5	0.05	0.79	1.0086	3.854	4.0261
Prune [20]	Slab	60	—	3.5	2.5	0.4054	3	1.0037	6.6905	108.49
Potato [20]	Cylinder	60	—	1.0	13.5	0.3139	0.7	1.032	6.7172	15.618
Potato [20]	Sphere	40	—	1.0	9	0.3736	9	1.0074	94.198	391.02
Starch [36]	Cylinder	59	—	2.0	5	0.0929	6	1.0181	12.991	2.4137
Yam [36]	Sphere	105	11	—	30	47.9471	46	1.2864	151.1	2.4151
Prune [35]	Slab	60	—	3.0	7.5	0.0745	0.7	1.0016	19.889	19.756
Potato [35]	Cylinder	80	—	1.2	3	0.0851	1	1.1981	0.0567	0.1610
Okra [35]	Sphere	40	—	1.0	9	0.3119	9	1.0074	94.259	326.65
Broccoli [28]	Slab	50	—	1.2	10	0.2716	13.7	1.006	357.8	1921.5
	Slab	50	—	1.75	10	0.2299	12.8	1.002	601.12	2731.9
	Slab	50	—	2.25	10	0.2060	12.3	1.003	488.86	1991.9
	Slab	60	—	1.2	10	0.2901	17.5	1.004	597.47	3517.2
	Slab	60	—	1.75	10	0.2595	17.6	1.002	826.54	4232.8
	Slab	60	—	2.25	10	0.2392	16.8	1.002	788.97	3613.4
	Slab	75	—	1.2	10	0.3228	18.9	1.001	1067.6	6469.1
	Slab	75	—	1.75	10	0.3000	22.7	1.001	1282.3	7224.3
	Slab	75	—	2.25	10	0.2629	24.0	1.000	1666.7	8725.6
Passion fruit peel [24]	Slab	50	—	2.0	6.7	0.1447	1.83	1.026	1.049	4.530
	Slab	60	—	2.0	6.7	0.1103	2.25	1.020	1.403	4.619
	Slab	70	—	2.0	6.7	0.1018	3.12	1.019	1.994	6.062
	Slab	50	—	3.5	6.7	0.3199	1.58	1.051	0.632	6.039
	Slab	60	—	3.5	6.7	0.2253	2.20	1.038	1.057	7.111
	Slab	70	—	3.5	6.7	0.2178	2.74	1.037	1.339	8.702

—: not measured, CD: characteristic dimensions.

of the diffusivity during convective drying (0.2798 × 10^{-9} m²·s⁻¹ for 40˚C and 0.8121 × 10^{-9} m²·s⁻¹ for 70˚C, respectively). Such results from this analysis are in accordance with the experimental observations (**Figure 3**). They are also similar with the results for onion convective drying reported by Mota *et al.* [4], by Demiray *et al.* [9], by Asiah and Djaeni [13] and with the results for the food convective drying such as potato [56], lemon [22], spirulina [39], blackwood passion fruit [24] and banana [64]. Torki-Harchegani *et al.* [21] obtained in saffron drying that any increment in the drying temperature leaded to an increment in the diffusivity. In fact, an increase in temperature caused a decrease in water viscosity and increased the activity of water molecules. These phenomena facilitated diffusion of water molecules in object capillaries and consequently, increased the moisture diffusivity [21]. Sharma *et al.* [8] reported that the moisture diffusivity of food material was affected by its moisture content, temperature as well as its composition and porosity. This may indicate that as the moisture content decreased, the permeability to water vapor increased as it provided more pore structure open. The temperature of the product would have risen rapidly in the initial stages of drying due to more absorption of convective heat. This increased the water vapour pressure inside the pores resulted into pressure induced opening of the pores. Furthermore, Süfer *et al.* [10] concluded in their study that slice thickness and pretreatment application affected Deff adversely, whereas temperature increase enhanced the moisture diffusivities at high temperatures, any augmentation in energy of heating causes an increase in the molecular activity of water, thus generating higher diffusivity. In addition, high salt concentrations in vegetable cells may reduce or prevent moisture removal from food system [10] [65].

3.5. Mass Transfer Coefficient

Knowing both the moisture diffusivities and mass transfer coefficients for the various systems is essential, as more complex mathematical models and correlations which can provide a more in depth understanding of the drying operations require data on specific mass transfer parameters. This is an important drying parameter that depends on mass diffusivity, viscosity, velocity of the fluid, and geometry of the transfer system [63]. The mass transfer coefficient values of "*Violet de Galmi*" onion drying in thin layers are obtained from Equation (17) using the Biot number and effective moisture diffusivities. Mass transfer coefficients hm are presented in **Table 2**. The values of hm obtained for drying conditions of "*Violet de Galmi*" onion slice vary between 3.37×10^{-7} $m \cdot s^{-1}$ and 13.38×10^{-7} $m \cdot s^{-1}$. These results were found in the range (0.16 - 8725.60×10^{-7} $m \cdot s^{-1}$) of those available in the existing literature for different foods and drying conditions (**Table 4**), such as the convective drying of potato (0.16 - 391.02×10^{-7} $m \cdot s^{-1}$, at 40˚C - 80˚C) [20] [35] [56], broccoli (1921.5 - 8725.6×10^{-7} $m \cdot s^{-1}$, at 50˚C - 75˚C) [28], passion fruit peel (4.530 - 8.702×10^{-7} $m \cdot s^{-1}$, at 50˚C - 70˚C) [24], lemon (0.163 - 9.008×10^{-7} $m \cdot s^{-1}$, at 50˚C - 75˚C) [22], saffron (2.6433 - 8.7203×10^{-7} $m \cdot s^{-1}$, at 60˚C - 110˚C) [21] and eggplant (6.478 - 2.190×10^{-7} $m \cdot s^{-1}$, at 50˚C - 70˚C) [29]. Ours results were also in accordance with those from Markowski [66] who determinates an average mass transfer coefficient value of 1.371×10^{-7} $m \cdot s^{-1}$ during drying of fresh carrot slices, those by Elbert *et al.* [67] with a value of 4.81×10^{-7} $m \cdot s^{-1}$ during parboiled rice drying, those by Tsami and Katsioti [68] with 4.026×10^{-7} $m \cdot s^{-1}$ during drying of prune slices, and those by Ruiz-Cabrera *et al.* [69] with 6.608×10^{-7} $m \cdot s^{-1}$ during carrot drying. Examination of the relative magnitude of the mass transfer coefficient for onion showed a variation

Table 4. The moisture diffusivities obtained from the conventional solution of Fick's second law of diffusion and the activation energy for onion drying.

Thickness (mm)	$D_{eff} \times 10^9$ (m^2/s)	E_a ($kJ \cdot mol^{-1}$ or $W \cdot g^{-1}$)	*Drying Conditions*	*Ref*
3 - 4	3.33 - 8.55	26.4	Convective (T_a = 30˚C - 60˚C, V_a = 0.35 m/s)	[4]
6 ± 0.01	0.025 - 0.032	5.06 - 10.63	Infrared Convective (I_R = 26.5 - 44.2 kW/m², T_a = 30˚C - 60˚C, V_a = 0 - 1.5 m/s)	[5]
6 ± 0.1	0.021 - 0.157		Infrared radiation (I_R = 0.3 - 0.5 kW, T_a = 35˚C - 45˚C, V_a = 1 - 1.5 m/s)	[7] [8]
	0.834		Sun (-)	
10 ± 0.1	0.747 - 1.554		Air oven (T_a = 50˚C - 70˚C)	[6]
	40 - 48.69		Microwave oven (210 - 700 W)	
7 ± 1	34.9 - 94.4	45.6	Convective (T_a = 50˚C - 70˚C)	[9]
	259 - 508	7.897 - 5.461	Microwave (I_R = 328 - 557 W)	
3 - 7	1.96 - 14	3.28 - 34.13	Convective (T_a = 50˚C - 70˚C, V_a = 0.5 m/s)	[10]
	9.757 - 17.23		Vacuum (T_a = 50˚C - 70˚C, V_a = 1.5 m/s)	
	32 - 914	2.25 - 6.08	Microwave (80 - 400 W)	
10 ± 0.1	0.0474 - 0.0527	2.367 - 9.779	Water blanching (60˚C - 80˚C) + convective (T_a = 60˚C)	[11]
2	0.102 - 0.209		Blanching–steaming (P_v = 0.2 - 0.5 MPa and vacuum of 5 kPa) + convective (T_a = 40˚C, V_a = 1 m/s, P_a = 267 Pa)	[12]
10 ± 0.1	2.084 - 2.271		Convective (T_a = 40˚C - 60˚C)	[13]

with the temperature parameters under the drying operations providing further comprehension of the mass transfer characteristics. For our onion drying experimentation, the value of h_m (3.37×10^{-7} $m \cdot s^{-1}$ at 40 - 5.69×10^{-7} $m \cdot s^{-1}$ at 50 - 8.46×10^{-7} $m \cdot s^{-1}$ at 60 - 13.38×10^{-7} $m \cdot s^{-1}$ at 70˚C) varied positively with drying temperature. It showed that the value of hm increased with drying temperature of onion. This is a confirmation of results obtained for drying constant S and diffusivity D_{eff}. This dependence result of temperature was also similar to that from McMinn [31] for dying lactose powder, form Torki-Harchegani *et al.* [22] for drying lemon, from Mrkić *et al.* [28] for drying broccoli, from Torki-Harchegani *et al.* [21] for drying saffron and Bezerra *et al.* [24] for drying passion fruit peel.

3.6. Average Activation Energy

The values of the diffusivity for "*Violet de Galmi*" onion drying at drying temperature are used to estimate the values of the diffusivity for an infinite temperature and the average activation energy E_a by Equation (18). Thus, the natural logarithm of the diffusion coefficient is represented according to the absolute temperature reciprocal (Equation (17)) [24]. The values obtained for the water diffusion coefficient at infinite temperature D0 and the average activation energy E_a for "*Violet de Galmi*" onion drying are respectively 1.372 $m^2 \cdot s^{-1}$ and 31.73

kJ·mol^{-1} with R^2 = 0.99, SSE = 2.666 × 10^{-6} and $RMSE$ = 0.001633. The values obtained for the average activation energy are close to those obtained in the literature of convective drying of onion (**Table 3**) such as E_a = 26.4 kJ·mol^{-1} from Mota *et al.* [4], E_a = 10.93 - 34.13 kJ·mol^{-1} from Süfer *et al.* [10] and E_a = 45.6 kJ·mol^{-1} from Demiray *et al.* [9]. The range of energy activation of 5.06 kJ·mol^{-1} to 10.63 kJ·mol^{-1} is reported for infrared convective drying of onion slices under air temperature conditions of 35˚C - 45˚C [5]. Ours E_a values are in the range of E_a = 12 - 110 kJ·mol^{-1} of food and agricultural products were, hence findings were in agreement with literature [70]. The differences between the values reported in the present work and the values highlighted in the literature are related with the dependence of the diffusion coefficient of a food with the conditions within the material on drying [24]. For Baia Periforme variety, the activation energy for convective drying of onion was E_a = 34.081 kJ·mol^{-1} at temperature range of 40˚C - 60˚C [71]. Ours Ea of onion slices were also close to green beans (E_a = 35.43 kJ·mol^{-1}, convective drying; [72]), radish (E_a = 15 - 40 kJ·mol^{-1}, vacuum drying; [73]), carrot (E_a = 22.43 kJ·mol^{-1}, infrared drying; [74]) and mulberry (E_a = 21.2 kJ·mol^{-1}, convective drying; [75]). These values can be interpreted as an energy barrier that must overcome the drying mechanism to remove moisture. This vision of the drying energy barrier is to advantage developed by other approach theory for drying modeling [76] [77] [78].

4. Conclusion

The results of this study indicate that the model developed by Dincer and Dost [19] can be used with reasonable accuracy and confidence to calculate the moisture diffusivity and mass transfer coefficient values for convective drying of "*Violet de Galmi*" onion for temperature range of 40˚C - 70˚C and a relative humidity of 20%. Through this model, effective diffusion coefficient values are obtained between 0.2578 × 10^{-9} m^2·s^{-1}and 0.5460 × 10^{-9} m^2·s^{-1}. Onion mass transfer coefficients vary between 3.37 × 10^{-7} m·s^{-1} and 13.38 × 10^{-7} m·s^{-1}. Mass transfers Biot Numbers of are found between 0.9797 and 2.9397. Activation energy is determined for using the Arrhenius Type equation on the drying temperature range. The activation energy E_a is 31.73 kJ·mol^{-1}. This study contributes to estimate the "*Violet de Galmi*" onion of mass transfer and drying process parameters, an onion variety consumed largely in West Africa. This information can be useful in designing and simulating drying equipment and in using this onion as a drying product. However, other parameters such as the fleshy leaves structure of "*Violet de Galmi*" onion could have effects on the water migration during drying. This could be the subject of other research on "*Violet de Galmi*" onion as the effect of drying on the nutritional composition of this variety.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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