Convective drying of onion: modeling of drying kinetics parameters

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Abstract Drying is a simultaneous heat and mass transfer processes. Drying kinetics is determined by both internal properties and external drying conditions. In this study, two important drying kinetics parameters of onions i.e. effective water diffusivity and relative activation energy of reaction engineering approach (REA) are determined. The generated parameters are used to model thin layer drying of onion at different temperatures (40, 50, 60, and 70 °C) and relative humidity of 20%. The effective water diffusivity is in the range of $2.8 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$ and $8.1 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$. Unlike the diffusivity, the relative activation energy of the REA is independent on drying conditions and thus the latter approach requires less effort in generating the transport properties. The transport parameters can be applied for assisting in designing dryer units and evaluating the performance of existing dryer units.

Keywords Drying · Diffusivity · Reaction engineering approach (REA) · Kinetics · Transport

Introduction

“*Violet de Galmi*” onion (*Allium cepa*) is one of the most important crops in West Africa. It belongs to *Amaryllidaceae* family and has been widely cultivated for a long time as a garden plant. Globally, the production was estimated to 82,851,732 tons in 2012 (FAO 2018). Onions contain important substances which play an important role as antimicrobial, antioxidant, anti-carcinogenic and prebiotic activities (Lanzotti 2006; Corzo-Martínez et al. 2007). Bulbs from onion species contain significant amounts of beneficial compounds such as allicin and their derivatives or flavonoid glycosides. These compounds are essentially good antioxidant and possess free radical scavenging power (Lombard et al. 2005; Ko et al. 2011). In terms of nutrition, fresh “*Violet de Galmi*” onion contains 89.15% of water, 1.25% of protein, 0.58% of fat, 7.37% of carbohydrates and 1.42% of dietary fiber. It also contains major minerals including potassium, calcium, selenium, chlorine, sulfur, and phosphorus.

For producing processed foods such as sausages and condiments, dried onions are preferred over fresh onions due to longer shelf life and ease for transportation. Convective dryers are commonly used to produce dried onions to extend the shelf-life. Nevertheless, designing convective drying system with maintained quality of food materials is challenging since alteration of flavor, taste, natural color and nutrients may occur during drying due to the high drying air temperature (Pan et al. 2008; Cnossen et al. 2002). In addition, drying is an energy-intensive process since vaporization heat of water is basically large. Because

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of this, drying systems need to be developed to lower energy consumption while minimizing quality changes. Alternatively, hybrid drying, involving ultrasound, infrared-heating and microwave-heating, can be implemented (Gunasekaran 1999; Carcel et al. 2012).

For designing drying systems, it is essential to capture drying kinetics of materials of interests. The drying kinetics determines drying time which directly affects size of dryer units. The drying kinetics parameters are essentially transport properties of the materials which are dependent on the physical, chemical and biological properties of the materials. The drying kinetics parameters also provide critical information for optimizing performance of existing dryers. Combined with the external heat and mass transfer coefficients, the transport properties are required to determine the optimum operating schemes and conditions (e.g. drying air temperature, drying air velocity, humidity) (Woo et al. 2008). In addition, the transport parameters give useful information to analyse the behaviors of materials as affected by external drying conditions. These parameters are needed to project the spatial profiles of variables (i.e. moisture content, temperature and concentration) inside the materials during drying (Brasiello et al. 2013; Putranto and Chen 2018). Based on these predictions, local quality changes and sensory properties can be estimated. The drying kinetics can be coupled with structural information to tailor the drying conditions to produce food materials with the desirable properties.

For internal transport parameters, there are two major approaches commonly used i.e. diffusion-based approach and reaction engineering approach (REA). In this paper, these two models are attempted to model the convective drying of onion due to the simplicity in mathematical modeling which helps the industry for quick decision-making. The diffusion-based model can be translated into algebraic equations which make easier for computation the diffusivity. Similarly, the computational approach of the reaction engineering approach is simple since the reaction engineering approach is represented in ordinary differential equations. The first approach basically assumes that internal transport during drying is governed by diffusion (Mariani et al. 2008; Vaquiro et al. 2009). Since during drying, liquid diffusion, evaporation and vapor diffusion occur simultaneously, ‘effective water diffusivity’ is commonly used as a single coefficient to lump the whole phenomena (Chen 2007). The reaction engineering approach (REA) essentially an application of chemical reaction engineering for drying in which drying is seen as reversible process of evaporation and condensation. In this approach, the relative activation energy, a material characteristics, is used to describe the internal behaviors of materials being dried.

This study is aimed to determine the diffusivity and the relative activation energy of “*Violet de Galmi*” onion and

evaluate the effectiveness of these two approaches to model convective drying. The validity of the two methods is validated towards the experimental data. The paper is organised as follows i.e. firstly, the experimental details are explained followed up by a review of diffusion-based approach and reaction engineering approach. Subsequently, the drying parameters generated by both methods are presented and discussions on the applications of both approaches to model the convective drying of onion is provided.

Experimental details

Thin-layer drying experiments were carried out in a laboratory dryer (Fig. 1) with electric controller Mincon 32 (VC0018, *otsch Industrietechnik GmbH, German*). The relative humidity, temperature and velocity of the drying air was regulated. The tray was made of nylon mesh allowing the crossing of the air on the surfaces of the sample. The balance was located in the center of the circular slot performed above the dryer. The experiments were undertaken at drying air temperatures of 40 °C, 50 °C, 60 °C and 70 °C and relative humidity of 20%. The measurement errors of temperature were ± 0.1 – ± 0.5 °C while those of relative humidity were ± 1 – ± 3 %.

Fresh onions of the variety “*Violet de Galmi*” purchased on the local market stalls were sorted, cleaned and cut into samples with thickness of 2 mm. A sample was placed on a tray hanging from an electric balance (Model S4002, DENVER Instrument with precision of 10^{-2} g) which is located at the top of the dryer (Fig. 1). During drying, the sample weight was monitored continuously and three

Fig. 1 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

replicates of measurement were undertaken. The acquisition system was composed of a data logger (NI USB-6210, National Instruments) where a LABview program is installed in the computer.

Mathematical modeling

Modeling using diffusion-based model

Generally, the diffusion-based model which describes the dynamics of moisture content inside the samples during drying can be expressed as:

$$\frac{\partial X}{\partial t} = D_{\text{eff}} \left(\frac{1}{y^n} \right) \left(\frac{\partial}{\partial y} \right) \left[y^n \frac{\partial X(y, t)}{\partial y} \right] \quad (1)$$

where X is the water content (kg water kg dry solids⁻¹), D_{eff} is the effective water diffusivity (m² s⁻¹), y is the space variable (representing the radius for a sphere and a cylinder and the half thickness of a plate), n is a number which take “0” for an infinite plate, “1” for a cylinder form and “2” for a spherical form. For flat samples, the mass balance can be represented as:

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

The initial and boundary conditions of Eq. (2) are:

$$t = 0, X = X_0 \quad (3)$$

$$y = 0, dX/dy = 0 \quad (4)$$

$$y = L, X = X_e \quad (5)$$

where h_m is the mass transfer coefficient (m s⁻¹) and X_e is the equilibrium moisture content (kg water kg dry solids⁻¹).

The solution of Eq. (2) with the initial and boundary conditions [Eqs. (3)–(5)] can be expressed as (Roberts et al. 2002; Akpınar et al. 2003):

$$\frac{X - X_e}{X_0 - X_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left(\frac{-\pi^2 (2n+1)^2}{4L^2} D_{\text{eff}} t \right) \quad (6)$$

For long drying time, Eq. (6) can be simplified as:

$$\ln \frac{X - X_e}{X_0 - X_e} = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{\text{eff}} t}{4L^2} \quad (7)$$

The effective water diffusivity (D_{eff}) was determined based on the slope of plot $\ln(X - X_e)$ versus $\ln(t)$. In this study, the diffusivity function is established based on drying run at temperature of 40 and 70 °C. The dependency of effective diffusivity (D_{eff}) on temperature can be expressed as (Mghazli et al. 2018; Cuevas et al. 2019):

$$D_{\text{eff}} = D_0 \exp \left(-10^3 \frac{E_a}{R(T(^{\circ}\text{C}) + 273.15)} \right) \quad (8)$$

where D_0 is the factor of the Arrhenius or the infinite temperature diffusion coefficient (m² s⁻¹), and E_a is the effective energy of activation (kJ mol⁻¹). Equation (8) is then used to predict diffusivity at temperature of 50 and 60 °C. A schematic diagram for modeling using diffusion-based model is shown in Fig. 2a.

Modeling using reaction engineering approach

By using the reaction engineering approach (REA), the mass balance of water during drying can be written as (Chen and Putranto 2013):

$$m_s \frac{d\bar{X}}{dt} = -h_m A \left[\exp \left(\frac{-\Delta E_v}{RT_s} \right) \rho_{v,\text{sat}}(T_s) - \rho_{v,b} \right] \quad (9)$$

where m_s is the dried mass (kg), $\bar{X}$ is the average moisture content (kg water kg dry solids⁻¹), A is the surface area (m²), T_s is the surface temperature (K), ΔE_v is the activation energy (J mol⁻¹), $\rho_{v,b}$ is the concentration of water vapor in the drying medium (kg m⁻³), $\rho_{v,\text{sat}}$ is the saturated water vapor concentration (kg m⁻³). For the thin sample, the surface temperature (T_s) can be assumed to be the same as the sample temperature (T) (Chen and Peng 2005).

The activation energy (ΔE_v) is determined experimentally by placing the parameters required for Eq. (4) in its rearranged form:

$$\Delta E_v = -RT_s \ln \left[\frac{-m_s \frac{d\bar{X}}{dt} \frac{1}{h_m A} + \rho_{v,b}}{\rho_{v,\text{sat}}} \right] \quad (10)$$

where dX/dt , average moisture content, surface area and temperature was experimentally determined. The dependence of activation energy on moisture content on a dry basis (X) can be normalized as:

$$\frac{\Delta E_v}{\Delta E_{v,b}} = f(X - X_e) \quad (11)$$

where f is a function of water content difference.

$\Delta E_{v,b}$ is the equilibrium activation energy (J mol⁻¹) which can be expressed as:

$$\Delta E_{v,b} = -RT_b \ln(RH) \quad (12)$$

where T_b is the temperature of drying air (K) and RH is the relative humidity of the drying air.

The relative activation energy ($\Delta E_v/\Delta E_{v,b}$) is relative activation energy which is material characteristics. The different drying conditions would result in the similar profiles of the relative activation energy provided the materials are the same and the initial moisture content is similar (Chen and Putranto 2013).

Fig. 2 **a** Schematic diagram of diffusion-based approach, **b** schematic diagram of reaction engineering approach

The heat balance during drying can be represented as :

$$\frac{d(m_s C_p (1 + X) T)}{dt} = hA(T_b - T) + \frac{m_s}{A} \frac{dX}{dt} \Delta H_{vap} \quad (13)$$

where C_p is the specific heat of dried sample ($\text{J kg}^{-1} \text{K}^{-1}$), T is the sample temperature (K), h is the heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$), T_b is the drying air temperature (K) and ΔH_{vap} is the vaporization heat of water (J kg^{-1}). A schematic diagram for modeling using reaction engineering approach (REA) is shown in Fig. 2b.

Results and discussions

Transport properties of diffusion-based approach

By using procedures described above, the calculated values of the effective water diffusivity of “*Violet de Galmi*” onion for all drying conditions are shown in Table 1. The diffusivity increases with the increase of drying air temperature which may be related to the enhanced evaporation at higher temperature. This is also in agreement with the previous study of effective water diffusivity of other food materials (Azzouz et al. 2002; Brasiello et al. 2013). The effective water diffusivity can be expressed as:

$$D_{eff} = 4.191 \times 10^{-5} \exp\left(\frac{-3.752 \times 10^3}{T + 273.15}\right) \quad (14)$$

where T is temperature ($^{\circ}\text{C}$). The effective water diffusivity of onion during microwave drying is between $1.554 \times 10^{-9} \text{ m}^2 \text{s}^{-1}$ and 4.869×10^{-8} (Arslan and Musa Özcan 2010). It is reasonable that the effective diffusivity is higher for the microwave drying as the mobility of water molecules is enhanced due to the microwave. In addition, higher temperature resulted by microwave may contribute to the increase of the effective diffusivity.

Modeling of convective drying of “*Violet de Galmi*” onion using diffusion-based approach

Based on the generated effective water diffusivity shown in Table 1, Eq. (14) is used to model the convective drying of onion. As shown in Fig. 3a, at drying air temperature of 40°C , the diffusion-based model describes well the drying kinetics at the beginning of drying but shows a slight underestimation of the drying kinetics after drying time of 1.5 h. Similarly, the diffusion-based approach indicates overestimation of the profiles of moisture content towards the end of drying period for drying at drying air temperature of 50°C . Figure 3b indicates that this approach

Table 1 Effective diffusivity of “*Violet de Galmi*” onion

Temperature	40 °C	50 °C	60 °C	70 °C
$D_{eff} (\text{m}^2 \text{s}^{-1})$	2.623×10^{-10}	3.801×10^{-10}	5.385×10^{-10}	7.477×10^{-10}

Fig. 3 The moisture content of convective drying of onion at drying air temperature of **a** 40 and 50 °C, **b** 60 and 70 °C modeled using diffusion-based approach

models relatively well the convective drying at drying air temperature of 60 °C but it underestimates the drying rate at drying air temperature of 70 °C.

Transport properties of reaction engineering approach (REA)

The transport properties of reaction engineering approach is the relative activation energy. In this study, the activation energy is generated based on convective drying run at drying air temperature of 50 °C by using Eq. (10). The activation energy (ΔE_v) is then divided by the equilibrium activation energy ($\Delta E_{v,b}$) shown in Eq. (12) to yield the relative activation energy ($\Delta E_v/\Delta E_{v,b}$). The relative activation energy is correlated towards difference in moisture content ($X - X_e$) by least-square method implemented in Microsoft Excel. The relative activation energy of “*Violet de Galmi*” onion can be expressed as:

Fig. 4 The relative activation energy of “*Violet de Galmi*” onion

$$\frac{\Delta E_v}{\Delta E_{v,b}} = -0.0021(X - X_e)^3 + 0.0361(X - X_e)^2 - 0.2339(X - X_e) + 1.0305. \quad (15)$$

The format of Eq. (15) can be varied but in this case, the format shown in Eq. (15) is sufficiently accurate to describe the relative activation energy. Figure 4 confirms the good agreement between the fitted and experimental relative activation energy. It is further indicated by R^2 of 0.999. As shown in Fig. 4, as drying progresses, the relative activation energy increases since the difficulty to remove the moisture from the solid matrix rises. From $(X - X_e)$ 3 to 9, the relative activation energy increases slightly but the relative activation energy increases significantly for $(X - X_e)$ below 3. This indicates that higher energy is required to remove the moisture in this region due to the higher internal material resistance.

Modeling of convective drying of “*Violet de Galmi*” onion using the reaction engineering approach (REA)

In order to yield the profiles of average moisture content during drying using the REA, the mass balance [Eq. (9)] was solved simultaneously with the heat balance [Eq. (13)] in conjunction with the equilibrium and relative activation energy shown in Eqs. (12) and (14), respectively. The profiles of average moisture content were then benchmarked towards the experimental data.

For drying air temperature of 40 °C, the REA models well the moisture content. The good agreement between the predicted and experimental data is shown in Fig. 5a and confirmed by R^2 of 0.98. In addition, Fig. 4a indicates that the REA accurately describes the moisture content during drying at drying air temperature of 50 °C as shown by R^2

Fig. 5 The moisture content of convective drying of onion at drying air temperature of **a** 40 and 50 °C, **b** 60 and 70 °C modeled using reaction engineering approach (REA)

of 0.999. Figure 5b further shows the capability of the REA to model the convective drying at drying air temperature of 60 and 70 °C, which is also indicated by R^2 of 0.997 and 0.998, respectively. The accuracy of modeling using the REA is shown but R^2 and $RMSE$ summarised in Table 2. By using the relative activation energy shown in Eq. (13), the REA can accurately predict the drying kinetics of convective drying of onion.

Comparisons of transport properties of drying of “Violet de Galmi” onion retrieved using the diffusion-based approach and reaction engineering approach (REA)

The accuracy of the transport properties for projecting the drying kinetics are shown by R^2 and $RMSE$ (Table 2). The REA yields closer agreement towards the experimental data than the diffusion-based approach. At drying air temperature of 40 °C, the diffusion-based approach underestimates the drying kinetics after drying time of 1.5 h. On the other hand, the REA models well the moisture content during whole period of convective drying at drying air temperature of 40 °C. Similarly, underestimation of drying kinetics at drying air temperature of 50 °C is shown by modeling using the diffusion-based approach. At drying air temperature of 60 °C, both the diffusion-based approach and the REA predicts well the drying kinetics. While the REA projects well the moisture content at drying air temperature of 70 °C, the diffusion-based approach only accurately models the profiles at the beginning of drying period.

The accuracy of the REA may be due to the accuracy of the relative activation energy shown in Eq. (15). The relative activation energy may be able to capture well the internal changes inside the “Violet de Galmi” onion during drying. Combination of the relative activation energy with the equilibrium activation energy seems to be flexible to capture the effects of environmental conditions and reflect those to the material structure. For the diffusion-based approach, the single value of effective diffusivity may not be sufficient to describe the drying process. This is since evaporation, vapor diffusion and capillary diffusion occur during drying (Datta 2007). In addition, the slight deviation of the modeling results from the experimental data may be because the values of effective water diffusivity were obtained under assumption of isothermal conditions during drying (Crank 1975) which may not be fully satisfied in this case. The assumption of negligible mass transfer resistance implied in Eq. (5) may also attribute to the deviation.

Since the effective water diffusivity basically lumps together a number of phenomena involved in drying, it tends to be an empirical constant rather than describing the

Table 2 R^2 and $RMSE$ of diffusion-based model and reaction engineering approach (REA)

Drying air temperature (°C)	R^2 diffusion-based model	$RMSE$ diffusion-based model	R^2 REA model	$RMSE$ REA model
40	0.919	0.572	0.979	0.374
50	0.993	0.235	0.999	0.092
60	0.982	0.370	0.997	0.141
70	0.985	0.342	0.998	0.11

fundamental diffusion. As drying is a multiphase phenomena, the use of multiphase drying approach is suggested (Zhang and Datta 2004). In this multiphase approach, the Fickian diffusion is used to describe the vapor diffusion while the capillary one is dependent on the moisture content and temperature and therefore the capillary diffusivity values need to be extracted from the experimental data (Zhang and Datta 2004; Chen 2007; Putranto and Chen 2018). In terms of range of validity, the effective diffusivity values are only valid for the range of conditions from which they are generated. This makes the extrapolation for other conditions not possible. For designing new processes, the effective diffusivity values corresponding to the operating conditions need to be used. This may require a number of experiments for generating the diffusivity parameters.

On the other hand, for the reaction engineering approach (REA), the physical meaning lies on the relative activation energy which basically describes the changes of internal structure of the materials during drying. Both the diffusivity and the relative activation energy needs to be established from the experimental data. Nevertheless, the REA is more efficient in generating the parameters since the relative activation energy is basically independent on the drying conditions. This also causes the range of applicability of the REA to be wider than that of the diffusivity. Therefore, from perspectives of process design, it seems that reaction engineering approach is more practical than the diffusion-based approach.

On top of providing inputs for designing new processes and units, the relative activation energy can readily be used for evaluating the performance of existing units by embedding these transport properties into equations of heat and mass transfer and combining them with flow-field of drying air. These transport properties can be integrated in CFD software such as Comsol Multiphysics® and Ansys® to determine the optimum drying routes and conditions. In addition, the relative activation energy can be readily employed to analyse the profiles inside the materials during drying by embedding them in a spatial heat and mass transfer model. Based on these predictions, the local phenomena can be modeled. The modeling framework can be used as a basis for determining the drying conditions to reduce the quality changes during drying.

Conclusion

In this study, the drying kinetics parameters of onion, based on diffusion-based approach and reaction engineering approach (REA), are captured. Based on the diffusion-based approach, the effective diffusivity of onion is in the range of 4.8×10^{-10} – $8.1 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$. For the latter

approach, the relative activation energy can be written as $\frac{\Delta E_v}{\Delta E_{v,b}} = -0.0021(X - X_e)^3 + 0.0361(X - X_e)^2 - 0.2339(X - X_e) + 1.0305$. When implemented to modeling drying of onion, the relative activation energy gives closer agreement towards the experimental data. Unlike the diffusivity, the relative activation energy established for one drying condition is applicable for other conditions. This makes the relative activation energy more appropriate to be implemented for process design. Compared to the diffusion-based approach, the reaction engineering approach (REA) also requires less effort in establishing the drying kinetics parameters. The relative activation energy is readily applied for designing new dryer units and optimising the existing units by combining with equations of conservation of heat and mass transfer.

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