CHEMICAL ENGINEERING TRANSACTIONS

VOL. 32, 2013

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Chief Editors: Sauro Pierucci, Jiří J. Klemeš
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ISBN 978-88-95608-23-5; **ISSN** 1974-9791

DOI: 10.3303/CET1332294

Characterizing The Drying Kinetics Of High Water Content Agro-Food Particles Exhibiting Non-Fickian Mass Transport

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This work deals with the study of drying kinetics of high water content materials such as agro-food particles. These materials exhibit significant structural and geometry changes during drying showing complex non-Fickian drying kinetics. Indeed, drying rate curves in these cases show multiple stages differing significantly from typical constant and falling rates periods. These observations justify the need to characterize the drying curves differently to account for this behavior. For instance, following experimental measurements, it has been found that Fickian type kinetics (Ae^{-kt}) do not hold for characterizing the drying curves; instead, the suitability of a modified Page's type model (1-term : $Ae^{-\alpha_i^2 \cdot (kt)^n}$) has been justified where the parameter (k) is the rate constant and (n) characterizes the tissue. For the purpose of analyzing the drying kinetics more suitably, multiple drying stages have been detected by the simultaneous use of the three typical curves : (i) MR.vs. t, (ii) –dMR/dt .vs. MR, and (iii) F_o^*.vs. t, where $F_o^* = (kt)^n$, where F_o^* is a modified mass transfer Fourier number. By plotting all three curves on the same graph one can trace all the drying stages corresponding to different water diffusion rates thus reflecting the structural changes due to thermal effects.

1. Introduction

In the food industry, drying is a major operation by which water content of various materials is reduced to specific levels. As mentioned by Fellows (2000), dehydrated foods with wide range of applications, become stable under ambient conditions, easy to handle, and can be easily incorporated during food formulation and preparation. The drying operation is used either as primary process for preservation, or as secondary process in certain product manufacturing operations. Indeed, as reviewd by McMinn and Magee (1999), the study of the mechanism of dehydration by drying consists on following the evolution of the mass of the dried food versus time as well as process parameters such as the mode of drying, experimental device, temperature, air flow-rate (Zielinska and Markowski, 2010), and geometry of particles (Katekwa and Silva, 2006). When these parameters are favourable, the evolution of the mass of the samples can be obtained in a continuous way without interruption of drying process (Khezami et al., 2010). Modeling the kinetics of drying is of primal importance to obtain specific parameters characterizing the dried material. In general, empirical models are used for such modeling; while in many cases Fickian type model is also used (Suarez. and Viollaz, 1991; Katekwa and Silva, 2006; Zielinska and Markowski, 2010). Brasiello *et al.* (2011) numerically studied the drying kinetics of eggplants and the effect of some pre-treatment on the drying kinetics by considering variable water diffusion coefficient.
The present study concerns the characterization of the drying kinetics for high water content agro-food tissue. It aims at proposing an original scheme to detect drying periods for such products and to adequately model the drying kinetic.

Please cite this article as: Bessadok-Jemai A., 2013, Characterizing the drying kinetics of high water content agro-food particles exhibiting non-fickian mass transport, Chemical Engineering Transactions, 32, 1759-1764 DOI: 10.3303/CET1332294

2. Materials and Method

2.1 Raw material and samples preparation

The test material used in this study is carrot which can be purchased from a local supermarket (see Table 1 for typical characteristics). For a given experiment, the same root is used to obtain samples for drying and for water content measurements. The cutting methodology is described by Figure1 which consists in obtaining disks from the center portion of a given root perpendicular to its axis. As indicated in Figure 1, the obtained samples are sytematically divided into particles for moister content control and the others for drying experiments. The test samples are disks having a diameter d=2.8(±0.02)cm and an initial thickness e=0.47(±0.02)cm. The average mass of a particle is about 3.35(±0.05)g.

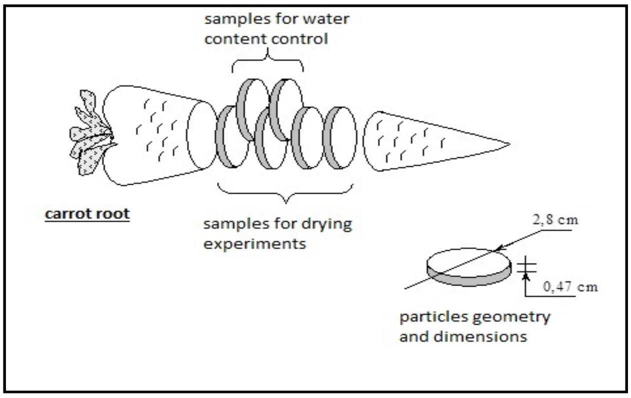

Figure 1 : Carrots cutting methodology

Table 1: *properties of carrot raw material.*

Property	Typical values
Density (g/cm^3)	1.158
Water (% weight)	87.71
Dry matters* (% weight)	12.29

* Dry matters estimated after oven drying at 105°C for 24hrs.

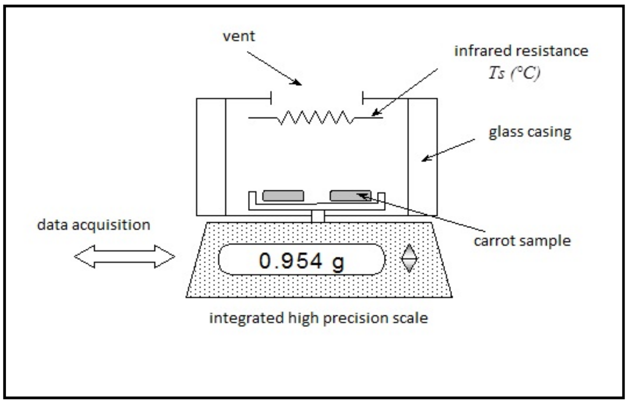

Figure 2 : Experimental setup

2.2 Experimental setup and measurements procedure

The drying kinetics were studied by means of an infrared desiccator (Scaltec model SMO 01 with temperature control feature 40°C ~130 °C). As can be seen in Figure 2, one or more samples can be dried at one time; in the present work, two disks were dried at one time every drying experiment. A high precision balance integrated with the desiccator and connected to a PC, insured continuous measurements and acquisition of the samples weights during drying. At least 7 runs have been performed during which two samples were dried each run.

2.3 Data analysis method

In general, knowledge of the mass of the samples (m) as a function of drying time (t), allows to characterize the drying kinetics. These are commonly studied by the drying rates and the normalized moisture content (wet/dry basis). Following are some useful equations used for the present study :

(a) Moisture content on the basis of final dry matter (in % *g-water/ g-dry matter)*

$$MC(\%) = 100 \times (m - m_{dm}) / m_{dm} \tag{1}$$

$$MC_o = 100 \times \frac{m_o - m_{dm}}{m_{dm}} \text{ and } MC_e = 100 \times \frac{m_e - m_{dm}}{m_{dm}}$$

Where,
m : is the weight a sample during time (g)
m_{dm} : is the mass of completely dried sample (following 24hrs drying at 150 °C)
m_0 : is the initial mass of a sample (g)
m_e : is the mass of a sample at equilibrium with the surrounding (after a long time)

(b) Normalized moisture content

$$MR^* = \frac{MC - MC_e}{MC_0 - MC_e} = \frac{m - m_e}{m_0 - m_e} = m^* \tag{2}$$

(c) Drying rates (% *g-water/g-dry matter)*

$$\frac{-dMC}{dt} \approx -100 \times \left(\frac{1}{m_{dm}}\right) \times \frac{\Delta m}{\Delta t} = \frac{-\left(MC_{i+1} - MC_i\right)}{\left(t_{i+1} - t_i\right)} \tag{3}$$

Where, the indices (i+1) and (i) correspond to successive measurments.

(c) Kinetic models
Simple decaying exponential of 1 term is used to model the kinetics of water loss from samples. This model can be extended by the use of infinite number of terms based on Fick's solution to the diffusion equation.

$$MR^* = A_1 \cdot e^{-k_1 \cdot t} \quad \text{1-term solution,} \tag{4}$$

$$MR^* = \sum A_i \cdot e^{-\lambda_i^2 \cdot F_o} \quad \text{infinite terms solution to Fick's law} \tag{5}$$

With, $F_o = D \cdot t / l^2 = k_i \cdot t$ is the mass transfer Fourier's number and,
Where,
D : is the mass tranfer coefficient (m^2/s)
l : is the characteristic thickness of the sample (m)
k_i : is a rate coefficient corresponding to D/l^2 (1/s)
A_i ,λ_i : are the coefficients determined from initial and boundary conditions.

It should be noted that for Fickian type kinetics the variation of Fourier number as a function of time is linear. A significant deviation from this trend is indication of a non-Fickian kinetics; which means that for non-Fickian type evolution this relationship is non-linear giving rise to a modified Fourier number. Page's type model is applicable in this case and is written as follows :

$$MR^* = A_1 \cdot e^{-(k_1 \cdot t)^n} \tag{6}$$

This model can be extended to multiple terms solution as :

$$MR^* = \sum A_i \cdot e^{-\lambda_i^2 \cdot (k \cdot t)^n} \tag{7}$$

Where the main parameters are :
k : is the rate coefficient (1/s)
n : is a parameter characterizing the material used (e.g. carrot tissue)
A_i ,λ_i : are the coefficients determined from initial and boundary conditions.

3. Results and discussion

The moisture loss in normalized form (MR*) is given by Figure 3. These collected measurements when plotted in terms of drying rate based on Equation (3) and as a function of MR*, allow to study the different drying stages (Figure 4). As shown by this figure, a relatively short constant period is detected followed by several falling rate periods.

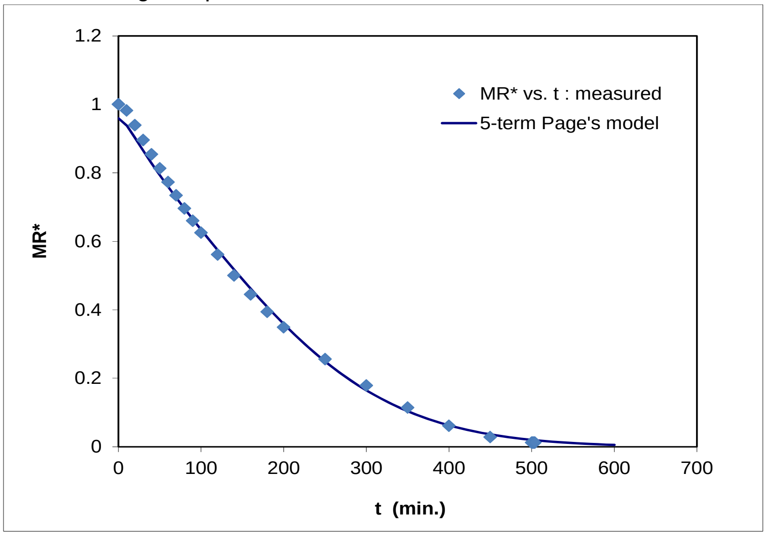

Figure 3: Normalized moisture content during time : experimental points and model curve.

Figure 4 reveals a characteristic behavior of the agro-food tissue during drying (i.e. structural deformation due to drying, hardening of the particles external layer in contact with drying air, etc…). In general, drying kinetic of materials that do not exhibit structural changes such as shringkage or hardening, reveals three stages : (i) constant drying period, (ii) falling rate period, and (iii) final falling rate (McCabe et al., 1993; Fellows, 2000). While for high water content agro-food particles, more than four stages are deteced mostly during the falling rate period.

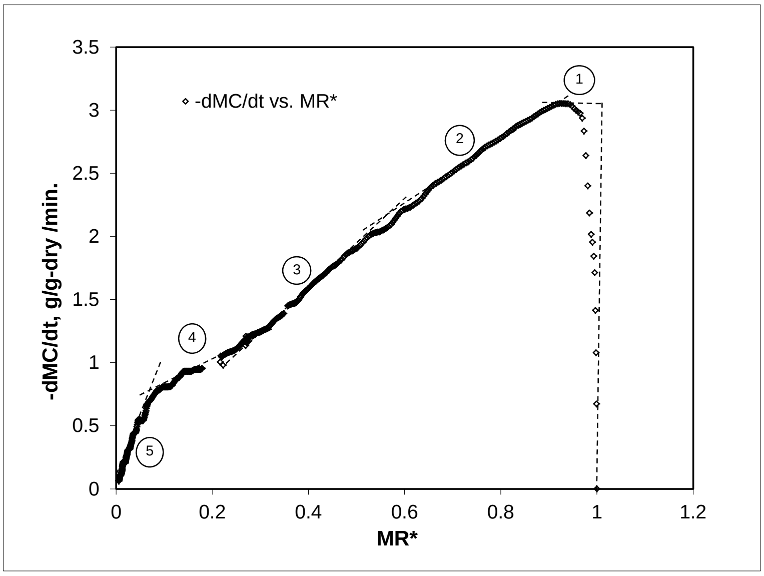

Figure 4: Drying rate as a function of normalized moisture content.

These observations indicate that Fickian type evolution does not hold for this type of material. Consequently, simple exponential model would not be adequate to describe the drying kinetics in his case. To support this finding, the experimental data was used to plot the analogous Fourier number (F_o) as a function of time (Figure 5).

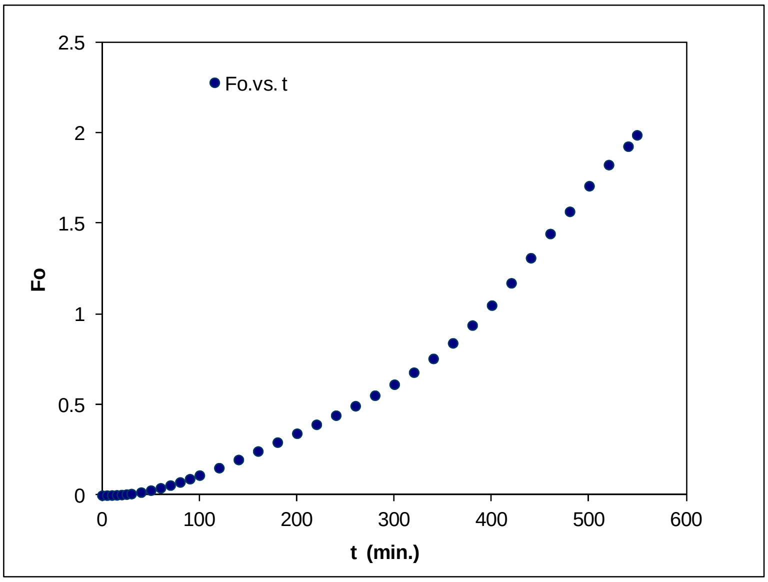

Figure 5 : Fourier number as a function of time revealing non-linear behaviour (non-Fickian).

Figure 5 clearly shows that a nonlinear evolution is obtained indicating a deviation from Fickian behavior. The curve in Figure 5 is composed of successive segments with somewhat clear limits. A non linear evolution is clearly obtained; So, a power law such that $F_o^* = (kt)^n$ holds and explains why Page's model is suited to modeling the kinetics of drying. A multiple-term Page's type model would be used to account for these successive stages.

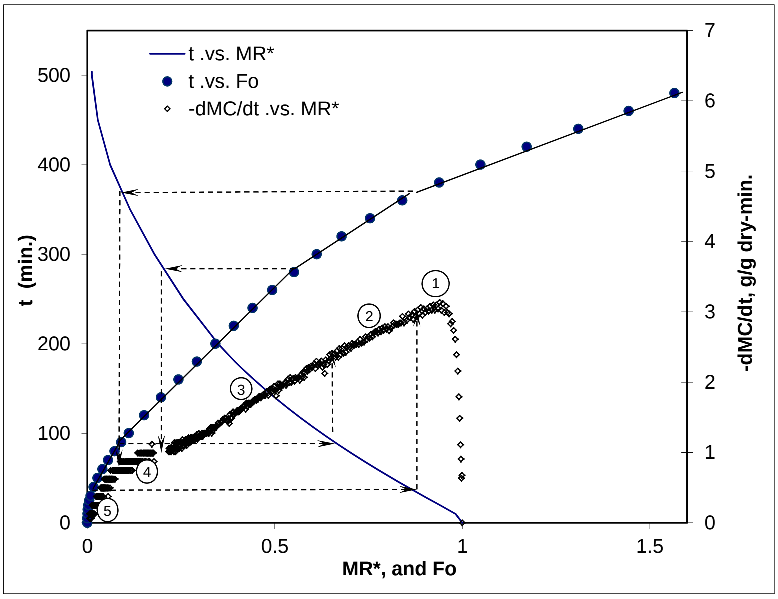

Figure 7: An original scheme for tracing multiple drying stages based on three curves.

By plotting Figures 3, 4 and 5 all in one plot putting *MR** and F_o in the horizontal axis, it has been possible to trace the different drying stages. As indicated by Figure 7, originating from the curve of F_o^* .vs. t and leading a horizontal line, then going vertical at the intersection with the *MR** .vs. *t* curve defines the first stage (1); this first stage corresponds to the constant rate period. Repeating the same scheme for the other subsequent limits allows to limit stages 2, 3, 4, etc…

Table 2: Model parameters obtained from Matlab© curve fitting toolbox.

	Constants	Value	95% conf. Interval	R^2
Fickian	A_1	1.09	(1.08 to 1.1)	0.990
	k_1	0.00596	(0.00589 to 0.00603)	
Non-Fickian	A_1	0.984	(0.979 to 0.989)	0.998
	k_1	0.00523	(0.00519 to 0.00526)	
	n	1.278	(1.264 to 1.291)	
Fickian (multi-terms)	$A_i^{\$}$	$8/((2i+1)\cdot\pi)^2; i=1..5$		--
	λ_i	$((2i+1)/2\cdot\pi)^2; i=1..5$		
	k	--	Too large interval	
Non-Fickian (multiterms)	A_i, λ_i	*Same as above*		0.997
	k^n	5.25×10^{-5}	$(4.86 \text{ to } 5.63)\times10^{-5}$	
	n	1.651	(1.638 to 1.665)	

$^{\$}$*$A_i$, λ_i are obtained based on "no convective" resistance condition*

Modeling of the kinetics of drying should then be best obtained by Equation (7) by using at least 5 terms. As can be found in Table 2, the correlation coefficient is much more adequate based on Equation (7) compared to that obtained by Equation (5). In addition, multiple terms of the solution to Fick's law lead to unreliable parameters as indicated by large confidence intervals. A better theoritical analysis is recommended taking into account convection resistance or shrinkage of samples, for obtaining the solution to the diffusion equation.

4. Conclusion

This study proposed a method to adequately characterize drying kinetics of high water content agro-food materials (e.g. carrot particles). It has been found that the drying rate curves reveal multiple stages kinetics typical of the agro-food products (i.e. structural deformation due to drying, hardening of the particles external layer in contact with the surrounding air, etc…). The proposed method showed that the drying rate ($-dMR^*/dt$) versus normalized water content (MR^*) reveals the existence of significant number of stages (more than 4 stages) needing multiple exponential terms to adequately model the drying kinetics. In addition, the evolution of the mass transfer Fourier number as function of time (F^*_o .vs. t) is highly non-linear indicating that the kinetics should be regarded as non-Fickian. In this case, F^*_o is equivalent to $(k.t)^n$ instead of using the common Fourier number as ($D.t/l^2$). Based on this analysis, the modified Page's type model (multiple terms) is more suited to predict drying kinetics of carrot tissue (typical agro-food material).

Acknowledgement

The author would like to acknowledge the support provided by the Deanship of Scientific Research at King Saud University, through Research Center at College of Engineering.

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