Journal of Food Engineering 114 (2013) 39–46

Contents lists available at SciVerse ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

A novel approach to evaluate the temperature during drying of food products with negligible external resistance to mass transfer

E. Barati [a,*], J.A. Esfahani [b]

[a] Department of Mechanical Engineering, Faculty of Eng., Khayyam Higher Education Institute, Mashhad, Iran

[b] Center of excellence on Modeling and Control Systems, (CEMCS) & Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad 91775-1111, Iran

ARTICLE INFO

Article history:
Received 26 April 2012
Received in revised form 17 July 2012
Accepted 27 July 2012
Available online 10 August 2012

Keywords:
Heat and mass transfer
Convective drying
Analytical solution
Biot number

ABSTRACT

The paper deals with modeling the convective drying process. A relevant and reliable mathematical model that captures the history and distribution of temperature is presented. The attention is focused on the simultaneous heat and mass transfer occurring during drying where dry and hot air flows about the food. In the present study, external resistance to mass transfer is considered negligible. As a result, the drying curve is almost independent of the boundary conditions, which means that drying is diffusion-controlled. The main connotation of present study regards to undertake analytical procedure to establish the novel model for practical applications. The results show that the temperature evolution can be evaluated from an advanced analytical solution in a quick and efficient manner. The model is validated with the literature experimental data obtained for carrot and mango slabs. A good agreement is obtained between the model predictions and the available experimental results.

1. Introduction

Drying of foods is one of the oldest procedures for food preservation. Drying also is one of the most extensively used operations in food process engineering, which is one of the most time and energy consuming processes in the food industry (Schössler et al., 2012; Barati and Esfahani, 2009). Predicting drying rates and internal moisture and temperature profiles are necessary for the process design and optimization. Drying of foods is widely accepted as an internally controlled process (Wang and Brennan, 1995), which implies the moisture gradient can be observed inside the food and the drying process is independent of boundary conditions, where Fick's second law of diffusion has been used to predict water loss during drying (Yang et al., 2001). Fick's is employed when the transport of water vapor can be neglected in the foods which their void fraction values are less than 0.3 (Curcio et al., 2008). It should be noted that several studies have shown that the Fick's diffusion model is unable to fully describe drying of porous materials (Sirikiatden and Roberts, 2005).

From the reviews by Mulet (1994), Guiné et al. (2011) and Barati and Esfahani (2011a), it becomes manifest that rational models yet of manageable complexity are essential to predict the coupled drying and heating rates to enable the prediction of drying curves, drying times and moisture and temperature history. These models should also be able to provide some insight into the drying mechanism.

In food drying, rigorous analytical solutions are only available for very limited cases under some assumptions mainly negligible heat transfer and constant food properties. Córdova-Quiroz and Ruiz-Cabrera (1996) proposed a model with interfacial resistance to mass transfer to reproduce the experimental behavior of moisture evolution during carrot slab drying, but they did not solve heat transfer equation. Hernández et al. (2000) considered the fruits drying process as isothermal, assuming drying temperature equal to air temperature and accounting only for mass transfer. The aim of their work was to show and validate an analytical solution of a mass transfer equation in which shrinkage was taken into account. Sahin et al. (2002) developed an analytical method for the determination of drying time of multi-dimensional products. Sahin and Dincer (2005) developed a new analytical method for predicting drying times of irregular shaped multi-dimensional moist solids. Ruiz-López and Garcia-Alvarado (2007) proposed a model that provides a simple mathematical description for food drying kinetics and considered both shrinkage and a moisture dependent diffusivity. They considered constant food temperature, which was also chosen by Simal et al. (2000) and Ben-Yoseph et al. (2000). Wu and Irudayaraj (1996) experimentally verified that drying can be actually supposed as an isothermal process only if the Biot number is very low. When Biot number is high, internal transport resistances are also to be considered. It is important to remark that Viollaz et al. (1980) presented an expression to predict the variation in time of the average temperature and moisture in infinite slabs by means of a simple method, while their proposed expression did not represent local temperature and moisture content of food. Mentioned analytical approaches, dealing with moisture diffusion

* Corresponding author. Tel.: +98 9358185400; fax: +98 5118763304.
E-mail addresses: barati.ebrahim@gmail.com, e.barati@khayyam.ac.ir (E. Barati).

0260-8774/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jfoodeng.2012.07.028

Nomenclature

a_w	water activity (–)
C_p	product specific heat (J kg^{-1} K^{-1})
D	effective diffusivity of water in food (m^2 s^{-1})
H_v	heat of vaporization of water (kJ kg^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
h_m	mass transfer coefficient (m s^{-1})
K_{eq}	partition constant between the moisture content of food and air (g dry solid/g dry air)
k	thermal conductivity of food (W m^{-1} K^{-1})
k_{air}	thermal conductivity of air (W m^{-1} K^{-1})
L	length of food, parallel to air flow (m)
l	characteristic length (m)
Le	Lewis number (–)
p	pressure (kpa)
t	time (hr)
T	temperature (°C)
X	food moisture content (kg water/kg dry carrot)
Y	air moisture content (kg water vapor/kg dry air)
Y_i	interface moisture content (kg water vapor /kg dry air)
Z	spatial coordinate (m)

Greek symbols

α	thermal diffusivity
μ	eigenvalue
ρ	density of food (kg m^{-3})
Δt	time step (second)
ζ	dimensionless spatial coordinate

Subscripts

c	center
o	at initial
∞	air
e	in equilibrium
dp	dry product
m	mass transfer
s or i	food surface
wv	water vapor

Dimensionless groups

Bi	Biot number
E	dimensionless evaporation term
Fo	Fourier number
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
θ^*	dimensionless temperature
ξ	dimensionless spatial coordinate
ψ	dimensionless moisture content
C_i	$\frac{4\sin\mu_i}{2\mu_i+\sin(2\mu_i)}$
θ_j	$\exp(-\mu_j^2\mathrm{Fo})\cdot C_j$

estimation to the mass transfer equation solution, are obtained under the hypothesis of invariable food temperature. Ruiz-López et al. (2012) indicated that the food temperature does not stay constant during drying. Nevertheless, constant food temperature is still accepted in drying studies due to some theoretical and experimental limitations, while this hypothesis is not inevitably a good estimate. It is the only way to deduce an analytical solution for unsteady state mass transfer equation. Barati and Esfahani (2011b) represented a new model which was able to capture moisture profile within the food while the temperature supposed to be uniform during drying process. They used lumped capacitance method for heat transfer and one-dimensional mass transfer equation within the food. The governing equations were solved simultaneously and boundary conditions had significant effects on the temperature and moisture histories. It is notable that recently Barati and Esfahani (2012) presented new solution method to solve coupled unsteady heat and mass transfer equations with taking internal resistances to temperature and moisture into account.

Most researchers have applied numerical methods and few investigators who employed analytical methods ignored heat transfer equation for simplification (Ruiz-López et al., 2012). In drying industry, practitioners need relevant and accurate analytical tools to conduct the design analysis and calculations effectively. There is scarce information on the formulations and drying-related properties, which would assist process design (Irigoyen and Giner, 2011). In this regard, the problem of one-dimensional heat and mass transfer in an infinite slab during drying is considered in the present work. A theoretical model describing the transport phenomena involved in food drying is presented. Heat is transferred by convection from the air to the food surfaces, and from there, by conduction, further into the food. Moisture is transported in the opposite direction, evaporates and passes on by convection to the air. Heat and mass transfer are solved with a new solution method. The main innovation introduced in this work is represented with establishment of novel approach to capture food temperature history in a quick and efficient manner for practical applications. The proposed solution is able to produce accurate results that can be applied to simulate the behavior of real drying processes. The need of an analytical tool for modeling spatially distributed uncoupled temperature and moisture in important industrial problems offers the major stimulus of present investigation. It is notable that in mentioned publications of authors (Barati and Esfahani; 2011a,b), the governing equations are coupled while in present investigation they are considered as uncoupled.

2. Mathematical model

When a food with high moisture content is placed in contact with a dry and hot air, two simultaneous transport mechanisms occur: heat is transferred to the food, while water is transferred from the food to the continuous phase. The energy required to sustain moisture migration comes from the convected energy to the food. The food experiences an increase in temperature toward air temperature while the evaporation at surface is responsible for the decline of food temperature during the drying process. The mathematical model proposed for the drying of foodstuff is based on the following assumptions:

- One-dimensional mass transfer in the product by diffusion.
- One-dimensional heat transfer in the product by conduction.
- Negligible shrinkage or deformation of product during drying.
- Constant physical and thermal properties of food.
- Convective heat and mass transfer at product surface.

The model is composed of two partial differential equations, accounting for the variations of temperature (T) and dry basis moisture content (X).

$$\begin{cases} \frac{\partial T}{\partial t} = \alpha\frac{\partial^2 T}{\partial z^2} \\ \frac{\partial X}{\partial t} = D\frac{\partial^2 X}{\partial z^2} \end{cases} \quad (1)$$