Chemical Engineering and Processing 70 (2013) 169–183

Contents lists available at SciVerse ScienceDirect

Chemical Engineering and Processing: Process Intensification

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

Multiphase modeling of intermittent drying using the spatial reaction engineering approach (S-REA)

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ARTICLE INFO

Article history:
Received 5 December 2012
Received in revised form 9 April 2013
Accepted 11 April 2013
Available online 18 April 2013

Keywords:
S-REA
Drying
Intermittent
Model
Multiphase
Non-equilibrium

ABSTRACT

Several schemes of energy minimization of drying process including intermittent drying have been attempted. Intermittent drying is conducted by applying different heat inputs in each drying period. An effective and physically meaningful drying model is useful for process design and product technology. The lumped reaction engineering approach (L-REA) has been shown previously to be accurate to model the intermittent drying In L-REA, the REA (reaction engineering approach) is used to describe the global drying rate. In this study, the REA is used to model the local evaporation/condensation rate and combined with the mechanistic drying models to yield the spatial reaction engineering approach (S-REA), a non-equilibrium multiphase drying model. The accuracy of the S-REA to model the intermittent drying under time-varying drying air temperature is evaluated here. In order to incorporate the effect of time-varying drying air temperature, the equilibrium activation energy and boundary condition of heat balance implement the corresponding drying settings in each drying period. The results of modeling using the S-REA match well with the experimental data. The S-REA can yield the spatial profiles of moisture content, concentration of water vapor, temperature and local evaporation/condensation rate so that better understanding of transport phenomena of intermittent drying can be obtained. It is argued here that the REA can describe the local evaporation rate under time-varying external conditions well. The S-REA is an effective non-equilibrium multiphase approach for modeling of intermittent drying process.
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1. Introduction

Drying is a complex process of removal of water involving simultaneous heat and mass transfer. It is energy intensive process since large amount of heat needs to be supplied to remove moisture from materials being dried. In addition, the quality of the materials being dried may also be affected by drying. Several schemes for minimization of energy consumption and maintaining product quality during drying including intermittent drying have been implemented [16,18,27,38,39,41,51,77].

For minimization of energy consumption, the intermittent drying was reported to be able to save drying time of 25%, 48% and 61% with fraction of heating time to total drying time of 0.25, 0.5 and 0.67 [16]. Intermittency of infrared drying was indeed reported to reduce the drying time significantly [70]. The intermittent drying was also shown to improve the product quality considerably [16,19,38,40]. Tempering of rice kernel was shown to result in minimized crack and fissuring because of better moisture content redistribution [19,40]. The intermittent drying of biomaterials was indicated to reduce non-enzymatic browning, retardation of ascorbic acid loss and color change and preservation of beta carotene content [16,51]. For non-food materials, the application of drying under constant environmental conditions during constant rate period of drying followed by periodically changed drying air temperature and humidity resulted in minimized cracks [38].

An effective and physically meaningful drying model is useful for designing of better dryer, evaluating of dryer performance and maintaining product quality during drying. Several models have been proposed and implemented to model the intermittent drying [2,16,18,28,31,49,74]. It can be observed that most of the physically meaningful models employ diffusion and/or Darcy flow to represent the intermittent drying [2,16,28,74]. The diffusion model can model the intermittent drying of banana tissues well but the CDRC (characteristic drying rate curve) cannot represent the intermittent drying accurately [2]. A combination of Darcy liquid flow and vapor diffusion was employed to model intermittent drying of potato tissues and a good agreement towards experimental data was indicated [16,28]. The diffusion-based model was also shown to model the intermittent drying of mango tissues reasonably well [74].

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http://dx.doi.org/10.1016/j.cep.2013.04.005

Nomenclatures

A	surface area of samples (m^2)
A_{in}	internal surface area per unit volume ($m^2\ m^{-3}$)
A_o	initial surface area of samples (m^2)
A_p	cell surface area (m^2)
C_p	specific heat of sample ($J\ kg^{-1}\ K^{-1}$)
C_{pmix}	specific heat of mixture ($J\ kg^{-1}\ K^{-1}$)
C_{ps}	specific heat of solids ($J\ kg^{-1}\ K^{-1}$)
C_{pw}	specific heat of water ($J\ kg^{-1}\ K^{-1}$)
C_s	solid concentration ($kg\ m^{-3}$)
C_v	water vapor concentration ($kg\ m^{-3}$)
$C_{v,s}$	internal-surface vapor concentration ($kg\ m^{-3}$)
$C_{v,sat}$	internal-saturated vapor concentration ($kg\ m^{-3}$)
D_v	effective water vapor diffusivity ($m\ s^{-2}$)
$D_{v,o}$	water vapor diffusivity ($m\ s^{-2}$)
D_w	capillary diffusivity ($m\ s^{-2}$)
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
h_m	mass transfer coefficient ($m\ s^{-1}$)
$h_{m,in}$	internal mass transfer coefficient ($m\ s^{-1}$)
I	local evaporation rate ($kg\ m^{-3}\ s^{-1}$)
k	thermal conductivity of sample ($W\ m^{-1}\ K^{-1}$)
m_p	dry mass of cell (kg)
m_s	dried mass sample of material (kg)
n	constant
N	number of cell in samples
n_p	number of cell per unit volume (m^{-3})
r	radial position (m)
RH_b	relative humidity of drying air
r_p	cell radius (m)
T	sample temperature (K)
T_s	surface sample temperature (K)
t	time (s)
T_b	drying air temperature (K)
V_p	cell volume (m^3)
w	mass fraction of water
X	moisture content on dry basis ($kg\ kg^{-1}$)
$\bar{X}$	average moisture content on dry basis ($kg\ kg^{-1}$)
X_b	equilibrium moisture content on dry basis ($kg\ kg^{-1}$)
X_o	initial moisture content ($kg\ kg^{-1}$)
ΔE_v	apparent activation energy ($J\ mol^{-1}$)
$\Delta E_{v,b}$	'equilibrium' activation energy ($J\ mol^{-1}$)
ΔH_v	vaporization heat of water ($J\ kg^{-1}$)
ε	porosity
ε_w	fraction by liquid water
ε_v	fraction by water vapor
ε_o	initial porosity
Θ	constriction factor
ρ	sample density ($kg\ m^{-3}$)
ρ_s	density of solids ($kg\ m^{-3}$)
$\rho_{v,b}$	vapor concentration in drying medium ($kg\ m^{-3}$)
$\rho_{v,s}$	surface vapor concentration ($kg\ m^{-3}$)
$\rho_{v,sat}$	saturated vapor concentration ($kg\ m^{-3}$)
ρ_w	density of water ($kg\ m^{-3}$)
τ	turtuosity

The diffusion-based models commonly use effective diffusivity in order to lump the whole phenomenon of drying. [6,22,48,62]. The effective diffusivity is actually a complex interaction of variables involved during drying including temperature, moisture content and pressure. The use of liquid diffusion only may not be sufficient to represent the drying process since unreasonable profiles are resulted [8]. For better understanding of transport phenomena of drying process, multiphase drying models need to be implemented. The models give the local water distribution both in liquid and vapor phases as affected by pore structure and shrinkage during drying [8,23,78].

Equilibrium and non-equilibrium multiphase models can be applied for multiphase drying approach but it is suggested that the non-equilibrium multiphase drying model is implemented because it can be applied for more general cases and used to assess the validity of equilibrium models [23,78]. The model implements the equations of mass conservation of water in both liquid and vapor phases linked by the internal evaporation rate [66,78]. However, to the best of our knowledge, there has been no published explicit formulation of the internal evaporation rate apart from the work of [33] and [34] which coupled the internal evaporation rate with the liquid diffusion only at the beginning of drying period and vapor diffusion only at the later period.

The reaction engineering approach (REA) was proposed by X.D. Chen in 1996 and has been implemented to model several challenging drying cases [11,13,14,41–43,55–59]. The REA was shown to be accurate and robust to model convective drying of thin layer or small food materials. For instance, modeling of drying of aqueous lactose solution droplet using the reaction engineering approach (REA) resulted in the average absolute difference of weight loss and temperature profiles of 1% of the initial weight and about 1.2 °C, respectively. Application of REA to model drying of cream and whey protein concentrate showed average absolute difference of weight profile of 1.9% and 2.1% respectively while that of temperature was about 3 °C and 1.9 °C for cream and whey protein concentrate respectively [42,43]. The REA was also accurate to model drying of non-food materials including the one with infrared-heating [55]. Application of the REA on the cyclic drying of polymer drying was also successful [56]. Application of the REA has also been extended not only on the thin layer or small food materials but also on materials with thickness of several centimeters including the one with time-varying external conditions [57,58]. The REA presented in lumped format (i.e. ordinary differential equation with respect to time) is further called lumped reaction engineering approach (L-REA) [59].

The REA has indeed been implemented to model the local evaporation/condensation rate and combined with a system of equations of conservation to yield the S-REA (spatial reaction engineering approach), a non-equilibrium multiphase drying model, in order to model the convective drying of mango and potato tissues under constant environmental conditions [61]. The S-REA can model the convective drying very well and the REA is accurate to model the local evaporation rate [61].

For modeling of intermittent drying using non-equilibrium multiphase drying approach, to the best of our knowledge, there has been no multiphase drying model implemented. Although the S-REA is accurate to model the convective drying under constant environmental conditions [61], it is still challenging to model the intermittent drying as the local evaporation/condensation rate has to cope with the change of environmental conditions.

The REA is different from Krischer's and characteristic drying rate curve (CDRC) (Krishcer and Kast, 1978; [35]). [37] mentioned that the characteristic drying curve can be generated from the drying kinetics data so that drying can be distinguished into constant and falling rate period. Krischer's approach is basically that of the characteristic drying rate curve (CDRC) approach.

The REA is indeed different from CDRC (characteristic drying rate curve), which is summarized by Professor Roger Keey [35]. The differences between REA and CDRC have been presented previously [10]. The CDRC relies on the critical moisture content, dependent on drying conditions (temperature, velocity and humidity) so that the change of environmental conditions cannot be modeled automatically. It sometimes evaluates the evaporation flux based on the wet bulb temperature which may not be correct since the saturation

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