Journal of the Taiwan Institute of Chemical Engineers 84 (2018) 67–75

Contents lists available at ScienceDirect

Journal of the Taiwan Institute of Chemical Engineers

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

A novel initial temperature-based methodology to predict the optimal thickness in microwave thin layer drying process

Jun Jiang[a], Hongsing Tan[b], Bochen Pan[a], Leping Dang[a,*], Zhanzhong Wang[a,*], Hongyuan Wei[a]

[a] School of Chemical Engineering and Technology, Tianjin University, Tianjin, China
[b] P&G Beijing Innovation Center, Beijing, China

ARTICLE INFO

Article history:
Received 19 September 2017
Revised 18 December 2017
Accepted 12 January 2018
Available online 3 February 2018

Keywords:
Thin layer
Microwave drying
Pre-heating stage
Temperature simulation
Optimal thickness prediction
Influential factors

ABSTRACT

Compared with traditional hot air drying method, the existence of optimal material layer thickness is a significant phenomenon in microwave thin layer drying process. In the current work, a new initial temperature-based methodology is proposed to predict the optimal thickness and to evaluate the effect of influential factors on optimal thickness. The evaluated optimal material layer thickness by the proposed methodology is consistent with experimentally measured value, and hence confirms that the optimal layer thickness can be predicted exactly through the average temperature of bulk material at the initial 1st min during pre-heating stage. With the help of the proposed methodology, it is discovered that attenuation factor, β, surface convective heat transfer coefficient, h, and environmental air temperature, T_e are the main factors that affect the optimal thickness. And a larger β or T_e tends to result in a smaller optimal thickness, while the situation for h is just the opposite. These results can play a crucial role in designing apt continuous microwave tunnel drying system or aid in guiding their operations.

1. Introduction

Drying is one of the most time and energy consuming chemical processes, which has been paid more attention to process optimization by researchers [1–3]. Comparing with traditional hot air convection drying method, microwave drying has the advantages of alternative heating, energy & time saving and less thermal pollution [4,5]. The “volumetric heating” mechanism of microwave energy signifies that the entire material body can be heated simultaneously. This leads to the possibility of conveying extra functional value [6–10], such as porosity, mechanical properties, and rehydration characteristics to the dried product. Therefore, a large number of traditional industrial drying processes have been gradually substituted by microwave drying.

Continuous microwave tunnel drying system has been widely used in practical industries [11–16]. In this system, the material layer thickness is one of the critical parameters, which directly affects the thermal uniformity, the dried product quality and the production capacity in the practical production process. On the one hand, a larger thickness always results in serious thermal non-uniformity along the direction of microwave propagation due to attenuation. On the other hand, although a smaller thickness endows benefit in regard to thermal uniformity, heat produced by microwave energy also can be more convenient to be transferred out and dissipated into the air. According to previous literature reports, there exists an optimal material layer thickness in thin layer microwave drying process, at which the most rapid drying rate can be achieved [17,18]. In these two reports, explanations were delivered based on the completely opposite variation tendency of total mass transfer driving force $\rho_v - \rho_{v,e}$ and material surface area S during the variation process of layer thickness (initial sample volume under different thickness experiments remained unchanged, $S \times H =$ constant, initial sample volume). Those explanations suggested that the drying rate or total mass transfer flux $(\rho_v - \rho_{v,e}) \cdot S$ is not a monotonous function of thickness. This phenomenon is fundamentally different from the traditional hot air drying process in which small material layer thickness aids the drying process [19]. The opposite direction of heat transfer between microwave drying and hot air drying should essentially be the reason behind this difference. Hence, it was established that there exists an optimal thickness in microwave thin layer drying process.

However, previous studies primarily focused on explaining the phenomenon, while how to determine the optimal thickness in an easier way and factors influencing the optimal thickness are yet to be reported in literatures. In addition, related investigation involves a huge workload if experimental method were employed. What's

* Corresponding authors.
E-mail addresses: dangleping@tju.edu.cn (L. Dang), wzz7698@tju.edu.cn (Z. Wang).

https://doi.org/10.1016/j.jtice.2018.01.020
1876-1070/

Nomenclature

A/B	sample variables (−)
c	specific heat capacity (J/kg/K)
E	microwave induced electric field intensity (V/m)
h	surface convective heat transfer coefficient ($W/m^2/K$)
H	height of the material layer (m)
k	microwave dissipation coefficient ($W/m/V^2$)
Q_{mic}	internal heat generation intensity of microwave ($J/m^3/s$)
$Q_{mic-total}$	total heat generation rate of microwave ($J/m^2/s$)
Q_{net}	net heat absorption rate of material ($J/m^2/s$)
Q_{out}	surface convective heat transfer flux ($J/m^2/s$)
S	material layer surface area (m^2)
T	temperature (°C)
y	position inside the material layer (m)

Subscripts

e	environmental
v	vapour
0	initial

Greeks

β	microwave attenuation factor (−)
ε'	material dielectric constant (−)
ε''	material loss factor (−)
λ	heat conductivity coefficient (W/m/K)
ρ	density (kg/m^3)
τ	time (s)

more, the experimental material layer thickness cannot be set to all kinds of sizes due to the restriction from containers. Hence, theoretical simulation is an appropriate alternative. There is a significant amount of relevant simulation work about microwave drying process in literatures [17,20–26], and almost all of them were conducted using the coupled heat and mass transfer equations. However, each run of these simulations was achieved based on a specific sample size configuration. If these methods were employed and the continuously changed material layer thickness was considered at the same time in the present work, the resulted model would be too complex to be solved, and the required computing resource would be increased exponentially. Therefore, we developed a simplified methodology based on the idea of initial temperature simulation. By this methodology, both the optimal thickness and the influential factors could be investigated in a relative easy way.

To sum up, the objectives of the current work are to: (1) develop a new methodology based on initial temperature evaluation of heating process to determine the optimal thickness in microwave thin layer drying process; (2) explore the factors influencing optimal thickness via theoretical analysis; (3) validate the proposed new methodology via experiments; and (4) apply simulation in order to understand the specific effect of all the potential influential factors on optimal thickness.

2. Development of methodology

2.1. Simplification

Fig. 1 illustrates an exemplification of theoretical drying curves and the corresponding temperature curves under different conditions during microwave thin layer drying process, similar curves also could be found in literatures [27,28]. It can be seen that different drying curves correspond to different temperature raising curves. Therefore, besides by comparing the drying curves, it is also feasible to determine the optimal drying condition by comparing the corresponding temperature raising curves. However, it is worth noting that the temperatures for different drying curves under rapid evaporation stage are approximate, as shown in Fig 1. A better solution is to focus on the temperature difference during the pre-heating stage, in which temperature could real-time represent the drying rate and be used to determine the optimal drying condition. As long as the chosen pre-heating stage could be shared by each drying curve, it is practicable to determine the optimal drying condition by comparing the temperature configuration during the chosen pre-heating stage. What's more, only consider the pre-heating stage delivers lots of benefit, such as evaporation could be ignored, material properties could be treated as constant and so on.

In the current work, the optimal layer thickness in microwave thin layer drying process was determined by simulating and comparing the average temperatures throughout the material layer at the initial 1st min in the pre-heating stage. This time node was chosen just based on the consideration that the period of initial 1st min for all the drying curves involved in the present study can be treated as the pre-heating stage.

Notably, the time node, 1st min, was chosen based on the current study instead of the proposed methodology. The present work emphasized on the methodology, and it is necessary to choose a different time node value when applying this methodology to other specific work. Totally speaking, according to the above-mentioned simplification principle, the choosing of time node must meet the requirement that the period before this time node could be treated as pre-heating stage for all the involved drying curves.

2.2. Temperature distribution attainment

2.2.1. Major assumptions

(1) Deformation of material is not considered based on the narrow temperature variation range during the involved pre-heating period.
(2) Thermo-physical properties of material are treated to be constant also due to the involved temperature range in the present simulation is relative narrow.
(3) Air conditions are treated to be constant because of air flow.
(4) Both bottom and lateral sides of the container are considered as insulated due to the using of tinfoil in experiments, and thus, microwave energy can only be introduced into the material from the top surface and radial temperature distribution can be treated as uniform.
(5) Due to insignificant evaporation in pre-heating stage, moisture variation during the initial 1st min is ignored to simplify the temperature simulation process.
(6) Dielectric properties can be treated as constant during the pre-heating stage because of insignificant evaporation and narrow temperature variation range.
(7) Convective heat transfer inside the material layer is not considered, because the starch particles used in experiments are fine enough.

2.2.2. Governing equation

As illustrated in Fig. 2 [17], geometry system of material layer with one-dimensional heat or mass transfer along the thickness direction was considered in the current study. 20 g pre-gelatinized potato starch was chosen as the drying medium.

The temperature distribution in such configuration can be determined by solving the Fourier's field equation with internal heat generation. According to the present methodology described in Section 2.1 and assumptions (5) and (7), evaporation heat and heat