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Thin layer drying kinetics of pre-gelatinized starch under microwave

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ABSTRACT

Absolutely dried starch is widely used in cooking and other industries. However, the prolonged drying time during falling rate drying period and low energy efficiency limit the application of traditional hot air drying. Microwave energy is the alternative choice considering the 'volumetric heating' mechanism. Then, investigations on microwave thin layer drying of starch were conducted by experimental studies and mathematical modeling. Results show that drying time can be reduced significantly with the increase in microwave power density. And there exists an optimal layer thickness, both greater and less than the value will result in a lower drying rate. This phenomenon is completely different from hot air dying and has not been reported in literature before. Explanations are given from the perspective of heat and mass transfer. Data fitting shows that 'Midilli–Kucuk' model is the best one to describe drying behavior of starch. An integrated 'Midilli–Kucuk' model is also given after considering the effect of operating variables on model parameters. Effective diffusivities vary from 6.08×10^{-7} to 6.10×10^{-5} m^2/s, and increase with the increase of microwave power density, decrease with the increase of surface area per unit mass, values are higher when compared with other materials dried under microwave in literature. Finally, nonlinear surface fitting was conducted in order to give a systematic prediction for effective diffusivities.

1. Introduction

Starch is a kind of polysaccharide, and can be treated as a polymer of glucose. Besides food engineering, starch is also widely used in various industry processes, such as paper-making, textile, pharmaceutical and gelatinizing agent. The preparation of starch is normally carried out in aqueous medium so that drying process in the post processing stage is necessary [1], usually, moisture content in the finished product is required to less than 14% in order to meet the need of storage. What's more, absolute dried starch is also widely used in cooking and starch-based drying agent [2,3]. Both of which need the fundamental unit operation of drying.

Hot air is the traditional drying medium used to drying starch [4] and other materials. In starch manufacturing process, convective dryer is used to reduce moisture content from 30–40% to approximately 13–14% [5]. Major disadvantages of hot air drying are the prolonged drying time during the falling rate drying period and low energy efficiency, especially in the process of preparing absolutely dried starch. Recently, considering the shortcomings of traditional convective drying methods, dielectric drying especially microwave drying, have been payed lots of attentions. The 'Volumetric Heating' method, means that the entire material body can be heated simultaneously, which is completely different from the heat transfer process from surface to interior by heat conduction in hot-air drying process. Based on this heating mechanism, microwave drying process usually possess a short drying time and high energy efficiency [6].

In order to design suitable microwave dryer, drying kinetics data from experimental studies are necessary. However, it is impossible to investigate all the drying conditions just by experiments due to time-consuming and high cost. Therefore, drying models are developed for various of materials. Many efforts have been made on developing models for microwave drying process, such as theoretical, empirical fitting or compromising thinking.

Theoretical models are represented typically by multiphase porous medium model [7,8], also including those models that detailed analyze the mass and heat transfer processes in each phase [9,10]. These models can be helpful for researchers to have a good understand of drying process. However, besides the problem of lacking properties data, the complexities of these models also restrict its widespread use. Another theoretical method is coupling Fick's Second Law and heat balance equations [11,12], this method assumes that moisture only evaporates at the surface of material, otherwise the using of diffusivity will be unsuitable.

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However, evaporation inside material exactly happens during microwave drying.

Empirical models include thin layer drying equations and artificial neural network (ANN) modeling. Actually, this method gives a statistical relationship between experimental conditions and the outputted experimental results. ANN is an effective tool in developing empirical models for various process, including drying [13,14], because parameters in physical models are not necessary. Actually, ANN method is more suitable and accurate in multivariable system, and lots of resource data are needed in order to train the model. In the situation when the amount of variable is relatively less, such as current microwave drying process, the employment of ANN is really reluctant and not necessary, and thin layer drying equations are the alternative choice. Thin layer drying equation is a simple empirical method and usually can obtain enough agreement. However, empirical models are material dependent, it is impossible to build a universal model which can describe the microwave drying process for various materials. Lots of drying kinetics work have been conducted for different material using thin layer drying equations [15,16]. Considering the simplicity and need no assumptions in geometric, diffusivity and conductivity aspect, thin layer drying equations are still widely used to describe drying process.

A compromising thinking is semi-empirical method. Reaction engineering approach (REA) is the typical one [17,18], which could model the drying kinetics by applying chemical reaction engineering principles. However, drying activity energy, the most important parameter used in this method, should be measured from experiments, and usually cannot be used to other situations when drying conditions are different.

Based the analyses of above mentioned methods, thin layer drying equations are chosen to model the drying process of starch. In literature, no published work had been done on microwave thin layer drying behavior and kinetics study for starch. Therefore, the major objectives of the current paper are to: 1) investigate the drying behavior of starch under microwave, 2) explain the existence of optimal layer thickness in microwave thin layer drying process, 3) determine the optimal drying model for microwave thin layer drying of starch, 4) determine the effective diffusivities of starch under thin layer microwave drying.

2. Materials and methods

2.1. Materials

Pre-gelatinized starch was chosen as the drying material and provided by Tianjin Guangfu Fine Chemical Institute. The initial moisture content is (11 ± 0.5) % (wet-basis) and the particle size range is 5–25 µm.

2.2. Experimental apparatus

Fig. 1 shows the experimental setup used in the current study. The microwave oven used in this work was special designed and fabricated by Tianjin Surui microwave company with a continuously adjustable microwave power input from 0 to nominal maximal 800 W. The magnetron (produce microwave) works continuously instead of the mode of "work-stop-work…" used by commercial microwave oven (the reason why household microwave oven was not applied). The dimensions of microwave cavity are 285 × 258 × 234 mm. The power used in this work was then calibrated according to the standard test method [19] provided by ASTM (American Society for Testing and Materials). This method is conducted by heating 1 l distilled water for 2 min, and determining the calibrated power P_0 by calculating the energy absorbed by water, see Eq. (1) ρ, V, $Cp$are density (1 g/ml), volume (1000 ml) and heat capacity (4.187 J/g/K) of water, heating time t is 120 s, T_1 T_2 are the temperature before and after heating. The working frequency of the microwave is 2450 MHz.

Fig. 1. the microwave oven used in the current study.

$$P_0 = \frac{\rho V C p (T_2 - T_1)}{t} = 34.9(T_2 - T_1) \tag{1}$$

2.3. Experimental procedure

Drying curves can be achieved by drying each 20 g sample in a beaker with different time. Once drying step finished, moisture content was measured directly and rapidly by a moisture analyzer (MB45, OHAUS) after mixing the sample sufficiently. This procedure guarantees the measured moisture content represents the average value of the entire sample. Every measured point on the drying curves was obtained independently. For example, moisture content at time t min can be measured after a 20 g initial sample experienced a drying time of t min, and the moisture content at time $t + 1$ min was then obtained by drying another identical 20 g initial sample with $t + 1$ min. Changing microwave power density and material layer thickness, repeating the drying process, then a series of drying curves can be obtained. It should be noted that changing the sample layer thickness can be achieved by putting the same weight sample into different containers with different bottom area. Moisture content at each point of drying curves should be measured for three times to calculate the mean value. Drying conditions for each group experiments are presented in Table 1.

2.4. Data analysis

The moisture analyzer can directly give the moisture percentage on wet basis based on Eq. (2). M_t (g water/g wet sample) is the moisture content at time t, W_0 is the initial sample weight, and W_t is the sample weight after processed by moisture analyzer. Then, considering from the perspective of non-constant environmental air conditions (non-constant equilibrium moisture content M_e) and simplification, the measured moisture content data then can be normalized just by dividing M_t by M_0 [20], as shown in Eq. (3). MR is the moisture ratio after normalization, and M_0 is the initial moisture content.

$$M_t = \frac{W_0 - W_t}{W_0} \tag{2}$$

$$MR = \frac{M_t - M_e}{M_0 - M_e} \xrightarrow{\text{non-constant}\, M_e} = \frac{M_t}{M_0} \tag{3}$$

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