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Short communication

A one-step non-isothermal method for the determination of effective moisture diffusivity in powdered biomass

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ABSTRACT

The effective moisture diffusivity (D_{eff}) is an important drying parameter. D_{eff} is usually calculated using a traditional two-step isothermal method. The current study presents a one-step non-isothermal method as a promising alternative for determining D_{eff} of biomass particles. Non-isothermal drying experiments were performed at various heating rates (2, 4, 6, 8, and 10 °C min^{-1}) from room temperature to 100 °C. Isothermal drying experiments were also performed to obtain D_{eff} at five temperatures (50, 60, 70, 80, and 90 °C) for comparison. All experiments were conducted using a thermogravimetric analyzer (TGA) due to its precise temperature control capability and accurate recording of mass loss. Thermal lag was significantly reduced under non-isothermal conditions, and the values obtained by the one-step non-isothermal method were in agreement with those obtained by isothermal procedures.

1. Introduction

Effective moisture diffusivity (D_{eff}) is one of the important drying parameters used to describe the drying mechanism, to predict the drying process, and to provide information for the dryer design [1]. The traditional two-step isothermal method has generally been used to determine drying parameters [2]. First, D_{eff} is determined by Fick's second law for each temperature. Then, a set of D_{eff} values is correlated with temperature using an Arrhenius-type equation, from which the activation energy (E_a) and the pre-exponential factor (D_0) can be obtained.

The two-step isothermal method is generally considered to be logical and applicable. However, various experiments (at least one for each temperature) and samples are required to obtain accurate results. The process is obviously expensive and time-consuming [3]. Moreover, the drying experiments are not usually performed isothermally in practical processes, and thus thermal lag implies a large error in the determination of parameters [4].

As an alternative, the D_{eff} of biomass can be determined by a promising one-step non-isothermal method. This method has some distinct advantages such as fewer experimental requirements and reduced thermal lag [5]. It was first introduced in 1963 by Rogers to study the decomposition of sucrose in aqueous solutions [6]. To achieve the best non-isothermal condition, linear heating is used due to its mathematical simplicity and procedural ease compared with other studies. However, the one-step non-isothermal method is not widely used, particularly in the identification of D_{eff} of powdered biomass. The key

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problem is that the non-isothermal condition of linear heating is difficult to achieve. Thermogravimetric analyzer (TGA) can achieve non-isothermal conditions perfectly due to its precise temperature control capability [7]. Therefore, TGA was used in the conduct of the experiments in this study.

The objectives of this study are to determine the effective moisture diffusivity of powdered biomass by a novel one-step non-isothermal method and to experimentally validate this method by comparing it with the traditional two-step isothermal method.

2. Materials and methods

2.1. Materials

The biomass materials used in this study were rice husk, corn straw, and fir wood, coming from the suburb of Hefei city in China. The varieties are *Oryza sativa* ssp. *indica*, *Gossypium hirsutum*, and *Pseudotsuga gaussenii* Flous for rice husk, corn straw, and fir wood, respectively. These materials were ground and particles from 0.125 to 0.3 mm in size were selected for the experiments based on the suggestions of previous studies [8,9]. Prior to the experiments, the materials were stored for 96 h at 25 °C in a sealed vitreous container (relative humidity: 50%) to obtain even distribution of moisture. The moisture contents of the materials were determined as 0.081, 0.075, 0.086 kg water (kg dry matter)$^{-1}$ for rice husk, corn straw, and fir wood, respectively, by the oven method at 105 °C for 24 h [10].

2.2. Drying experiments

The drying experiments were performed using a thermogravimetric analyzer (TGA Q5000IR, TA Instruments, USA). The TGA has a new infrared furnace that offers precise control of temperature. Isothermal and non-isothermal drying conditions that required in this study can be achieved [4]. The main technical parameters are expressed as follows: weighing range, 0–100 mg; heating rate, 0.1–500 °C min^{-1}; weighing sensitivity, <0.1 μg; weighing accuracy, ±0.1%; temperature range, ambient to 1200 °C; and isothermal temperature accuracy, ±1 °C.

The samples used in the experiments were 7, 9, and 10 mg of uniformly thick (1 mm) corn straw, rice husk, and fir wood, respectively. The sample was first distributed uniformly in the sample pan (platinum), and then TGA automatically placed the sample pan in the furnace. The experiment ran in accordance with the predetermined operating procedures, with an air flow of 100 cm^3 min^{-1}. The more information of TGA and experimental procedure can be found in the literature [3,11].

The isothermal experiments were performed at 50, 60, 70, 80, and 90 °C. Non-isothermal experiments were performed from room temperature (27 °C) to 100 °C at different heating rates of 2, 4, 6, 8, and 10 °C min^{-1}. A computer connected to the TGA automatically recorded the mass loss and temperature, and then processed the data. Each experiment was repeated three times, and the average values were used. These selected conditions were in agreement with some previous studies [3,9,11].

3. Mathematical considerations

3.1. The two-step isothermal method

The Fick's second law [Eq. (1)] has been widely used to describe the drying process of biomass, since moisture diffusion is generally controlled by internal mass transfer [12]. The mathematical solution of Eq. (1) is shown in Eq. (2).

$$\frac{\partial \mathrm{MR}}{\partial t} = \nabla\left[D_{\mathrm{eff}}(\nabla \mathrm{MR})\right] \tag{1}$$

$$\mathrm{MR} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{\mathrm{eff}}t}{4L^2}\right) \tag{2}$$

where

$$\mathrm{MR} = \frac{M - M_e}{M_0 - M_e} \tag{3}$$

MR is the moisture ratio of biomass; M is the moisture content at any time; M_0 is the initial moisture content; M_e is the equilibrium moisture content; n is a positive integer; t is the drying time and L is the half thickness of the sample. As indicated by previous studies [1,13], M_e was obtained from the drying curves and was set to the moisture content when no mass loss is detected during the drying process.

The effect of temperature on effective diffusivity is described by the Arrhenius relationship.

$$D_{\mathrm{eff}} = D_0\exp\left(-\frac{E_a}{R(T+273.15)}\right) \tag{4}$$

where D_0 is the pre-exponential factor, E_a is the activation energy, R is the ideal gas constant, and T is the drying temperature. From Eqs. (1)–(4), D_{eff} and E_a can be obtained. The procedures are introduced in detail in the literature [13–15].

3.2. The one-step non-isothermal method

For the linear heating procedure in this study, the relationship between temperature and time is expressed as the following:

$$T = T_0 + \alpha \cdot t \tag{5}$$

where T_0 is the initial temperature of the experiment and α is the heating rate.

Under non-isothermal conditions, moisture transport is described by Eqs. (1) and (4). D_0 and E_a are the unknown parameters in Eq. (4). The alteration of one parameter will change the other parameter simultaneously. A large number of iterative calculations and a certain time were required for regression analysis to obtain better results (consistent with the experimental data). It is thus needed to make an appropriate mathematical transformation of Eq. (4). The same method to accelerate the convergence was reported in the literature [3]. Then Eq. (4) can be rewritten as Eq. (6).

$$D_{\mathrm{eff}} = \exp\left[\delta - \frac{E_a}{R}\left(\frac{1}{T+273.15} - \beta\right)\right] \tag{6}$$

where

$$\delta = \ln(D_0) - \frac{E_a}{R}\beta \tag{7}$$