Experimental Determination and Modeling of Drying Process of Woody Biomass

Xiao He1,* and Lianjun Wang1

1Jiangsu Key Laboratory of Chemical Pollution Control and Resources Reuse, School of Environmental and Biological Engineering, Nanjing University of Science and Technology, Nanjing, Jiangsu Province, 210094, China

*Corresponding author’s e-mail: xhe@njust.edu.cn

Abstract. Birch is a kind of readily available woody biomass resource, which can be used to crush and manufacture fuel particles and animal bedding. One of the important aspects during the production system is the drying of biomass prior to storage or processing. Moisture migration in wood is a particularly important factor in determining the drying process. The objectives of this study are to investigate the drying characteristics of Birch and develop a model to simulate moisture diffusion in Birch during the drying process. Experiments were conducted in a controlled environment chamber. Different temperatures and relative humidity were set to simulate the different drying conditions. The mechanism of moisture movement in Birch samples during the drying process was represented by a diffusion model according to Fick’s second law. A computer program in Matlab software was developed to simulate the infinite element model. Moisture diffusivity of Birch was determined by minimising the sum of squares of the residuals between experimental results and numerically predicted data. Results showed that the moisture diffusion coefficients of Birch ranged from $1.2 \times 10^{-7}$ m$^2$/hr to $9.6 \times 10^{-7}$ m$^2$/hr with temperature varying from 20°C to 60°C. And the trend of diffusion coefficient versus temperature was in accordance with the Arrhenius equation.

1. Introduction

Due to the increasing consumption of energy and environmental pollution, alternative fuel sources and clean energy are receiving more concerns in the recent decade [1]. A large quantity of biomass residues with high moisture content are left in the forest after logging operations. As one of the alternatives, woody biomass can be used to produce bioenergy and biobased products including panel, chemicals and other energy feedstocks [2]. Generally, the materials always contain relatively high moisture content (from 70% to 130% dry basis) after harvesting. High moisture content could increase the cost of transportation and pelletization, thus reflecting the price of fuel [3]. Furthermore, moisture leads to the reduction in the maximum temperature of combustion and combustion efficiency.

The storage of biomass materials with high moisture content prior to operation may cause problems. The properties of biomass can change due to degradation process, in terms of the quality deterioration, dry matter losses and fire risk [4]. Therefore, biomass is usually dried before storage to reduce moisture content to a safe level. Conventional ways of drying are effective but also energy intensive. Thus, it is important to estimate the drying rate for the biomass materials and terminate the drying process in a timely manner in order to minimize the energy inputs. Under certain circumstance, biomass materials can reach the equilibrium moisture content (EMC) with the environment. The difference between the instantaneous moisture content and the equilibrium moisture content of the
materials results in the desorption and adsorption of moisture [5]. Thus, it is significant to investigate the EMC of biomass at different temperatures and relative humidity.

A large number of researches have been carried out to describe the drying process of various materials in the past decades [6-10]. Many studies have been reported on moisture diffusivity of food products, which vary from $10^{-12}$ to $10^{-8}$ m$^2$/s [11,12]. Studies conducted on drying of wood chips show that the effective moisture diffusivity in wood was found to range from $10^{-10}$ to $10^{-9}$ m$^2$/s at temperature of 40°C to 90°C. And the diffusion coefficient was found to increase exponentially with moisture content [10,13].

The objective of this study is to investigate the drying characteristics of woody biomass and to present a model to simulate the moisture diffusion during the drying process. The model can provide information on the moisture migration in biomass without measurements, along with giving the relevant data to predict drying and terminate the drying process timely.

2. Materials and methods

2.1. Materials

The woody materials used in this study were obtained from Northern China. The Birch samples comprised small-size stems with bark. The Birch materials with bark intact were then cut to average length of 200-250 mm, with the diameter of 5 to 10 mm.

2.2. Drying test

A controlled environment chamber was used to conduct the drying experiments. Tests were performed to study the desorption characteristics of Birch with temperature ranging from 20°C to 60°C to simulate drying under different climate conditions. Materials were stored for 24 h before all tests. In experiment, the weight of the samples with time was recorded by a digital balance till reaching the equilibrium moisture content. The moisture contents of the samples before and after tests were measured in the oven at 103°C for 24 h to obtain the bone dry biomass [14]. Replicates were carried out for each test and average results were reported.

2.3. Diffusion model

Moisture movement inside the samples was modeled using Fick’s second law. It assumes that the moisture migration is due to the moisture concentration gradient in the material. A one-dimensional diffusion model was assumed:

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial W}{\partial x} \right)$$

(1)

where $W$ is the moisture content, $D$ is the diffusion coefficient.

The geometry of Birch samples may be represented by an infinite cylinder. For this case, Equation (1) can subsequently be replaced by an axisymmetrical model:

$$\frac{\partial W}{\partial t} = D \left( \frac{\partial^2 W}{\partial r^2} + \frac{1}{r} \frac{\partial W}{\partial r} + \frac{\partial^2 W}{\partial z^2} \right)$$

(2)

Where $r$ is the radial coordinate, $z$ is the longitudinal coordinate.

The initial and boundary conditions for this study are assumed that: (1) The initial moisture content of samples is uniform. (2) The surface instantaneous moisture of samples is equilibrium with the drying environment. (3) The drying environment is maintained constant. (4) The samples are homogeneous and the shape of them remains constant. The analytical solution of the equation for diffusion coefficient in terms of infinite cylinder is expressed by:

$$\frac{M - M_r}{M_r - M_e} = \sum_{n=1}^{\infty} \frac{4}{x_n} \exp \left( -x_n^2 \frac{D}{r^2} \right)$$

(3)
Where $M$ is the moisture content of samples, $M_e$ is the equilibrium moisture content, $M_i$ is the initial moisture content, $x_n$ is $n$th positive root of Bessel function of order zero, $r$ is radius of cylinder, and $t$ is time.

3. Results and discussion

3.1. Drying process

The drying characteristics of Birch samples are shown in Figure 1. Under higher drying temperature, the samples had lower equilibrium moisture content and higher drying rate. The drying time of moisture content from initial values to equilibrium moisture content reduced from 300 hr to 100 hr, as drying temperature increased from 20°C to 60°C. It reaffirmed that the drying temperature is one of the key parameters that affects the drying rate. The results from this study are in accordance with some researches in the literature [15].

![Figure 1. Drying characteristics of Birch samples at different temperatures.](image)

3.2. Diffusion coefficient

Results from the drying tests were used to estimate the diffusion coefficient in Equation (3). A Matlab program was developed for simulation. Moisture diffusion coefficient of the samples was obtained by minimizing the sum of squares of the residuals between the measured and predicted values. The results ranged from $1.2\times10^{-7}$ m$^2$/hr to $9.6\times10^{-7}$ m$^2$/hr with the temperature varying from 20°C to 60°C. The values of $ln\,D$ were plotted against $1/T$ and displayed in Figure 2. The diffusivity was found to be positively related to temperature, and the trend of coefficient followed Arrhenius equation with regard to temperature.

![Figure 2. Relation between moisture diffusivity of Birch and temperature.](image)
4. Conclusion
Moisture migration of biomass is one of the significant factors that affect the drying process. The drying characteristics and moisture diffusivity of Birch were investigated in this study. Results indicated that the drying temperature was positively related to the drying rate. The mechanism of moisture movement within Birch samples was represented by a diffusion model. A computer program in Matlab software was developed to simulate the process. Calculation results showed that the moisture diffusion coefficients ranged from $1.2 \times 10^{-7}$ m$^2$/hr to $9.6 \times 10^{-7}$ m$^2$/hr with temperature varying from 20°C to 60°C. The relation between the moisture diffusivity and temperature was found to follow the Arrhenius equation.

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