Experimental Determination of Moisture Diffusivity of Birch

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Abstract. Birch is one of the renewable biomass resources. The high moisture content of raw materials increases the cost of transportation and pelletization. Drying is an effective approach to reduce the moisture content of biomass before storage and other operations to a safe and manageable level. Moisture diffusion in wood could affect the drying process significantly. In this study, the drying process of Birch materials was modeled by Fick's second law. Results from the experiment were utilized to determine the moisture diffusivity with parameter estimation. It showed that the diffusion coefficients of Birch increased from $1.2 \times 10^{-7}$ to $9.6 \times 10^{-7}$ $m^2 h^{-1}$ with the temperature ranging of 20-60°C. The trend of moisture diffusion coefficients followed Arrhenius equation with respect to temperature. For high-temperature drying, this model can help to terminate the drying process in a timely manner, thus conserving energy consumption.

1. Introduction
The logging operations produce abundant biomass residues with high moisture content. These materials are generally left behind in the forest, which are either left to rot or burned to minimize the risk of fires. Due to the large demand on renewable energy, people are actively searching for alternative fuel sources [1]. As one of the alternatives, biomass is converted to bioenergy and used to produce paper and pulp, panel, chemicals and other energy feeds tocks [2]. Generally, the materials always contain relatively high moisture content after harvesting. The moisture content of woody biomass varies from 70% to 130% (dry basis). The high moisture content will increase the cost of transportation and pelletization, thus reflecting the price of fuel [3]. Furthermore, high moisture content reduces the maximum temperature of combustion and combustion efficiency. The storage of woody biomass materials with high moisture content prior to operation may cause problems. The properties of biomass can change due to degradation process, which would lead to the deterioration in quality, dry matter losses, fire risk, or generation of microbes that are harmful to human beings [4]. Hence, biomass is usually dried before storage and other operations to reduce the moisture content to a safe and manageable 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 timely in order to minimize the energy inputs. Biomass materials may reach the equilibrium moisture content (EMC) when stored at certain temperature and relative humidity. The difference between the instantaneous and equilibrium moisture contents of the materials allows the potential desorption (drying) or adsorption of moisture [5]. Thus, it is necessary to estimate the drying rates of biomass by investigating the EMC at a range of equilibrium relative humidity and temperature conditions.
A large number of researches have been carried out in the past decades to describe the drying process of various materials [6-10]. Many studies have been reported on moisture diffusivity of food products, which reveal a huge variability and vary from $10^{-12}$ to $10^{-8}$ m$^2$/s [11-13]. Studies conducted on drying of wood chips showed that the effective moisture diffusivity in wood was found to range from $10^{-10}$ to $10^{-9}$ m$^2$/s at temperature of 40$^\circ$C to 90$^\circ$C. And the diffusion coefficient was found to increase exponentially with moisture content [10,14].

The objective of this study is to investigate the drying characteristics of biomass materials and to present a model to simulate the moisture diffusion during the drying process. The model can be utilized to provide basic information on the moisture migration without measurements and can also be used to provide the data and guidelines to terminate the drying process in a timely manner. This would contribute towards energy saving, along with the planning of regional biomass storage.

2. Materials and methods

2.1. Materials
The woody biomass used in this study was obtained from Northern China. The Birch samples consisted of small-size stems with bark. The Birch materials with bark intact were cut to uniform length of 200-250 mm, with the diameter ranging from 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$^\circ$C to 60$^\circ$C to simulate drying under different climate conditions. Materials were equilibrated for 24 h before test. For all the tests, the weight of the materials with time was recorded by a digital balance till reaching equilibrium moisture content. The initial and final moisture contents of the materials were measured in a convection oven at 103°C for 24 h to obtain the bone dry biomass [15]. 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 and $D$ 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 and $z$ 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:

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

(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 the $n$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 [16].

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

#### 3.2. Diffusion coefficient

![Figure 2. Relation between moisture diffusion coefficient of Birch and temperature.](image)

Results from the drying tests were used to estimate the moisture diffusion coefficient in Equation (3). A Matlab program was developed for simulation. Moisture diffusion coefficient of Birch sample was obtained by minimizing the sum of squares of the residuals between the measured and predicted values. The results ranged from $1.2 \times 10^{-7}$ m$^2$/hr to $9.6 \times 10^{-7}$ m$^2$/hr with the temperature increasing from 20°C to 60°C. Results indicated that the trend of diffusion coefficients followed Arrhenius equation with respect to temperature. The relation between moisture diffusivity and temperature was displayed in Figure 2.
4. Conclusion
Moisture migration of biomass is a significant factor that influences the drying process. The drying characteristics and moisture diffusivity of Birch were investigated in this study. Results showed that drying temperature had the positive relation with the drying rate. The mechanism of moisture movement within Birch samples was represented by a diffusion model (Fick’s second law). A computer program in Matlab software was developed for simulation. Calculated results showed that the moisture diffusion coefficients ranged from $1.2 \times 10^{-7}$ m²/hr to $9.6 \times 10^{-7}$ m²/hr with temperature from 20°C to 60°C. The relation between the diffusion coefficients and temperature was found to follow the Arrhenius equation.

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