Fuel 103 (2013) 171–178

Contents lists available at SciVerse ScienceDirect

Fuel

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

Moisture sorption characteristics of switchgrass and prairie cord grass

C. Karunanithy *, K. Muthukumarappan, A. Donepudi

Agricultural and Biosystems Engineering Department, South Dakota State University, 1400 North Campus Drive, Brookings, SD 57007, USA

HIGHLIGHTS

- Moisture content (MC) plays an important role in the bio/thermochemical conversion of feedstocks into energy.
- Knowledge of the relationship between air relative humidity (RH) and feedstock MC is essential for drying and storage.
- Equilibrium MC at different equilibrium RH and temperatures were determined and fitted with five–three parameter models.
- Modified Halsey emerged as the best model followed by modified Oswin model for switchgrass and prairie cord grass.

ARTICLE INFO

Article history:
Received 22 February 2012
Received in revised form 1 May 2012
Accepted 2 May 2012
Available online 23 May 2012

Keywords:
Sorption isotherm
Relative humidity
Temperature
Model evaluation
Fitting

ABSTRACT

Moisture content plays an important role both in the biochemical and thermochemical conversions of various feedstocks into energy. Knowledge of the relationship between relative humidity of air and moisture content of the feedstock is essential for drying and storage. The aim of this work was to determine the sorption isotherms of switchgrass and prairie cord grass and to compare the experimental data with isotherm models found in the literature. The equilibrium moisture content (EMC) of switchgrass and prairie cord grass was determined using the static gravimetric method at equilibrium relative humidities (ERH) and temperatures ranging from 12 to 89% and 20 °C to 40 °C. Depending upon the ERH values, the EMC values ranged from 9.2 to 20.8%, and 7.0 to 21.0% db for switchgrass and prairie cord grass, respectively and they followed typical the type II isotherm found in food materials. Non-linear regression was used to fit five commonly used three-parameter isotherm models to the experimental data: modified Oswin model, modified Halsey model, modified Chung–Pfost model, modified Henderson model, and the modified Guggenheim–Anderson–de Boer (GAB) model. Modified Halsey emerged as the best model followed by modified Oswin for both feedstocks with high *F*-statistic and R^2 values with low E_m and E_s and fairly random scattered residual plots. Because of the range of the environmental temperature and RH values, these models can be used to predict the equilibrium moisture content of these feedstocks starting from harvesting, drying, and preprocessing, through transportation, storage, and conversion/processing.

1. Introduction

A search for renewable resources has been in place for the past few decades in order to fulfill the ever-growing demand for and escalating cost of fossil fuels coupled with global warming issues. Because of renewability, positive environmental impacts, abundance, and cheapness (compared to corn/sugarcane), biomass appears to be an attractive feedstock [1,2]. Corn stover and switchgrass are two biomass feedstocks that have attracted most of the attention in the biofuel arena. The US Department of Energy identified switchgrass as a model herbaceous energy crop because of its high biomass production capability from which renewable sources of fuel and electricity can be generated [3,4]. Prairie cord grass (PCG) is the most widely distributed C4 perennial grass. It can be grown in wider environmental range in the northern Great Plains than can switchgrass. Further, PCG has comparable productivity, reasonable yield (10 dry tons/ha) and high bulk density (195 kg/m^3) [5]. Based on the above facts, switchgrass and prairie cord grass were selected for this study.

In the biochemical or thermochemical conversion of biomass into biofuels or bio-oil, moisture content is of significant interest. Moisture content has a strong influence on harvest, preprocessing/grinding, transportation, storage, conversion/processing, and the resultant products. Feedstocks with high moisture require more energy for harvesting, grinding, and drying; and cost more to transport; they also have an increased char yield in pyrolysis, resulting in bio-oil with high moisture and a higher cost of thermochemical conversion [6–8]. Feedstocks in dry form are much more stable, safer to store, and easier to preprocess, all are important for

---

* Corresponding author. Tel.: +1 605 688 5670; fax: +1 605 688 6764.
E-mail address: Chinnadurai.karunani@sdstate.edu (C. Karunanithy).

0016-2361/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2012.05.004

Nomenclature

Symbols

df	degree of freedom
E_m	mean relative percent error
E_s	standard error
N	number of data points
R^2	coefficient of determination
Y	experimental equilibrium moisture content% (db)
$\hat{Y}$	predicted equilibrium moisture content% (db)
%	percentage
°C	degree celsius

Abbreviations

A, *B*, and *C*	constants specific to each equation
ASAE	American Society of Agricultural Engineers
ASABE	American Society of Agricultural and Biological Engineers
db	dry basis
EMC	equilibrium moisture content
ERH	equilibrium relative humidity
exp	experimental
GAB	Guggenheim–Anderson–deBoer
m	meter
M	moisture content,% (db)
mm	milli meter
NLIN	non-linear
NREL	National Renewable Research Laboratory
prd	predicted
RH	relative humidity
SS	sum of squares
T	temperature, °C

the successful operation of biorefineries [9]. In general, a feedstock is expected to be stored in ambient atmospheric conditions in an open field or in an enclosure due to its bulky nature. According to Krupińska et al. [10], one of the most difficult problems is how to store the harvested feedstock without the loss of mass. Some of the known problems are the loss of dry matter due to microbial deterioration, self-ignition due to heat development, and health risk associated with the release of high concentrations of allergenic microbes into the air [11]. Deterioration of the feedstock depends on the moisture content and the types of storage. The moisture content for safe storage depends upon the type of feedstocks. For long-term storage, the moisture content should be below 17.65% db for most of the feedstocks [8], but it is 20% (db) for willow [12].

Feedstocks are subjected to different temperatures and relative humidity (RH) during harvesting, preprocessing, transportation, and storage in a wide variety of climates. Knowledge of the relationship between the temperature and the RH of air is useful in the selection of correct drying and storage operations to preserve the quality of feedstocks. In general, feedstocks are hygroscopic in nature, meaning that they may adsorb and desorb the moisture from the surrounding atmosphere [7,13]. Knowledge of the equilibrium moisture content (EMC) is useful to determine whether a feedstock will gain or lose moisture under a given set of temperature and RH conditions. The EMC of feedstocks depends upon the species, variety, maturity [14–16], porosity and microstructure [17], specific surface area [18], amount of extractives and strength of feedstock/wood [19], and type of processing or treatment the feedstock was subjected to [20], in addition to temperature and RH of the environment.

Static and dynamic methods are used for EMC determination. In the static method, saturated salt solutions or acids of different concentrations are used to obtain different equilibrium relative humidity (ERH) in a closed chamber. The principal static methods are gravimetric, manometric, and hygrometric. The advantage of static methods is their ability to maintain constant conditions easily [21,22]. The gravimetric technique has several advantages over the manometric and hygrometric techniques such as the ability to determine the exact dry weight of the sample, to minimize temperature fluctuations between the samples and their surroundings, to record the weight change in equilibrium with the respective water vapor pressures, and to achieve hygroscopic and thermal equilibrium between the samples and water vapor source [23]. Among the static methods, the gravimetric technique has been considered preferable/reliable to obtain complete sorption isotherms [23,24] and has been recommended as the standard method [25]. The form of the feedstock dictates the method selection: for example, the dynamic method is more suitable for pellets/briquettes, whereas the static method is suitable for powdery materials.

Because of the recent focus on biofuel research, researchers have started looking into the EMC of different feedstocks such as selected corn stover components [26], flax straw, hemp stalk, and reed canary grass [13,27]; miscanthus leaves and stems [8]; pine, birch, spruce, and willow [10], and briquettes or pellets made from cotton stalk and sawmill waste [7], switchgrass [28], softwood [29], peanut hull [30], sorghum stalk, corn stover, wheat straw, and big bluestem [31]. In general, moisture sorption isotherms describe the relationship between the ERH and the EMC at constant temperatures and pressures [32]. Several researchers have reviewed the suitability of isotherm models for various biological materials and concluded that no “universal model” adequately describes sorption behaviors over a broad range of temperatures and RHs [33,34]. Therefore, there is need to search for the most appropriate EMC/ERH equation for each specific feedstock [26,33,35,36]. A literature survey revealed that the EMC/ERH relationships for switchgrass and prairie cord grass have not been published. Therefore, the objectives of this study are to determine the moisture adsorption data of switchgrass and prairie cord grass and to evaluate the suitability of commonly used isotherm equations for predicting the EMC of these feedstocks at different ERH.

2. Materials and methods

2.1. Sample preparation and characterization

Switchgrass and prairie cord grass were obtained from local farms and ground in a hammer mill (model Speedy Jr, Winona Attrition Mill Co, Minneapolis, MN) using a 4 mm sieve. The ground feedstock was stored in sealed bins (0.68 m height and 0.47 m dia) at room temperature (20 ± 1 °C) until needed. The initial moisture content of the feedstocks was determined based on the ASABE Standard S358.2 for forage moisture determination [37]. The amount of extractives for each feedstock was determined following the NREL protocol [38].

2.2. Experimental procedure

In general, the adsorption isotherm data can be used for establishing a storage method [39]. The moisture adsorption