Energy 106 (2016) 400–407

Contents lists available at ScienceDirect

Energy

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

Two equations for estimating the exergy of woody biomass based on the exergy of ash

Yaning Zhang [a, b, *], Wenke Zhao [a], Bingxi Li [a, *], Haochun Zhang [a], Baocheng Jiang [a], Cunfeng Ke [a]

[a] School of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China
[b] School of Chemical Engineering and Technology, Harbin Institute of Technology, Harbin, China

A R T I C L E I N F O

Article history:
Received 24 July 2015
Received in revised form
5 March 2016
Accepted 8 March 2016
Available online 6 April 2016

Keywords:
Exergy
Woody biomass
Easier equations
Ash exergy

A B S T R A C T

Szargut et al. [1] proposed an appropriative equation for calculating the exergy of woody biomass. Cumbersome work is involved in calculating the exergy of woody biomass as the complicated ash compositions are included for obtaining the ash exergy in the equation. Based on the exergy values of ash contents of sixty four woody biomass investigated in this study, the average value of wood ash is obtained and a positive linear relationship between ash exergy and ash content is observed. An equation based on the average exergy of wood ash with relative errors of −0.76% to 1.38% and another equation based on the relationship between ash exergy and ash content with relative errors of −1.16% to 0.88% are observed. These two easier equations can be well used for expeditious estimation of the exergy of woody biomass with high accuracies.

1. Introduction

Woody biomass can satisfy at least 87% of the world's renewable primary energy consumption [2], it is therefore an very important renewable energy source on the earth. Except for energy sources, woody biomass can also be used as construction materials for house building, composting fertilizer for tree planting, habitat resources for fungi species [3], activated carbons for dye adsorption [4], biological templates for manufacturing ceramics [5], wood flour for polyester composites [6], wood fibres for interaction matrix [7], wood-plastic composites for manufacturing panels [8], and so on. The physical, chemical, mechanical, and thermo-chemical properties of woody biomass are therefore wildly studied [2,9–13].

Among the various properties of woody biomass, exergy is a very important index of the material characteristics as exergy is a measurement of how far the material deviates from a state of equilibrium with its environment [14,15] and it is efficiently used to evaluate the material characteristics, transfer processes, and utilization systems [1,2,16–19]. Obtaining the exergy of woody biomass is therefore of great scientific importance and has wide practical applications. Theoretically, the exergy of woody biomass can be calculated based on the information of its chemical potential and the chemical exergy of its elemental concentrations [15]. However, the chemical potential of woody biomass can not be obtained due to the fact that it is not regular material and its compositions are very complex (especially the ash compositions). Many empirical equations were therefore used to calculate the exergy of woody biomass, the main equations are summarized and shown in Table 1.

Among the equations shown in Table 1, the Equation (3) proposed by Szargut et al. [1] is widely used and some new equations were developed for engineering purposes based on this equation [2,23,24]. With regard to this equation, however, cumbersome work is involved in calculating the exergy of woody biomass as the complicated ash compositions (Al_2O_3, CaO, Fe_2O_3, K_2O, MgO, MnO, Na_2O, P_2O_5, SO_3, SiO_2, TiO_2, etc.) are included for obtaining the ash exergy in the equation. The objectives of this study are therefore (a) to study the exergy characteristics of wood ash, (b) to develop easier equations for estimating the exergy of woody biomass based on the ash exergy, and (c) to check the reliability of the proposed equations by detailing the relative errors between the estimated and calculated exergy values.

* Corresponding authors. School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China. Tel./fax: +86 451 86412078.
E-mail addresses: ynzhang@hit.edu.cn (Y. Zhang), libx@hit.edu.cn (B. Li).

http://dx.doi.org/10.1016/j.energy.2016.03.040
0360-5442/

Nomenclature

h	evaporation enthalpy (kJ/kg)
s	entropy (kJ/kg K)
w	weight percentage (%)
ex	specific exergy (kJ/kg, kcal/kg)
$\overline{ex}$	specific average exergy (kJ/kg)

Greek letters

β	correlation factor

Subscripts

i	indicates ash composition
w	related to water/moisture
ash	related to ash
C	related to carbon
H	related to hydrogen
O	related to oxygen
N	related to nitrogen
S	related to sulphur
F	related to fluorine
Cl	related to chlorine
Br	related to bromine
I	related to iodine

Abbreviations

HHV	higher heating value (kJ/kg)
LHV	lower heating value (kJ/kg)

2. Materials and methods

2.1. Materials

The sixty four woody biomass samples used for estimating the exergy of woody biomass by means of heating values (HHV (higher heating value) and LHV (lower heating value)) in our previous work [2] are still used in this study. In the previous work [2], the moisture contents, ash contents, element contents (C, H, O, N, and S), and heating values (HHV and LHV) of the sixty four woody biomass were uniformed to on wet basis, and the ash compositions (Al_2O_3, CaO, Fe_2O_3, K_2O, MgO, MnO, Na_2O, P_2O_5, SO_3, SiO_2, and TiO_2) were transferred to a basis of mol per kg of woody biomass (mol/kg biomass). In this study, the moisture contents, ash contents, element contents, and LHVs of the sixty four woody biomass are still used on wet basis as shown in Table 2. The ash compositions were calculated to a basis of mol per kg of wood ash (mol/kg ash) and the values are given in Table 3.

2.2. Exergy of woody biomass

The equation proposed by Szargut et al. [1] for calculating the exergy of woody biomass is used:

$$ex = (LHV + w_w h_w)\beta + ex_w w_w + 9683 w_s + ex_{ash} w_{ash} \quad (1)$$

where:

ex is the exergy of woody biomass on wet basis (kJ/kg).
ex_w is the exergy of water (900 kJ/kmol [53]).
w_w is the moisture content of woody biomass (%).
w_s is the weight percentage of sulphur in woody biomass (%).
ex_{ash} is the exergy of ash (kJ/kg).
w_{ash} is the weight percentage of ash in woody biomass (%).
β is the correlation factor.
LHV is the lower heating value of woody biomass (kJ/kg).
h_w is the evaporation enthalpy of moisture (2442 kJ/kg [1]).

Szargut et al. [1] gave an appropriative equation for calculating the correlation factor of woody biomass:

$$\beta = \frac{1.0412 + 0.2160\frac{w_H}{w_C} - 0.2499\frac{w_O}{w_C}\left(1 + 0.7884\frac{w_H}{w_C}\right) + 0.0450\frac{w_N}{w_C}}{1 - 0.3035\frac{w_O}{w_C}} \quad (2)$$

where:

w_C is the weight percentage of carbon in woody biomass (%).
w_H is the weight percentage of hydrogen in woody biomass (%).
w_O is the weight percentage of oxygen in woody biomass (%).
w_N is the weight percentage of nitrogen in woody biomass (%).

2.3. Exergy of wood ash

The last term on the right side of Equation (1) is defined in this study as wood ash exergy or the exergy of wood ash. It can be calculated based on the average exergy of wood ash:

$$ex_{ash} w_{ash} = \overline{ex_{ash}} w_{ash} \quad (3)$$

where:

$\overline{ex_{ash}}$ is the average ash exergy of woody biomass (kJ/kg ash)

or it can be calculated from the sum of exergy of ash compositions:

$$ex_{ash} w_{ash} = \sum ex_{ash-i} w_{ash-i} \quad (4)$$

where:

ex_{ash-i} is the specific exergy of ash component i as shown in Table 4 (kJ/mol).
w_{ash-i} is the weight percentage of ash component i (%).

3. Exergy characteristics of wood ash

3.1. Average exergy of wood ash

Based on the ash compositions of woody biomass in Table 3 and the specific exergy of mineral oxides in Table 4, the exergy values of wood ashes are obtained and the values are shown in Fig. 1. The exergy values of the sixty four wood ashes are between 79.82 (No. 50, Wood pellet) and 3064.52 (No. 44, Paulownia chip) kJ/kg ash. The Wood pellet ash (No. 50) shows the lowest exergy value (79.82 kJ/kg ash) is mainly resulted from the fact that it has lower amounts of K_2O (which has the highest specific exergy of 413.10 kJ/mol as shown in Table 4) and P_2O_5 (which has the second highest specific exergy of 412.65 kJ/mol as shown in Table 4). However, the Paulownia chip ash (No. 44) shows the highest exergy (3064.52 kJ/kg ash) is mainly due to its highest amount of K_2O which is 4.958 mol/kg ash as shown in Table 3. This indicates that the exergy of wood ash is not only determined by the species of ash compositions but also the amounts of ash compositions [54].

Based on the exergy values shown in Fig. 1, the average exergy value of wood ash was obtained and the value of 1685.63 kJ/kg ash is shown in red in Fig. 1. It is observed that the exergy values of wood ashes (79.82–3064.52 kJ/kg ash) are widely scattered around the