Energy Conversion and Management 99 (2015) 50–61

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Semi-continuous feeding and gasification of alfalfa and wheat straw pellets in a lab-scale fluidized bed reactor

Shiplu Sarker [a],*, Jesús Arauzo [b], Henrik Kofoed Nielsen [a]

[a] University of Agder, Faculty of Engineering and Science, Jon Lilletuns vei 9, Service boks, 4898 Grimstad, Norway
[b] University of Zaragoza, Thermochemical Process Group, Aaragon Institute of Engineering Research (I3A), I+D building, C/Mariano Esquillor s/n, E-50018 Zaragoza, Spain

ARTICLE INFO

Article history:
Received 1 February 2015
Accepted 7 April 2015
Available online 22 April 2015

Keywords:
Fluidized-bed
Alfalfa
Wheat straw
Pellets
Gasification
Equivalence ratio

ABSTRACT

Small scale air-blown fluidized bed gasification of alfalfa and wheat straw pellets were conducted for semi-continuous solid feeding and range of operating conditions varied due to the modifications in equivalence ratio (ER) (0.20–0.35) achieved both by varying solid and air input. Alfalfa pellets displayed an improvement in several gasification variables such as gas lower heating value (~4.1 MJ/Nm^3), specific gas yield (1.66 Nm^3/kg), cold gas efficiency (~42%) and carbon conversion efficiency (~72%) as ER maximized to 0.35 which was found optimum for this feedstock for the present course of experiments. Gasification parameters of wheat straw pellets on the other hand were characterized by a great degree of variation as the ER progressively increased. The optimum performance of this biomass was likely to achieve at ER = 0.30 when gas lower heating value and cold gas efficiency maximized to ~4 MJ/Nm^3 and ~37% respectively. Moreover, a substantial drop in tar yield (58.7 g/Nm^3) at this ER was also indicative to the optimal thermal conversion at this point of operation. Overall, both the feedstocks presented promising alternatives for utilization into the small-scale fluidized bed gasification which is increasingly emerging as a sustainable solution towards processing lignocellulosic biomass.

1. Introduction

In the worldwide energy policy, renewable energy is of interest based on the fact that fossil fuel is rapidly diminishing and the energy demand is exorbitantly rising due to the imminent surge in population [1]. There is thus an urgent need to integrate all categories of renewable energy where the contribution of biomass is ever increasing. Biomass resource is abundant and covers a wide range, starting from terrestrial to marine, all of which bearing huge potential to get converted into renewable energy by means of the prevailing technologies such as: biological, thermal, and biochemical [2]. Producing liquid biofuel from straw, starch and oil seed crops, one example of biomass utilization, has been a popular approach for the last few decades which however recently brought into a serious attention as a result of controversy towards competition to agricultural lands for feed rather than for food, or the dilemma of "Food vs. Fuel" [3]. This therefore shifted a deeper attention towards lignocellulosic biomass, or the biomass deriving from the agricultural wastes and energy crops to contribute to the liquid biofuels as well as to the gases. In line with that, the focus of the present study deals with the gases that can be produced by utilizing lignocellulosic biomass, particularly by alfalfa and wheat straw pellets, via a process called gasification.

Gasification basically is a thermochemical process, occurring at oxygen (oxidizing agent) suppressed condition, typically transforming solid biomass into producer gas that subsequently being utilized into further energy applications and value added products. The emanating gas once dried in general composed of CO, H_2, CO_2, CH_4, C_2H_4, C_nH_n and minor amounts of tar and particulates [4,5], which as a part of renewable energy exploited into the downstream units. Existing gasification technologies (fixed-bed, fluid-bed, entrained flow, etc.) differ widely according to the availability, type, and form of the fuel, and to the amount of energy that can be produced. Among these, fluidized bed gasification is commonly utilized because of its flexibility in dealing with a range of biomass including difficult fuels such as wastes [6], straw [7], husk [8] and bagasse [9], and high conversion efficiency due to the greater solid gas contact reactions [10]. This technology also suits operation for diverse gasifying agents (air, steam, O_2, CO_2, etc.) and results higher efficiency than a Rankine cycle (a cycle that models the performance of a steam turbine system), once integrated with I.C. (internal combustion) engine for small to medium scale (0.5–5 MW$_e$) applications [11].

As a herbaceous crop, the availability of alfalfa (*Medicago sativa* L.) is primarily dependent on the geographic and climatic conditions

---

* Corresponding author. Tel.: +47 37233144.
E-mail address: Shiplu.sarker@uia.no (S. Sarker).

http://dx.doi.org/10.1016/j.enconman.2015.04.015
0196-8904/© 2015 Elsevier Ltd. All rights reserved.

with a high dry matter yield exhibited in the temperate regions [12], such as around the Ebro valley areas in Spain [13], and many places in the USA [14]. This feedstock has historically been used for livestock feed because of the less cell wall carbohydrates and abundant protein on its leaves which are suitable for animals' digestion [15]. However, the stems of alfalfa, sharing as much as 50% of the total biomass, are mostly comparable with the conventional lignocellulosic structure – composing mainly of cellulose and hemicellulose, and thus least applied as animal diet [16]. This leaves opportunity for this feedstock to exploit into the energy conversion, besides as a fodder crop. In fact, many literatures have already evaluated the potential of lignocellulosic alfalfa in several areas, especially towards production of second generation (2G) biofuel [17] in respect to the environmental [15] and to the economic aspects [18], and characterization [19], and scarcely to gasification using fixed bed downdraft gasifier [20] and recently through pilot-scale bubbling fluidized bed gasifier [21]. The motivation of using alfalfa as a feedstock for biofuel production favors predominantly due to the agro-ecological conditions, i.e.; requirement of less N fertilizer, better conversion economics, etc. allowing crop rotation with corn and hence higher final yields [18]. However, the inevitable byproducts from the bioethanol industries together with the insignificant net savings from the greenhouse gas emission and the unattractive economic competitiveness with the fossil fuel based oil are still a major concern [22], hindering the rapid expansion of this technology. These all therefore lead gasification, especially the small scale technology that can be readily integrated on farm operation [7], a feasible option for thermochemical conversion of alfalfa, resulting producer gas with an upgrading possibility to heat, electricity chemicals, bio-oil, etc. and the residual ash potentially be recycled as fertilizer.

Wheat straw is another biomass examined in the present work. Unlike alfalfa, wheat (*Triticum aestivum* L.) straw has been extensively studied in many literatures with diverse investigations in several areas, such as: [23–30]. In regards to gasification, this crop residue is interesting as a result of its increasing availability [31], less impact to land use changes since no additional agricultural land is required for its production [32], and superior environmental performances [33]. However, implications such as high tar content, ash agglomeration, and ash slagging [34], are still major drawbacks towards using this feedstock for gasification. Overcoming some of these issues to effectively achieve gasification, significant efforts have already been paid in which modifications of the reactors [35] and pretreatment of feedstock were suggested [36]. This study does not report any modifications of such to the existing technologies, however, proposes to utilize a small scale fluidized bed gasification system which potentially is economically attractive due its easy access to the fuel source together with the opportunity to effectively enhance biomass utilization.

Number of documented researches [37,38] has already demonstrated the fluidized bed gasification of lignocellulosic biomass for various operating conditions, i.e.; effect of air ER (Equivalence ratio), effect of bed temperature, etc. but low density, complex fuel handling, feeding, etc. has been a challenge to apply these feedstocks for gasification as these studies concluded. So far successful utilization of various forms of lignocellulosic biomass starting from raw straw [8] to milled straw [39] has been mentioned. The effect of several feeding locations has also been inspected [40]. Nevertheless, direct feeding of biomass pellets to a lab-scale (<10 g/min throughput) reactor and to evaluate the corresponding gasification performance at varying operating conditions has been hardly reported, as far as authors know. Considering this, the present study focuses on comparing the gasification performance on direct pellet feeding of two different lignocellulosic biomasses (alfalfa and wheat straw) at numerous ER that varies between the range of 0.20 and 0.35 for which corresponding effect in-terms of temperature and other major parameters are also examined.

2. Materials and methods

2.1. Biomass feedstock

Alfalfa and wheat straw pellets with average dimensions of ∅6 mm × 25 mm length and ∅8 mm× 20 mm length respectively were used as feedstocks for the gasification tests conducted in this work.

Alfalfa was grown and harvested around the Ebro valley, in the surroundings of the village Pina de Ebro, located 40 km southeast from Zaragoza (capital of Aragon, a region in the Northeast of Spain). Approximately 100 kg of alfalfa pellets with 100% purity (no additives) from the first harvest (April 2013) were manufactured by Cooperativa Campo San Gregorio and kindly supplied by Molinos Afau S.L. (Pina de Ebro, Spain).

Wheat straw on the other hand was harvested from Castilla y Leon fields, in the surroundings of the village Valladolid and Tordesillas, located 70 km south from Valladolid (capital of Castilla y León, a region in the West of Spain). Pellets of approximate amount of 100 kg with 100% purity (no additives) were manufactured by Pitesa (on Tordesillas, Spain) and kindly supplied by Molinos Afau S.L. (Pina de Ebro, Spain).

2.2. Assessing physiochemical quality of the feedstock

Prior to the gasification tests, the pellets were assessed in terms of physical and chemical quality by means of proximate and ultimate analysis. By proximate analysis, several physical variables such as moisture, volatiles, ash and lower heating value (LHV) were determined for which following standards were used: moisture as according to EN 14774-3:2009, volatile matter as according to EN 15148:2009 and ash as according to EN 14775:2009 respectively. To analyze calorific value, an in-situ bomb calorimeter (IKA C2000, Germany) set to comply with the protocol ASTM D 4809-95 was used. Additionally, theoretical LHV was also determined based on the empirical correlation (developed from the ultimate analysis) proposed by Gaur and Reed [41].

Ultimate analysis determined the chemical composition in-terms of the percent amount of C, H, O, Cl, N and S by using an in-situ elemental analyzer (Leco TruSpec Micro, USA). C, H and N was evaluated based on the standard EN 15104:2011, while S was determined following the protocol EN 15289:2011. Oxygen was calculated by difference, as direct measurement by the present instrument was not possible.

Prior to the above analyses, the samples were prepared by grinding to an average size of <5 mm by using an in-situ hammer mill manufactured by Mercanofil.Mateu y Solè, Spain.

2.3. Determining ash fusion temperature

Ash fusion temperature of the feedstocks was determined by using a Rhodium ash fusion furnace (EM 201-17, Hesse instruments, Germany) featured with a camera and image processing software, capturing images at predefined intervals of temperature. For the analysis, the sample ash was first prepared into paste by adding a few drops of distilled water to improve stability. Afterwards, it was molded into compact cylinder of 3 mm (height) and 3 mm (Ø) by using a die and allowed to dry. The cylindrical sample was then placed on a Al_2O_3 slab located inside the furnace heated in an oxidizing environment (air) at two steps constant heating rate of 30 °C/min between 0 °C (or, the room temperature) and 550 °C and 5 °C/min between 550 °C and 1750 °C respectively. A thermocouple positioning underneath the slab enabled to trace the progress of temperature while a digital probe fitted inside the furnace displayed the evolutions of images at every 5 °C rise