Fuel 116 (2014) 388–394

Contents lists available at ScienceDirect

Fuel

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

# Effect of steam injection location on syngas obtained from an air–steam gasifier

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## HIGHLIGHTS

- Studied effects of steam injection location and steam-to-biomass ratio (SBR).
- A lab-scale autothermal air–steam fluidized-bed gasifier was used for the study.
- Steam injection location and SBR had significant effects on $H_2$ and CO yields.
- Steam injection location had significant effects on the gasifier efficiencies.
- The best syngas yield was at the steam injection location of 254 mm and SBR of 0.2.

## ARTICLE INFO

*Article history:*
Received 25 June 2013
Received in revised form 11 August 2013
Accepted 12 August 2013
Available online 28 August 2013

*Keywords:*
Fluidized-bed gasifier
Biomass
Steam port location
Syngas

## ABSTRACT

For a fluidized-bed gasifier, reaction conditions vary along the height of the reactor. Hence, the steam injection location may have a considerable effect on the syngas quality. The objective of this study was to investigate the effects of steam injection location and steam-to-biomass ratio (SBR) on the syngas quality generated from an air–steam gasification of switchgrass in a 2–5 kg/h autothermal fluidized-bed gasifier. Steam injection locations of 51, 152, and 254 mm above the distributor plate and SBRs of 0.1, 0.2, and 0.3 were selected. Results showed that the syngas $H_2$ and CO yields were significantly influenced by the steam injection location ($p < 0.01$) and SBR ($p < 0.05$). The steam injection location also significantly influenced hot and cold gas, as well as carbon conversion efficiencies. The best syngas yields (0.018 kg $H_2$/kg biomass and 0.513 kg CO/kg biomass) and gasifier efficiencies (cold gas efficiency of 67%, hot gas efficiency of 72%, and carbon conversion efficiency of 96%) were at the steam injection location of 254 mm and SBR of 0.2.

## 1. Introduction

Dependence on fuels and chemicals derived from petroleum resources has created a major challenge to meet world's demands on a sustainable basis. Biomass is a sustainable and renewable energy resource, which has the potential to reduce a significant portion of world's dependency on petroleum resources with subsequent reduction in global warming due to greenhouse gas emissions [1–3]. Biomass gasification, a thermochemical conversion technology, is one of the promising routes for producing fuels and chemicals using biomass-derived syngas. However, synthesis of liquid fuels and chemicals using various conversion processes typically requires a syngas with a wide range of $H_2$/CO ratio, i.e. between 0.4 and 4 [4–8], as well as concentrations of $H_2$ and CO and $CO_2$ [8,9].

Syngas quality generated from biomass depends on several parameters such as biomass properties, gasifier design, gasifier operating conditions, and type of oxidizing agent [1]. Different gasifier designs such as downdraft, updraft, and fluidized-bed have been optimized to produce syngas having high $H_2$ and CO contents. Biomass properties such as size, shape, moisture content, and chemical compositions, also significantly influence syngas quality in terms of gas composition and impurities. $H_2$ concentration of the syngas can also be increased by optimizing the design and operating conditions of the gasifier [10]. Gasifier operating conditions such as biomass feed rate, gasification temperature, and flow rate of oxidizing agent have influence on syngas quality [1]. The biomass feed rate into the gasifier must be optimized to yield high heating value syngas with maximum energy efficiency [1]. Gasification temperature controls reactions occurring inside the reactor. A gasification temperature above 800 °C is desired to obtain high gas yield and $H_2$ and CO contents [1].

The type of oxidizing agent such as air, oxygen, and steam, used in biomass gasification also significantly effects quality and yield of

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0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.08.026

syngas. Using air as an oxidizing agent results in a syngas highly-diluted with nitrogen (up to 65%) with low heating value [11,12]. Using oxygen as an oxidizing agent results in a syngas with high CO and $H_2$ concentrations [13]. Using steam as an oxidizing agent results in syngas with high $H_2$ content [14,15]. Overall, air gasification yields a low-calorific syngas containing much less $H_2$ than that obtained through air–steam or steam-only gasification [11,16–18]. Air–steam gasification using fluidized bed gasifier at equivalence ratio (ER) of 0.22, steam-to-biomass ratio (SBR) of 2.7 and gasifier temperature of 900 °C resulted in syngas with a high $H_2$ yield (71 g/kg of biomass, wet basis) [17]. Air–steam gasification of rice hull in a fluidized bed gasifier at 800 °C showed high $H_2$ content (40%) in the syngas [19]. Kumar et al. (2009) studied air–steam gasification in a fluidized-bed gasifier and reported significant increase from 4% to 15% in syngas $H_2$ content with an increase in temperature from 650 to 850 °C [20]. Overall, air–steam gasification studies [2,17,20] showed that both steam injection and higher gasification temperatures (above 800 °C) resulted in a $H_2$ rich syngas, making it more suitable for further conversion into liquid fuels and chemicals.

In air–steam gasification, major reactions contributing to the high $H_2$ yield are water–gas and water–gas shift reactions (Eqs. (1)–(3)) [17,21]. The methane steam reforming reaction (Eq. (4)) also contributes to the $H_2$ content of the gas [22].

$$C + H_2O \rightarrow CO + H_2 \quad (\text{water—gas reaction},\ \Delta H = 131.3\ \text{kJ/mol}) \tag{1}$$

$$C + 2H_2O \rightarrow CO_2 + 2H_2 \quad (\text{water—gas reaction},\ \Delta H = 89.7\ \text{kJ/mol}) \tag{2}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (\text{water—gas shift reaction},\ \Delta H = -41.2\ \text{kJ/mol}) \tag{3}$$

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (\text{methane steam reforming reaction},\ \Delta H = 206\ \text{kJ/mol})$$

An important consideration in maximizing efficiency and $H_2$ production in air–steam gasification is the location of steam injection, which can significantly affect the reaction conditions inside the gasifier. Injection of steam into a high temperature zone of the fluidized bed gasifier favors $H_2$ forming reactions (Eqs. (1) and (2)) and can yield $H_2$-rich syngas. On the contrary, injecting steam into a low temperature zone can further reduce the gasifier temperature, and thus adversely affect gasification reactions (Eqs. (1)–(3)) leading to low $H_2$ yield. Additionally, the formation of $H_2$ depends upon the residence time of reactants involved in gasification reactions. The residence time can also be optimized by changing the location of steam injection, which can further increase the $H_2$ content of the syngas.

Further, based on the temperature condition and carbon availability, steam injection in the reduction zone of the gasifier can increase $H_2$ production through reducing reactions (Eqs. (1)–(3)). In fluidized-bed gasification, drying and devolatilization of biomass occur at the bottom of the fluidized bed, which can be considered as the virtual location of both drying and pyrolysis zones. Oxidation of de-volatized products and char occur next in the middle and top of the bed, which can be considered the virtual oxidation zone. Reduction occurs in the final step of the gasification and involves conversion of pyrolysis products into syngas, and thus, the region above the combustion zone i.e. top of the bed plus the freeboard region can be considered as the virtual reduction zone. Injection of steam into the reduction zone at the top of bed and in freeboard regions may lead to high $H_2$ yield through reducing reactions (Eqs. (1)–(3)).

Reaction conditions vary along the height of the reactor in especially autothermal fluidized-bed gasifiers. This study is based on the hypothesis that the location of steam injection has a significant effect on syngas quality. The objective of present study was to investigate the effect of steam injection location on the quality of syngas generated from an air–steam gasification in a 2–5 kg/h autothermal lab-scale fluidized-bed gasifier.

## 2. Materials and methods

### 2.1. Biomass feedstock and bed material

All experiments were performed using Kanlow switchgrass which was grown at the Agronomy Research Station of Oklahoma State University and harvested in the fall of 2010. Proximate and ultimate analyses of switchgrass were performed by Hazen Research, Inc. (Golden, CO). A bomb calorimeter (model A1290DDEB, Parr Instrument Co., Moline, IL) was used to determine higher heating value of switchgrass (18.83 MJ per kg dry biomass). Switchgrass bales were chopped using a 25 mm screen in a Haybuster tub grinder (Model: H1000, Duratech Industries International, Inc. Jamestown, ND). Silica sand, supplied by Oglebay Norton Industrial Sands, Inc. (Brady, TX), was used as inert bed material. Bulk densities of switchgrass and silica sand were measured using a 0.0001 $m^3$ container. Switchgrass was poured into the container from 100 mm above the container and mass of the switchgrass in the container was determined. The bulk density was determined by dividing the mass of the switchgrass in the container with the container volume. The bulk density of silica sand was measured using the similar procedure. A digital vernier caliper (Digimatic, Mitutoyo, Japan) with 0.1 mm resolution was used to measure the particle length of switchgrass while a sieve shaker (CSC Scientific, Fairfax, VA) was used to perform particle size distribution of silica sand. The geometric mean sizes by mass of switchgrass and silica sand were determined using ANSI/ASAE Standard S319.3-February 2008 [23].

### 2.2. Test setup and instrumentation

Fig. 1 shows the gasifier test setup. Details of the gasifier system are described elsewhere [22]. A fluidized-bed gasifier test setup with a biomass throughput of 2–5 kg/h was used for this study. The test setup consisted of a fluidized-bed gasifier (0.1 m i.d. × 1.1 m height), a hopper, a double dump valve, a screw feeder, two cyclone separators, a producer gas burner, an air supply unit, a heat torch, and a steam boiler. The inside wall of the gasifier was thermally insulated with 1 inch refractory lining of conventional castable (Resco Products Inc., Pittsburgh, PA) while the outside wall was covered with 1 in. layer of thick cerawool (Kaowool RT Blanket-RCF-24/SW-24, Thermal Ceramics Inc. Augusta, GA). A distributor plate (0.28 m o.d. × 5 mm thickness) was located at the bottom of the gasifier to uniformly distribute the inlet air, and to support a bed of silica sand. A 30 × 30 mesh size wire screen was placed on the top of the distributor plate to prevent the silica sand from falling down through the distributor plate. The biomass hopper was fitted with a stirrer to prevent bridging of the biomass feedstock and a screw coupled with a 90 V DC motor (Model: 2M168D, Dayton Electric Mfg. Co., Niles, IL) at the bottom for discharging biomass to the gasifier screw feeder. A DC speed regulator (Model: 4Z829B, Dayton Electric Mfg. Co., Niles, IL) was used with the gasifier screw motor to control the biomass flow rate into the gasifier. A double dump valve (Fig. 1) between the hopper exit and screw feeder was used to isolate the hopper from the gasifier and thus prevented backflow of hot gases into the biomass hopper. Two cyclone separators were connected in series to remove partic-