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Pure oxygen fixed-bed gasification of wood under high temperature (>1000 °C) freeboard conditions

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HIGHLIGHTS

- Oxygen blown fixed bed and entrained flow gasification of wood were compared.
- Both gasifiers efficiently produced a high quality syngas with high CO and H_2 yields.
- Generation of high quality syngas is not restricted to entrained flow gasification.
- Instead, it is technology independent and coupled to high process temperature.

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ABSTRACT

In this paper, the performance (syngas composition, syngas production and gasification efficiency) of an 18 kW atmospheric fixed bed oxygen blown gasifier (FOXBG) with a high temperature (>1000 °C) freeboard section was compared to that of a pressurized (2–7 bar) oxygen blown entrained flow biomass gasifier (PEBG). Stem wood in the form of pellets (FOXBG) or powder (PEBG) was used as fuel. The experimentally obtained syngas compositions, syngas production rates and gasification efficiencies for both gasification technologies were similar. Efficient generation of high quality syngas (in terms of high concentration and yield of CO and H_2 and low concentration and yield of CH_4, heavier hydrocarbons and soot) is therefore not specific to the PEBG. Instead, efficient gasification seems to be linked to high reactor process temperatures that can also be obtained in a FOXBG. The high quality of the syngas produced in the FOXBG from fuel pellets is promising, as it suggests that in the future, much of the cost associated with milling the fuel to a fine powder will be avoidable. Furthermore, it is also implied that feedstocks that are nearly impossible to pulverize can be used as un-pretreated fuels in the FOXBG.

1. Introduction

High temperature (>1000 °C) oxygen blown entrained flow gasification is a well proven gasification technology for the production of high quality synthetic gas (syngas). The produced syngas typically exhibits high concentrations of CO and H_2 and low concentrations of undesirable products, such as CH_4 and heavier hydrocarbons, tar and soot. Due to its favorable composition, the syngas produced in oxygen blown entrained flow gasification can be used in the synthesis of motor fuels and other chemicals [1–3]. Other potential areas of application for the syngas produced in high temperature gasification systems include the steel industry, where the syngas can be used to generate fuel for heat treatment furnaces [4]. However, in order to achieve high fuel conversion, throughput and gas quality in the entrained flow gasification process, the fuel needs to be introduced in fine powder form or as droplets into the gasifier. For most solid fuels, this requires the extensive pretreatment of the feedstock, including drying, milling or liquefaction. Depending on the feedstock, especially in the case of biomass and waste raw materials, the pretreatment procedure may be very complicated and expensive, which lowers the overall efficiency of the gasification process [5,6]. Therefore, there should be an incentive to develop a high temperature gasification technology that does not require the extensive pretreatment of the feedstock.

Air, oxygen or steam blown fixed bed gasifiers can be operated with a wide range of different feedstocks (coal, biomass and waste) and are reasonably insensitive to fuel pretreatment [7–15]. Fixed bed gasifiers can be either updraft (fuel enters at the top, while the gasifying agent is introduced at the bottom) or downdraft (both

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fuel and gasification agent enter from the bottom, with the fuel coming from a lock-hopper system [2]).

Regardless of fuel type, a combustion zone is formed in the fuel bed where the temperature reaches ~1000–1400 °C, depending on the gasification agent. The drawback with traditional fixed bed gasifiers is that the hot gas produced in the combustion zone cools significantly as it percolates through the reduction, pyrolysis and drying zones (updraft gasifiers) or reduction zone (downdraft gasifiers). The gas produced during traditional fixed bed gasification therefore contains significant amounts of tar and has a relatively high CH_4 concentration. Without extensive gas cleaning, these properties make the gas unfavorable for upgrading to motor fuels.

The hypothesis explored in this paper is that the syngas produced in oxygen blown fixed bed gasification has comparable qualities to the syngas produced in entrained flow gasification, if the fixed bed gasifier is constructed with a high temperature (>1000 °C) freeboard section. To the best of the authors' knowledge, this has not been investigated in the open literature before and therefore also defines the novelty of the work. The work was carried out by (i) designing and constructing an oxygen blown fixed bed gasifier with a high temperature freeboard, (ii) determining the characteristics of the gasifier (gas composition, gas production, and gasification efficiency) and (iii) comparing the results, when possible, with earlier published results obtained during oxygen blown entrained flow gasification [16] using the same feedstock, stem wood from pine and spruce as fuel.

2. Fixed bed gasification with high temperature freeboard

The general behavior of an oxygen blown, entrained flow gasifier in thermodynamic equilibrium has been described by Weiland et al. [16]. The results can be generalized as design criteria for oxygen blown fixed bed gasifiers and are therefore shortly reviewed here. Theoretical and experimental investigations have shown that the most important operating parameter is the O_2 stoichiometric ratio, λ, since it affects the temperature and composition of the produced gas and also the efficiency of the gasification process [16,17]. Therefore, in this work, the performances of both the entrained and the fixed bed gasifier were experimentally evaluated as a function of λ. The stoichiometric ratio λ is defined as the ratio of the supplied O_2, $\dot{m}_{O2}$ (kg/h), and the stoichiometric O_2 demand for complete combustion, $\dot{m}_{O_2,stoich}$ (kg/h) as the following:

$$\lambda = \frac{\dot{m}_{O_2}}{\dot{m}_{O_2,stoich}}. \tag{1}$$

The efficiency of a gasification process is often described by the cold gas efficiency, *CGE* which is the ratio of the amount of chemical energy stored in the produced cooled syngas and the amount of energy introduced into the gasifier with the fuel. The *CGE* is calculated as the following:

$$CGE = \frac{\dot{m}_{cg} LHV_{cg}}{\dot{m}_{fuel} LHV_{fuel}}, \tag{2}$$

where $\dot{m}_{cg}$ (kg/s) and $\dot{m}_{fuel}$ (kg/s) are the mass flows of cold gas from the gasifier and the mass flow of fuel input, and LHV_{cg} (MJ/kg) and LHV_{fuel} (MJ/kg) are the lower heating values (LHV) of the cold gas and the fuel, respectively. Two different definitions of *CGE* are used in this work. The CGE_{power} is calculated using all energy containing species in the syngas, whereas CGE_{fuel} only uses CO and H_2 concentrations. The CGE_{power} represents a case where the produced gas is used for heat and power generation in a downstream combustion process (e.g., gas engine or gas turbine), while CGE_{fuel} is more practical in cases where the syngas is used for motor fuel production in a downstream synthesis process, with only CO and H_2 as active species. For the wood used in the present work, at low λ (<0.25), the amount of oxygen and the resulting process temperature are too low for complete gasification, which affects the *CGE* negatively, due to the presence of carbon residues. Increasing λ beyond 0.25 increases the process temperature and gas production, and the maximum *CGE* occurs at λ values between 0.27 and 0.3. Further increasing λ results in a further increase of the process temperature due to oxidation reactions until the temperature is high enough for dissociation of CO_2 and H_2O. As a consequence of the oxidation the *CGE* is also reduced. The theoretical operating window in terms of λ for oxygen blown gasifiers is thereby between 0.27 and 0.6.

In the following, the theory specific to the design of oxygen blown, fixed bed gasification processes of wood with a high temperature freeboard is described. A simplified sketch of the process is presented in Fig. 1 and important reactions are listed in Table 1. Fuel is introduced into the gasifier from the top and the gasification agent (pure O_2) is introduced from the bottom into three different regions: (i) primary, (ii) secondary and, (iii) tertiary oxygen supply zones. As explained above, the gasifier can therefore be classified as an updraft gasifier. The char left after pyrolysis of the fuel is converted to gas in two steps. Close to the bottom of the gasifier where primary O_2 is introduced, the carbon in the bottom layer reacts with O_2 producing CO_2 and heat (char combustion region, R1). Due to the exothermic reactions, the temperature rises to above 2000 °C. After the O_2 has been consumed, the remaining char in the top layer of the char bed reacts with the CO_2 percolating through the bed from the char combustion region forming CO (char gasification region, R2). The reactions specific to this process are endothermic, thus the temperature decreases to approximately 750 °C by the end of the char gasification region. The amount of O_2 supplied through the primary oxygen inlet corresponds to the amount of O_2 needed to convert all of the carbon in the char to CO.

Above the char gasification zone, the wood pellets dry (R3) and pyrolyze (R4) and the produced gas (CO, CO_2, H_2, H_2O and CH_4) from the pyrolysis (R4) and tar destruction (R5) reacts with the O_2 supplied through the secondary oxygen inlet producing CO, CO_2, H_2, and H_2O (R6–R9). The amount of O_2 supplied here corresponds to the amount that is needed to raise the temperature to 1000 °C ($\lambda \sim 0.3$). In this work, the O_2 supply was not intended to be reduced below 0.3, since when the temperature decreases below 1000 °C, tar destruction becomes incomplete, leading to an undesirable gas composition.

The important high temperature freeboard zone is found above the bed zone. In the high temperature freeboard zone, the intent is to destroy all light and heavy hydrocarbons and to reduce the amount of formed soot. The extra amount of O_2 which is needed to increase the temperature above 1000 °C is supplied through the tertiary oxygen inlet. Depending on λ, different process temperatures are reached in the freeboard zone, as indicated in Fig. 1. With a temperature above 1400 °C, significant CH_4 destruction is also possible in an O_2-free H_2O and CO_2 environment [18], probably due to the steam and CO_2 reforming reactions (R10 and R11). Furthermore, there is a coupling between the tar and soot in biomass gasification since soot is assumed to form from the thermal decomposition of tars (R5). Several investigations in drop tube furnaces simulating entrained flow gasification have shown that as the temperature increases above 1000 °C, the tar yield in the gas decreases, while the soot yield increases significantly [19,20]. Maximum soot production occurs at a temperature of approximately 1200 °C [20]. Again, a temperature above 1400 °C is needed to reduce the amount of soot to trace levels in the gas [21]. Given the above, one can therefore assume that roughly the same process conditions (temperature above 1400 °C, $\lambda > 0.36$) are needed in the freeboard zone during fixed bed gasification in order to significantly reduce the production of CH_4 and soot. Finally, the resulting gas composition in the freeboard zone is believed to be controlled by the water gas shift reaction (R12).