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Research article

Influence of oxidizer injection angle on the entrained flow gasification of torrefied wood powder

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ABSTRACT

In the present work, 5 different axisymmetric burners with different directions of the oxidizer inlets were experimentally tested during oxygen blown gasification of torrefied wood powder. The burners were evaluated under two different O_2/fuel ratios at a thermal power of 135 kW_{th}, based on the heating value of torrefied wood powder. The evaluation was based on both conventional methods such as gas chromatography measurements and thermocouples and in-situ measurements using Tunable Diode Laser Absorption Spectroscopy. It was shown that changes in the near burner region influence the process efficiency significantly. Changing the injection angle of the oxidizer stream to form a converging oxidizer jet increased process efficiency by 20%. Besides increased process efficiency, it was shown that improvements in burner design also influence carbon conversion and hydrocarbon production. The burner with the best performance also produced less CH_4 and achieved the highest carbon conversion. The effect of generating swirl via rotating the oxidizer jet axes was also investigated. Swirl broadened or removed the impingement area between the fuel and oxidizer jets, however resulting in differences in performance within the measurement uncertainty.

1. Introduction

A large fraction of the CO_2 emission in the world originates from the consumption of fossil fuels in the transport sector [1]. Introducing alternative, carbon-neutral fuels produced from low value biomass — a feedstock that does not find use in other areas — is an attractive solution for the reduction of the carbon footprint of the sector. For the production of such alternative fuels, entrained flow gasification (EFG), coupled with downstream gas synthesis, is a well established method. Using coal as feedstock [2], this technique has shown techno-economical potential on large scales [3]. In EFG, the fuel is fed in powder or spray form. As oxidizer, pure oxygen is introduced in high-momentum jets into a hot reactor (> 1000 °C) at high pressure (> 30 bar). The produced synthesis gas (syngas) is rich in H_2 and CO. After cleaning, the syngas can be converted to methanol [4], hydro-carbons [5] or nitrogen-based energy carriers [6].

Compared to other gasification processes, a benefit of EFG is high process temperature that is normally above the melting point of the produced ash. The molten ash is easily separated from the syngas and can be continuously extracted at the bottom of the reactor. Due to the high process temperature, the EFG technique produces a clean, relatively tar-free gas, ideal for further synthesis. However, the EFG process also produces byprodcuts such as soot, CO_2, H_2O and CH_4 that have to be removed prior to synthesis — consequently, the formation of unwanted byproducts reduces the overall conversion as well. The formation of CO_2 and H_2O can be considered inevitable if the process is operated autothermally; however, the formation of soot and hydrocarbons, past works has shown that hydrocarbons can be minimized by operating at a high temperature [7,8]. At large scales, even a mild reduction of soot and CH_4 leads to a significant overall impact on plant economics.

Recently, Weiland et al. estimated that the theoretical maximum cold gas efficiency (CGE) in the EFG of wood powder was 81% and 83%, for fuel and energy production, respectively, assuming a heat loss of 5% [8]. Here, the CGE for fuel production was calculated based on the heat of formation of CO and H_2 alone, while for energy production, all measurable components were included. The experimental work carried out in order to confirm these calculations showed a CGE of 70% and 75%, for fuel and energy production, respectively. The discrepancy between the calculations and the experimental results is believed to be

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attributed to soot and char formation, and uncertainty in insulation efficiency. Since the reactor was designed to operate under high pressure and temperature, and molten ash is present in the process, previous research has focused on increasing the reactor lifetime [9]. The literature lacks studies on the influence of reactor geometry on gasification efficiency; however, the shape is generally constrained to cylindrical in order to withstand pressure. Considering the importance of minimizing heat loss [8], an optimization of vessel geometry would most likely entail the minimization of surface area. Given the above, it follows naturally that targeting the optimization of the burner is the next logical step in improving EFG.

For various combustion burners, a significant amount of optimization work has been carried out. Most studies in the combustion literature focused on the minimization of pollutants such as NO [10-13] and soot [14]. Numerous burner design parameters affect NO formation by changing mixing, temperature and local stoichiometry in the near burner region. Due to the absence of oxygen, combustion under fuel rich conditions has been shown to promote the formation of HCN and NH_3 over NO. The problem of NO formation in gasification is therefore naturally solved by the fuel rich process itself, and the inevitably formed nitrogen compounds can be removed by gas cleaning processes in the syngas plant. For reducing soot production in combustion, excess oxygen and intensified mixing can be used. Combustion burners are designed for high oxidizer flow rates, therefore only a few designs are directly transferable to oxygen blown gasification. Due to low oxidizer flow rates, in oxygen blown gasification, the use of individual oxidizer jets is more convenient. In gasification, obtaining a high temperature zone for tar cracking and minimization of CH4 [15] is important, but such a high temperature region would lead to excessive NO formation in combustion. In fact, studies of entrained-flow coal gasification using oxygen as an oxidizer have shown that burner designs successful in gasification are usually not efficient for combusting coal or gas [16].

Burner designs for EFG are often confidential or patented [9]. However, a number of designs and optimization have been reported for heavy oil [17], and coal [16,18]. In EFG using heavy oil as fuel, CGE was shown to be affected by the oxidizer injection pattern [17] — in a semi-industrial scale, 5 MW EFG reactor, supplying the oxidizer in a central tube surrounded by an annular fuel stream increased CGE from 76.6% to 77.6%, together with an increased soot production. For solid fuels, an annular fuel inlet is challenging to maintain due to powder accumulation and channel blockage. Indeed, feeding fuel powders can be one of the most technically challenging aspects of EFG [19]. Sowa et al. tested three gasification burners under different pressures (1–5 atm), using coal as fuel and pure oxygen as oxidizer at a thermal power of 275 kW_{th} [16]. It was shown that a swirl burner yielded the highest CGE (57%), while burners using impinging or axial jets resulted in 35–40%. All burners showed similar coal conversion — the values were compared to results reported by Azuhata et al. [20], who used a burner firing coal powder premixed with O_2 that reached an even higher conversion. Increasing pressure reduced the difference in conversion between the two burners that became negligible at 5 bar [16]. The results indicate that diffusion burners can still be used without losing efficiency.

For biomass-based fuels, a few EFG burner designs have been reported. On laboratory-scale (~ 9.5 g/h), Qin et al. [21] showed that the gas production was relatively insensitive to residence time above approximately 2.5 s and that increasing residence time reduced the amount of produced soot. The study suggested that the gas composition is most significantly affected by the characteristics of the near-burner region and the operating temperature — the latter is constrained by the autothermal efficiency and heat losses. Göktepe et al. demonstrated in a laboratory-scale gasifier (~ 10 g/h) that the dispersion of fuel particles influences soot formation [22]. Based on this discovery, the active dispersion of the particles has been suggested as a measure to suppress soot formation [23]. In a pilot-scale environment (100 kW_{th}), Simonsson et al. compared a swirl and jet burner, and two different fuels, wood and peat powder [24]. Here, the swirl burner resulted in a slightly lower soot volume fraction in the reactor. However, since the work was performed with air as oxidizer, flow velocities almost 5 times higher than those in oxygen gasification were achieved. With pure oxygen, the swirl burner concept would most likely be unsuccessful, and would essentially function as an axial jet burner due to the low flow rates.

From an overview of the available literature, a lack of non-confidential information on pilot-scale, oxygen-blown biomass gasification burners is apparent. The aim of this work therefore was to investigate the influence of the burner parameters on gasification efficiency. Based on the literature, we restricted burner designs to diffusion types with a central fuel passage and focused on the optimization of the direction of the annularly positioned oxidizer jets by using Computational Fluid Dynamics (CFD) — routinely used in burner design [17] — and pilot-scale experiments. The results reported here target researchers and engineers working in the field of gasification with the aim to increase gasification efficiency and improve burner design.

2. Experimental setup and procedure

2.1. Gasifier

A schematic of the entrained flow gasifier used for testing the different burners is shown in Fig. 1. The reactor was 4 m tall and had a cylindrical shape with a diameter of 1 m. The gasifier had an outer shell made of steel and was internally lined with refractory. The internal diameter was 0.5 m. Fuel was fed by hopper through a screw-feeder located directly above the reactor. From the outlet of the screw-feeder the fuel travelled gravimetrically, and was dispersed by a co-flow of air (30 l/min) through a 2 m long steel pipe, directly connected to the burner. The fuel used in the experiments was pelletized and torrefied stem wood, delivered by BioEndev AB [25]. The fuel was milled to a size smaller than 0.75 mm. The particle size distribution and proximate and ultimate analysis for the fuel is shown in Table 1. Torrefaction is a heat treatment process that reduces the oxygen content of the fuel and makes the fuel nearly hydrophobic [26]. Torrefaction improved the feeding characteristics of the raw stem wood. Table 1 compares properties of ordinary and torrefied stem wood — the main differences being the lower oxygen- and volatiles-, and higher carbon content of the torrefied biomass. After the fuel entered the burner mounted axially on the top of the reactor, the powder-air mixture passed through the central fuel passage and entered the reactor. The oxidizer was introduced through the burner. Inside the reactor, thermocouples were installed in the ceramic lining and in the center of the reactor core inside 8 mm Al_2O_3 tubes. A number of thermocouples was distributed along the reactor. The gasifier was constructed with optical access at 4 different heights and directions allowing comprehensive optical instrumentation. Off-gas from the reactor was sent through a 90° bend to a boiler where the combustible products were combusted. A schematic of the facility along with photographs is shown in Fig. 1.

The hopper was calibrated to feed 23 ± 0.4 kg/h of fuel corresponding to a thermal power of 135 ± 2 kW_{th}. The hopper was equipped with weight cells allowing for the on-line measurement of the feeding rate, also allowing for the verification of the calculated equivalence ratio (λ) after the experiments. In order to ignite the fuel and stabilize the flame, prior to start-up, the gasifier was heated to approximately 1200 °C by using an oil burner. One burner was tested each day of the campaign — the heat-up procedure ensured consistent initial conditions among the cases. The experimental protocol included initiating gasification at $\lambda = 0.3$ with an O_2 flow of 119 l/min for 2 h, then at $\lambda = 0.4$ with an O_2 flow 155 l/min of for an additional 2 h. The air co-flow used to transport fuel from the hopper also served to reduce the risk of backfiring — in order to correct for the additional air, the burners were operated with slightly lower O_2 flow rates. A summary of the experimental conditions is provided in Table 2.