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Full Length Article

Soot reduction in an entrained flow gasifier of biomass by active dispersion of fuel particles

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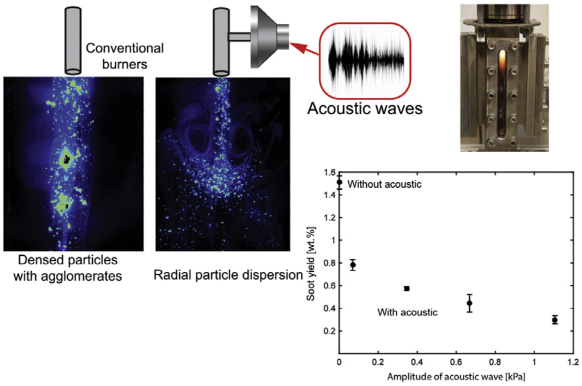
HIGHLIGHTS

- Synthetic jet actuator to disperse pulverized biomass particles and reduce soot.
- Particle dispersion improved and aggregates broke up in both hot and cold gas flows.
- Soot yield significantly reduced with the application of synthetic jet actuator.
- Potential to reduce soot without changing major operation performance.

GRAPHICAL ABSTRACT



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ABSTRACT

Soot is an undesired by-product of entrained flow biomass gasification since it has a detrimental effect on operation of the gasifier, e.g. clogging of flow passages and system components and reduction of efficiency. This study investigated how active flow manipulation by adding synthetic jet (i.e. oscillating flow through orifice) in feeding line affects dispersion of fuel particles and soot formation. Pine sawdust was gasified at the conditions similar to pulverized burner flame, where a flat flame of methane-air substoichiometric mixture supported ignition of fuel particles. A synthetic jet flow was supplied by an actuator assembly and was directed perpendicular to a vertical tube leading to the center of the flat flame burner through which pine sawdust with a size range of 63–112 μm were fed into a reactor. Quartz filter sampling and the laser extinction methods were employed to measure total soot yield and soot volume fraction, respectively. The synthetic jet actuator modulated the dispersion of the pine sawdust and broke up particle aggregates in both hot and cold gas flows through generation of large scale vortex structures in the flow. The soot yield significantly reduced from 1.52 wt.% to 0.3 wt.% when synthetic jet actuator was applied. The results indicated that the current method suppressed inception of young soot particles. The method has high potential because soot can be reduced without changing major operation parameters.

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1. Introduction

Gasification in combination with further catalytic conversion is an efficient and flexible process for the production of advanced biofuels. The gasification process must generate an ultra-clean syngas to avoid deactivation of catalyst by contamination with impurities [1]. Entrained flow gasifiers are promising technologies, which are well proven in large-scale coal gasification, to produce syngas with very little or no tar content. As a result research in entrained flow biomass gasification (EFBG) has been growing significantly in recent years [2–6]. EFBGs employ pulverized burner with higher particle loading ratio (solid-to-gas mass flow ratio) than conventional suspension firing technologies. Typical forest residues with 10 wt.% of moisture content result in approximately 0.14 kg kg^{-1} of mass loading ratio for conventional burners (fired with air, air-fuel equivalence ratio, $\lambda = 1.25$) while it will be around 1.5–2 for oxygen blown entrained flow gasifiers ($\lambda = 0.35–0.5$).

The EFBG is operated at high temperature (1000–1400 °C) to achieve high carbon conversion within relatively short residence time. In the temperature range of EFBG, soot production is pronounced, in extreme cases, as high as 5–15 wt.% of biomass input [3,7]. Pilot-scale experiments at 1 MW EFBG plant showed that particulates in syngas mainly consist of soot [8], which may lead to low cold gas efficiency. Moreover, soot can accumulate in the quenching water [9,10], making cleaning system cost-intensive. Detailed soot formation models have suggested that soot forms from large PAHs (polycyclic aromatic hydrocarbons) with 5 and 6 aromatic rings in the gas phase [11]. General mechanisms of soot formation in EFBG should be similar considering the chemical and physical structures of soot [12] although prediction from available models could be poor due to the lack of chemical species and reaction pathways specific to EFBG [13]. Experimental studies have demonstrated that soot formation is noticeably affected by residence time, reactor temperature, equivalence ratio, oxygen concentration and steam/carbon ratio [3,4].

Due to high particle loading ratios, fuel particles may form a dense cloud and change the combustion chemistry by particle-particle interactions. In fact, some studies have reported that a particle surrounded by a dense cluster of particles is exposed to a different reaction environment than an isolated particle. This results in different ignition behavior [14], pyrolysis and reaction rates [15], combustion rates of char particles [16], and soot formation [6]. Such interaction with neighbor particles becomes evident at the particle distance less than 10 times the diameters as indicated by the deviation of Nusselt number, Sherwood number, and drag coefficient from isolated particles [17]. Moreover, solid-to-gas force and solid-to-solid forces become significant for particulate flow with higher volume fraction of solid particles than 0.1 [18].

Dispersion characteristics of particle-laden flows are, therefore, of importance for the optimization of the main gas composition and pollutant emission in EFBG. Large-scale flow structures, which are naturally present in jet flows due to background turbulence [19], can alter the particle concentration locally [20,21]. However, it is also possible to enhance and control large scale coherent structures by using acoustic forcing. This method has been applied to particle-laden flows to investigate the particle-vortex interactions and the resulting dispersion of particles [19–25]. In gaseous flames, flame-vortex interactions lead to variations in soot formation, which are influenced by the reactant streams at which a shedding of vortices are initiated [26]. No experimental study was found on the effect of acoustic forcing on soot formation in entrained flow biomass gasification.

In this context, this study aims at investigating the influence of acoustic forcing on dispersion of pulverized biomass particles and how it affects soot formation in a laboratory scale atmospheric entrained flow biomass gasifier. Pine sawdust with a sieve size of 63–112 μm was used as a representative of biomass feedstock and was gasified in the presence of a fuel rich laminar flat flame of methane-air mixture. Particle dispersion was controlled by a synthetic jet actuator (i.e. acoustic forcing through small opening). Soot was measured by using both filter sampling and a non-intrusive 2-color laser extinction method.

2. Experimental section

2.1. Feedstock

Pine sawdust was used as a biomass feedstock for the atmospheric entrained flow gasification. Pulverized pine particles were screened to the size class of 63–112 μm with a sieving machine (AS200, Retsch Technology). Properties of the feedstock can be found in a previous publication [6].

2.2. Experimental apparatus and procedure

The experiments were carried out in a laboratory scale, atmospheric entrained flow gasification system. It mimics the conditions in the near-flame region of an entrained flow gasifier where hot syngas is partially combusted with oxygen that carries the fuel particles into the reactor. Simultaneously, the fuel particles are advected through the hot flame sheet and rapidly heated before ignition. The setup, shown in Fig. 1, is comprised of a gas supply unit, a biomass feeder, a synthetic jet actuator, a flat flame burner (FFB), a reactor tube (i.d.: 80 mm, length: 300 mm), a char collector, a quartz filter, and a gas cleaning/analysis system. Information of major components can be found in the previous publication [6]. In this study, biomass particles were supplied with a suspending stream of air (0.136 L min^{-1}). A premixed mixture of CH_4 (1.54 L min^{-1}) and air (11.7 L min^{-1}) was combusted to produce a fuel rich flame at a few mm below the porous disc (air-to-fuel equivalence ratio, $\lambda = 0.8$). A flow of N_2 (6.79 L min^{-1}) was purged through an annular sintered bronze disc to prevent recirculation zone. Gas flow rates were controlled by mass flow controllers (EL-FLOW, Bronkhorst High-tech B.V.). The stainless reactor has four optical viewports (200 mm in length and 35 mm in width) that are aligned perpendicular to each other. 3 mm-thick fused silica glass plates provided optical access for non-intrusive measurement techniques. The reactor outer walls are insulated by glass wool to minimize heat losses through the walls. The absolute pressure in the reactor was constantly monitored at the reactor outlet by a water-cooled piezo-resistive absolute pressure sensor (4049B05DS, Kistler), and kept between 110 and 120 kPa by an adjusting the vacuum generator (E-Vac®, Exair corporation) at the exhaust line.

A synthetic jet actuator was connected perpendicular to the central feed pipe to create pulsations in the air flow carrying biomass over a range of frequencies and amplitudes. The synthetic jet actuator consists of a 4 Ω loudspeaker (ND140-4-5-1/4″, Dayton) as a vibrating element, a cavity (259.6 mm^3), and a centralized orifice with the diameter of 4 mm. A porous steel mesh was attached to the entrance of the arm of the Tee-union adapter to prevent the deposition of pulverized particles in the cavity. The loudspeaker was driven by a sinusoidal signal that was generated by a data acquisition board (DT-9841-VIB, Data Translation) and amplified by an audio amplifier (Integrated amplifier A-10, Pioneer). Induced by the loudspeaker, the synthetic jet actuator forms a jet with a net-zero mass flux by a periodic suction and ejection of an ambient fluid through the orifice. An acoustic pressure sensor (106B, PCB) was mounted into the cavity to measure the