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Fluidization characteristics of a mixture of gasifier solid residues, switchgrass and inert material

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ABSTRACT

Effective fluidization of materials present in the reactor bed is critical for optimizing reaction conditions in a fluidized-bed gasifier. An improper fluidization leads to inefficient conversion due to many reasons such as low heat and mass transfers, ineffective gas–solid phase reactions, and uneven reactor temperature in autothermal gasification. The objective of this study was to investigate effect of reactor bed composition, i.e. a mixture of gasifier solid residues (GSR), switchgrass, and inert material, on fluidization using a 0.25 m i.d. transparent column. In this cold-flow study, the amount of inert material, i.e. silica sand, in the bed was held at 20 kg. The switchgrass in the mixture ranged from 0.17 to 5% of the sand quantity while the GSR ranged from 5 to 35% of the switchgrass. The particle geometric sizes by mass of sand, GSR and switchgrass were 348 ± 1.6 μm, 80 ± 2.6 μm, and 10.3 ± 1.7 mm, respectively. For all conditions, with an increase in gas superficial velocity, i.e. ratio of volumetric gas flow and bed cross-sectional area, the pressure drop across the bed increased reaching a maximum level at the minimum fluidization condition. Results showed that when the bed consisted of only GSR and sand, with an increase in the GSR from 5% to 35%, the gas superficial velocity at minimum fluidization condition, called minimum fluidization velocity (U_{mf}), decreased significantly ($p<0.05$); however, corresponding bed pressure drop (dP_{mf}) remained constant. When the bed consisted of GSR, switchgrass and sand, there were significant effects ($p<0.001$) of GSR, switchgrass and their interaction (GSR*Switchgrass) on U_{mf} and dP_{mf}. Fluidization improved with an increase in GSR up to 35% in the mixture. Overall, both U_{mf} and dP_{mf} increased with an increase in levels of GSR (5 to 35%) and switchgrass (0.17 to 3%) in the mixture. Fluidization characteristics were found to be strongly dependent upon mixture's effective properties, which were determined using properties of all mixture components. Correlations available in literature were used to predict U_{mf} using effective properties of tertiary mixture with GSR, switchgrass and sand. Prediction of U_{mf} from all selected correlations did not match well with the experimental data for the entire range of tertiary mixture compositions. Fluidization of bed materials sustained up to 3% level of switchgrass. However, segregation of bed materials and in-bed channelization caused ineffective fluidization at 5% level of switchgrass in the mixture.

1. Introduction

Effective fluidization of materials present in the reactor bed is essential for optimizing reaction conditions in a fluidized-bed gasifier. Gasifier bed normally consists of gasifier solid residues (GSR), such as char and ash, biomass and inert material such as silica sand. An improper fluidization of bed materials can result in low heat and mass transfers [1], ineffective gas–solid phase reactions, and inability to maintain a uniform reactor temperature in autothermal gasification. Such conditions can also cause an in-bed accumulation of GSR and biomass, further resulting in choking of the gasifier bed and can ultimately stop the gasification process. Therefore, a thorough understanding of fluidization characteristics of all participating solids during gasification is essential for reactor design [2] and optimizing reaction conditions of the gasifier.

A typical fluidized bed gasifier is a cylindrical reactor that consists of a bed of inert material, such as sand, or a mixture of sand and catalyst. A distributor plate is used to support a bed material inside the gasifier. For gasification, initially, the bed is preheated by an external heat source. Thereafter the bed is fluidized by supplying an oxidizing agent, such as air, through the distributor plate. Finally, a biomass feedstock is injected into a fluidized-bed using a screw feeder. Biomass particles then pass upward through the bubbling fluidized-bed, undergo a series of gasification reactions, and finally convert into gaseous products [3]. Both fluidization of bed materials and gasification of biomass are occurred simultaneously during gasification. Several parameters such as flowrates and types of oxidizing agent and biomass, properties of oxidizing agent, biomass and bed material, and operating temperature and pressure have influence of fluidization characteristics of materials that are normally present in the gasifier bed. These, in turn, play key roles in the gasification process and influence gasifier performance in terms of gas composition and yield, gas impurities and gasifier efficiencies [4].

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The flow rate of oxidizing agent supplied to the fluidized-bed gasifier is a key parameter to maintain effective fluidization of bed materials. The fluidization condition is usually described using a gas superficial velocity which is the ratio of volumetric gas flowrate and bed cross-sectional area. The gas superficial velocity, at which the drag force on the bed materials equals the gravitational force, is defined as the minimum fluidization velocity (U_{mf}) of the bed materials. At minimum fluidization condition, the bed materials lift upward and remain in suspension; bed pressure drop (dP_{mf}) reaches to a maximum and remains constant with further increase in the gas superficial velocity. Fluidization characteristics, such as U_{mf} and dP_{mf}, depend upon the particle size and composition of the bed materials [5]. U_{mf} and dP_{mf} are also influenced by segregation and mixing behaviors of bed materials. Segregation is a process during which a bed material with higher particle density, such as sand, moves downwards in the bed while a material with lower particle density, such as biomass, floats upwards [6,7]. This, in turn, causes separation of biomass from sand and results in a localized accumulation of biomass particles as smaller and/or bigger sized lumps throughout the bed. These lumps further lead to channel formation, called in-bed channelization, that give rise to larger void space and a shorter path to the gas flow [8]. As a result, the gas easily escapes through in-bed channels, which affect bubble formation, and thus turbulence level in the bed resulting in ineffective fluidization. Segregation occurs due to differences in densities or sizes of the bed materials such as a sand and biomass [7,9–14]. Further, segregation tendency increases with an increase in the biomass weight fraction in a mixture [10]. Thus, the quantity of biomass in the mixture plays a crucial role in segregation behavior of bed materials. Also, a bed consisting of a material, such as particulate matters, that has adhesive or cohesive properties may enhance segregation tendency and suppress fluidization [1]. In case of segregation or channelization, comparatively a higher gas superficial velocity than U_{mf} is needed for fluidization of bed materials [10]. This is because at higher gas velocity, formation and collapsing of bubbles become predominant leading to high turbulence in the bed. The high turbulence breakdowns segregated lumps and removes in-bed channels. Hence, higher gas velocity eradicates segregation of bed materials resulting in a better particle mixing. As opposed to segregation, mixing prevents separation of bed materials resulting in a uniform distribution of mixture particles in the bed. Mixing enhances particle–particle interactions, and thus improves heat and mass transfers in fluidized bed. Chok et al. [11] indicated improved mixing with decrease in the particle size ratio from 30 to 20 of palm shell and sand mixture. The author also reported that segregation and channelization were predominant at higher particle size ratio, and biomass weight fraction (10% and 15%) in the mixture. Correlations to determine U_{mf} and bed expansion of coal particles were suggested for coal gasification [15]. Equations to determine U_{mf} for a mixture of sand and biomass, such as sawdust, rice husk and groundnut shell, have been developed [8,16]. However, fluidization behavior and correlations for determining U_{mf} for a tertiary mixture of GSR, switchgrass, and silica sand have not been reported. The specific objective of this study was to investigate the fluidization characteristics of a mixture of switchgrass, GSR, and silica sand for determining the optimum operating conditions in terms of fluidization velocity and bed pressure drop.

2. Materials and methods

2.1. Bed materials

GSR, biomass and silica sand were used as bed materials, shown in Fig. 1, for fluidization experiments. GSR was obtained by gasification of switchgrass in a 0.25 m i.d. pilot-scale bubbling fluidized-bed gasifier with constant switchgrass and air flow rates of 12 kg/h and 17 m^3/h (i.e. 0.096 m/s superficial velocity), respectively. The gasifier was connected to three cyclone separators in series for removing the GSR from the producer gas. The GSR in the cyclone separators were collected, weighed, and analyzed for its properties. On an average the GSR production rate was 0.5 kg/h, which contained 64% ash and 36% char. A Kanlow switchgrass, a perennial grass, was used as a biomass material in this study. It was grown at the Agronomy Research Station of Oklahoma State University and harvested in the fall of 2010. A Haybuster tub grinder (H1000, Duratech Industries International, Inc. Jamestown, ND) with a screen size of 25 mm was used to grind the switchgrass. Moisture and ash contents of the switchgrass, determined through proximate analyses, were 12.76% and 4.72%, respectively. A silica sand is the most commonly used inert bed material for fluidized-bed gasifier. In this study, silica sand, supplied by Oglebay Norton Industrial Sands, Inc. (Brady, TX), was used as an inert bed material.

2.2. Density of bed materials

Bulk densities of bed materials were determined by using a container of 0.001 m^3 volume. To measure bulk density of GSR, weights of the empty container and container filled with GSR were measured. Bulk density was calculated by dividing the mass of the GSR in the container with the volume of the container. A similar method was used to determine bulk densities of ground switchgrass and silica sand. Particle densities of silica sand and switchgrass were obtained from supplier and literature [17], respectively. A 3 g GSR pellet was prepared to measure particle density of GSR, which was determined by dividing the mass with the volume (3.22 cm^3) of the GSR pellet. Table 1 shows the bulk and particle densities of GSR, ground switchgrass, and silica sand.

2.3. Particle size distribution of bed materials

Particle size distributions of GSR and silica sand samples were determined following ANSI/ASAE standard S319.3 JUL97 (ASAE, 2000) using a sieve shaker (CSC Scientific, Fairfax, VA). The sieve shaker consisted of seven screens, a lid, and a pan. The screen size ranged from 850 to 106 μm. Initially, the empty screens and pan were weighed and arranged in a descending order of screen sizes in the sieve shaker. The pan was placed below the lowest screen. A 50 g representative sample was kept in the first screen (850 μm), and the screen was closed with the lid. The sieve shaker was set to sieve the sample for 10 minutes. After each sieving test, the mass of the sample in each screen and pan was measured. A total of six samples were used to determine its particle size distribution. An average of the data was used to calculate a percentage mass distribution of GSR on each screen and on the pan. Six representative samples (500 g each) of silica sand were analyzed using the sieve shaker. Particle size distribution (length and width) of ground switchgrass was measured manually with a digital vernier caliper (Digimatic, Mitutoyo, Japan) having a resolution of 0.1 mm. The geometric mean sizes by mass of bed materials were determined using ANSI/ASAE standard S424.1 (ASABE, 2007). The particle size ratio of GSR, silica sand and switchgrass (i.e. GSR/silica sand/switchgrass) was calculated using geometric mean sizes by mass of GSR, silica sand and switchgrass particles.

2.4. Test setup and instrumentation

The fluidization test setup, shown in Fig. 2, consisted of a cylindrical column (0.25 m i.d. × 2 m height) made of a transparent acrylic glass to facilitate visual observation during the experiment. A distributor plate (0.28 m o.d.) located at the bottom of the column supported the bed materials and also helped to ensure a uniform distribution of inlet air supply. The distributor plate was made of a 6.4 mm-thick acrylic glass sheet with 145 equally-spaced 1.6 mm i.d. holes. To prevent bed materials from falling through the distributor plate, a wire screen (40 mesh size) was placed on top of the distributor plate. Air was supplied into the test setup by an air compressor (TS10K10 model, Ingersoll Rand, Davidson, NC) connected to a mass flowmeter (8059MPNH model, Eldridge Products, Inc., Monterey, CA), a flow control valve, and a pressure regulator. A water tube manometer was installed across the bed of