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Novel intermittent solid slug feeder for fast pyrolysis reactors: Fundamentals and modeling

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ABSTRACT

To prevent plugging and help the raw biomass particles effectively penetrate and spread into the pyrolysis fluidized beds, one could inject the particles using intermittent slugs created by propelling loosely packed particles with gas pulses and transporting them along horizontal or inclined feeding pipes into the fluidized bed section of the reactor; this would combine the advantages of the low gas consumption of the screw feeders and the short residence time in high temperature zones of dilute phase feeders.

Dried distillers' grain (DDG) and meat and bone meal residues (MBM) were selected as model feedstocks for experimental testing and modeling of a novel intermittent solid slug feeder technology. These feedstocks were chosen as much work has been done to attempt to process them into value-added products via fast pyrolysis, but they also possess very challenging flow characteristics and properties that are very different from each other (particle size, cohesivity, temperature sensitivity, density). As a result, creating a predictive model that can successfully model these challenging feedstocks is the basis to model any biomass of interest.

The biomass flow in the feeding tube begins as an induced dense-phase flow and develops into a high velocity 'aerated bed flow'. Gas leakage, solid friction and force-momentum balances were considered in the model. The model was developed from experimental data collected with simplified plugs (modified nylon ball), as well as real biomass slug flow.

Several important variables were identified. They included the material flow properties, the gas capacitance pulse pressure and volume, and the length and material of feeding tube. The goals of this study were to (a) characterize the fundamental dynamic behavior of the biomass slugs in the feeder, (b) maximize the solid-to-gas feeding ratio, and thus minimize energy consumption, (c) minimize the accumulation of "straggler" biomass material in the feeding tube between pulses, and thus preventing biomass pre-cooking in the feeding tube and plugging (d) develop and validate a predictive model for the slug velocity at any point in the feeding tube (and thus the maximum feeding tube length), that can be applied for feeder and reactor design for any biomass feedstock, and (e) identify future areas of work for the ICFAR intermittent solid feeder.

1. Introduction

Fluidized bed technology has been demonstrated to have good potential as a reactor technology of choice for the production of pyrolysis oil and bio-char, via fast biomass pyrolysis [1]. In a fluidized bed pyrolysis process, raw biomass material particles must be conveyed and injected into the reactor using the least energy intensive and most practical feeding system. Dilute phase pneumatic transport lines and screw feeders are currently being used by several pyrolysis processes. However, in the flash pyrolysis process, where the temperature of the reactor is high, typically between 450 and 550 °C, and where relatively high mass flow rates of raw biomass can be processed, these commonly used feeding systems tend to encounter some serious problems [2]. For example, the high temperature coupled with pressure fluctuations at the inlet into the reactor can often lead to severe plugging in screw feeders, potentially causing significant damage to the equipment or down time in the operating process. This is especially the case for temperature-sensitive and cohesive biomass residues such as Kraft lignin and meat and bone meal residues [2–4]. Dilute phase pneumatic transport feeders consume a large amount of gas, which is typically recycled product gas, which results in higher energy consumption and requires a more sophisticated condensation train due to product vapor dilution. In addition, many industrial operators attempting to feed challenging biomass into reactors are usually forced to feed above the bed, which often results in poor mixing with the hot sand, as the biomass simply floats on top of the hot bed [5].

To prevent plugging and help the raw biomass particles effectively penetrate and spread into the pyrolysis fluidized beds, one could inject the particles using intermittent slugs created by propelling loosely packed particles with gas pulses and transporting them along horizontal or inclined feeding pipes into the fluidized bed section of the reactor [6]; this would combine the advantages of the

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low gas consumption of the screw feeders and the short residence time in high temperature zones of dilute phase feeders.

Among many other potential applications, intermittent solid slug feeders can be used to effectively inject biomass materials into fluidized bed reactors for pyrolysis. In particular, these feeders can be used to convey biomass materials that are highly cohesive to prevent plugging or undesirable reaction in the feeding tube. Although feeders of this design have been tested, roughly optimized through trial and error, and shown to work very effectively for pyrolysis applications [2,7], fundamental results and a verified model are required for full optimization and, eventually, scale-up.

The objective of this study was to develop a predictive model for the solids flow induced by a gas pulse, and thus the solids velocity at any point in the feeding tube, by utilizing a sequential approach and validation with dedicated instrument data.

2. Materials and methods

2.1. The ICFAR intermittent solid slug feeding technology

The Institute for Chemicals and Fuels from Alternative Resources (ICFAR) intermittent solid slug feeder technology [7] designed for this work and illustrated in Fig. 1 has been used extensively at ICFAR for bubbling bed pyrolysis reactor experiments for long operation and has also been scaled up [2]. The feeder for this work consisted of a slightly pressurized vertical solids storage silo (P_0 — kept between atmospheric pressure and 120 kPa) leading to a 19 mm diameter pneumatic pinch valve. The silo had a 4 L volume, with a cone angle of 40°. Within the silo, a specially-designed rotating 'egg-beater' mixer prevented the bridging of solids. The instantaneous mass flow of gas flowing into the silo was determined by acquiring the Gas-Trak Sierra mass flowmeter signal responsible for delivering the nitrogen gas to the silo. The pinch valve was controlled by Granzow Inc. solenoid valves (SV_{1A} and SV_{1B} in Fig. 1, series 21EN) connected to a relay timer (IMO iSmart Relay, 10 I/O AC). Solids exiting the pinch valve flowed into a 15.3 mm (inner diameter), electrically-grounded clear PVC or carbon steel horizontal feeding tube through a ninety degree angle connection. Various feeding tube lengths were studied from 0.08 m to 1.145 m, as the optimum length for this size of feeder would very likely fall within this range. The volume between the end point of the pinch valve and the start of the horizontal feeding tube is called "slug chamber". For the purpose of the current study, a simple "T" fitting of constant diameter (15.3 mm) has been utilized, with a vertical, 63.5 mm long section (measured from the base of the horizontal part of the "T" block). Intermittent pulses of nitrogen were fed at a set pressure (P_1 — usually above 240 kPa to ensure that the biomass can exit the longest feeding tubes tested) to propel the biomass slugs, delivered from a control volume consisting of an 80 mL steel canister. The timing of the pulses was controlled by Granzow Inc. solenoid valves (SV_2 and SV_3 in Fig. 1, series 21EN) with the relay timer. When the pinch valve opens and closes, the biomass falls into the 'slug chamber' forming a plug, which is then propelled into the reactor through the feeding tube by a pulse of pressurized nitrogen gas (or recycled product gas) from the canister. The pressures in the silo (P_0), capacitance volume (P_1), and feeding tube (P_2), were measured by an Omega PX181 series semiconductor pressure transducer at 2 kHz. The pressure transducer is reported to have a response time of less than 2 ms, with a best-fit straight line accuracy measurement of 0.3%.

The entire apparatus was manufactured using clear PVC to allow for visual inspection of the feeder operation and for characterization (position and velocity) of the solid flow with red lasers and a photo-resistor apparatus, which gave a continuous signal, recorded at 10 kHz by a National Instruments NI USB-6008 data acquisition card and NI LabVIEW software. As the slug passed through the laser, the photoresistor outputted a signal peak due to the change in light intensity, the start of which was interpreted as the point at which the bulk of the slug passed in front of the laser. The response time

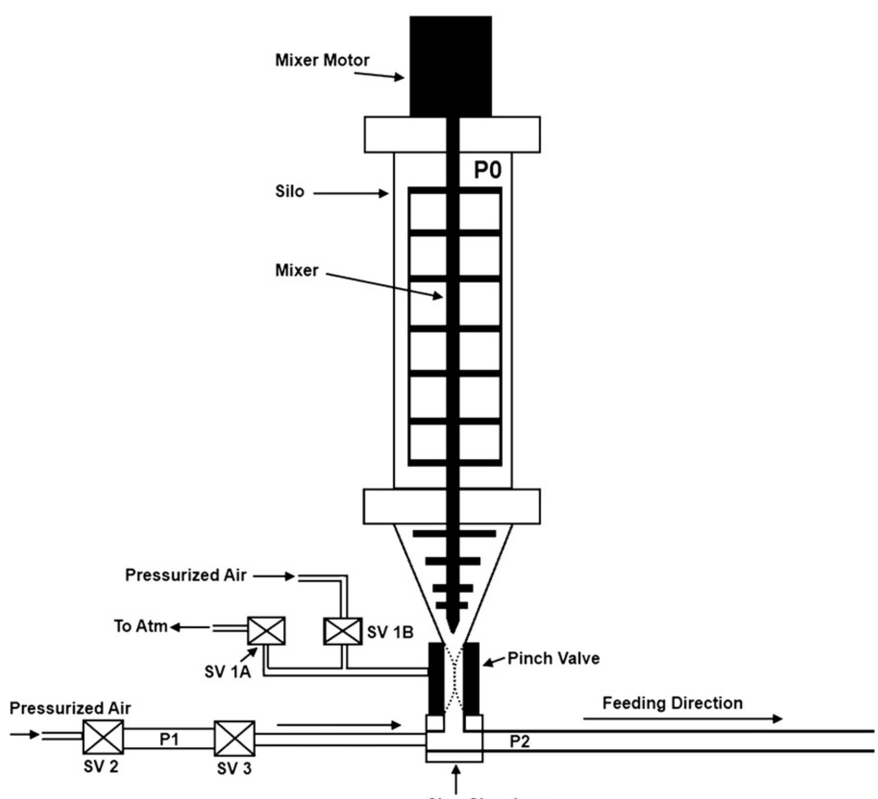

Fig. 1. ICFAR intermittent solid slug feeder schematic.