Powder Technology 214 (2011) 69–76

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

The influence of granular flow rate on the performance of a moving bed granular filter

Ibrahim A. El-Hedok [a], Lysle Whitmer [b], Robert C. Brown [b,c,*]

[a] Department of Chemical and Biological Engineering, Iowa State University, Ames, IA 50011, USA
[b] Department of Mechanical Engineering, Iowa State University, Ames, IA 50011, USA
[c] Center for Sustainable Environmental Technologies, Iowa State University, Ames, IA 50011, USA

ARTICLE INFO

Article history:
Received 30 November 2010
Received in revised form 14 June 2011
Accepted 28 July 2011
Available online 4 August 2011

Keywords:
Hot gas cleanup
Moving bed
Granular filter
Fast pyrolysis
Char dust

ABSTRACT

The goal of this study is to evaluate the effect of granular flow rate on the performance of a moving bed granular filter designed for hot gas filtration of fine char particles (dust) produced during fast pyrolysis of biomass. The filter employs a counter-current configuration, in which down-flowing granular material spreads out at the bottom of the filtration vessel to form an interfacial area where the dusty gas enters the granular bed and much of the gas cleaning is hypothesized to occur. This study uses a real-time particle counter to measure the instantaneous filtration efficiency during cold flow tests of the filter. Differential pressure measurements at various locations within the granular bed are used to assess the level of char dust hold-up over time. These experiments reveal a critical granular residence time below which the filter must be operated to achieve filtration efficiencies exceeding 99%. Operating above the critical value causes the filter to "clog" and decrease in efficiency. The clogging is characterized by a critical dust volume fraction as determined through a fixed bed filtration test. The filter is found to accumulate most of the dust at the interfacial region. Also the interfacial region is more efficient than the downcomer section of the granular bed in removing dust. Decreasing residence time of granular material in the filter reduces the hold-up of char dust in the filter, which is expected to mitigate coking reactions of organic vapors when the filter is used to remove char from fast pyrolysis gas streams.

1. Introduction

The goal of this study is to evaluate the effect of granular flow rate on the performance of a moving bed granular filter designed for hot gas filtration of fine char particles (dust) produced during fast pyrolysis of biomass. Fast pyrolysis of biomass is a thermochemical technology for conversion of biomass into a liquid product called bio-oil [1]. Like petroleum, bio-oil can be upgraded to higher value fuels and chemicals. Fast pyrolysis involves rapid heating of biomass in an oxygen-free environment to produce vapors, which are subsequently condensed into bio-oil, non-condensable gases and a solid residue known as char. Char must be separated from the gas stream at elevated temperatures (>450 °C) before the vapors are recovered by condensation to prevent contamination of the bio-oil product. It is believed that char particles catalyze the polymerization of bio-oil, which increases the viscosity of bio-oil over time [2]. Thus, hot gas filtration has to be highly efficient in removing fine particulate matter.

A moving bed granular filter (MBGF) utilizes continuously flowing granular material, such as gravel or sand, as filtration media. Because the filtration media is refractory material, MBGFs can be operated at very high temperatures. Unlike conventional barrier filters, they do not require periodic blow-back to remove dust hold-up since dust is continuously removed from the filter with the granular flow. Several kinds of MBGF have been described in the literature [3,4]. The granular flow in MBGF is typically downward aided by gravity and controlled at the bottom by a rotating auger or a moving belt. MBGF designs differ in how the dust-laden gas enters and pass through the filter. These filters can be classified as cross-flow, co-current and counter-current.

The cross-flow MBGF minimizes gas passage through the granular media, which is an advantage when low pressure drop is required. However, engaging the gas flow with the granular media requires containing walls constructed of mesh or containing louvers, which are susceptible to clogging.

While co-current and counter-current designs are similar in construction, they differ in how the granules interact with the particulate-laden gas flow. In a co-current MBGF the dirtiest gas is filtered by the cleanest granular media while the cleanest gas is filtered by the dirtiest granules. Such a configuration sets a limiting factor on the overall efficiency of filtration. On the other hand, in a counter-current MBGF the dirtiest gas is

* Corresponding author at: Center for Sustainable Environmental Technologies, Iowa State University, 1140 BRL, Ames, IA 50011, USA. Tel.: +1 515 294 7934; fax: +1 515 294 3091.
E-mail address: rcbrown@iastate.edu (R.C. Brown).

0032-5910/$ – see front matter
doi:10.1016/j.powtec.2011.07.037

filtered by the most dust-laden granules and the gas flow encounters progressively cleaner gas media, which allows theoretical filtration efficiencies to approach 100%.

In 2000 Brown and co-workers [5] described a MBGF that employs two distinctive filtration sections: an interfacial region that removed the bulk of the dust burden from the gas flow and a downcomer section where the counterflow of gas and granular filter media allows attainment of very high filtration efficiencies. The design and performance of this filter were previously reported in several publications: Soo [6], Shi [7], Brown et al. [8] Ritzert [9,10] and Huisenga [11].

As illustrated in Fig. 1 dust-laden gas enters this MBGF through a square tangential inlet which induces cyclonic flow. Although this cyclonic flow may help remove some of the particulate material from the gas stream, its main purpose is to minimize expansion loses as the gas flow enters the body of the filter. Fins are used to direct the flow horizontally downward to the interfacial region where the gas flow enters the granular media.

Up to 86% of particulate removal in the MBGF occurs at this interface, where a prominent filter cake sometimes forms [10]. The filter cake enhances filtration by decreasing the void spaces between the granular particles [5,7]. From here the gas flow is directed upward into the downcomer region where the gas is in counterflow with the granular filtration media, which flows downward under the action of gravity. The counter-flow arrangement in the downcomer is conducive to high filtration efficiency since the gas exits the filter where the granular material is the cleanest, a condition not achieved in many other kinds of MBGF.

Although the formation of filter cake in the interfacial region is desirable from the stand point of filtration, the hold-up of char particles in a filter cake may be undesirable in fast pyrolysis applications as the vapors in the gas stream can react with char particles to produce additional char [12]. Hence, reducing char hold-up in the granular bed by increasing granular flow rate may be desirable.

The effect of granular flow rate on filtration efficiency is unresolved in the literature. A study by Brown et al. [8] concluded that filtration efficiency improves with granular flow rate. Other studies have reported that increasing granular flow rate decreases filtration efficiency [13,14], presumably do to disturbances of the dust cake in the filter as granules are more rapidly conveyed through the filter. Yang et al. [15] concluded that granular flow rate has little effect on filtration efficiency.

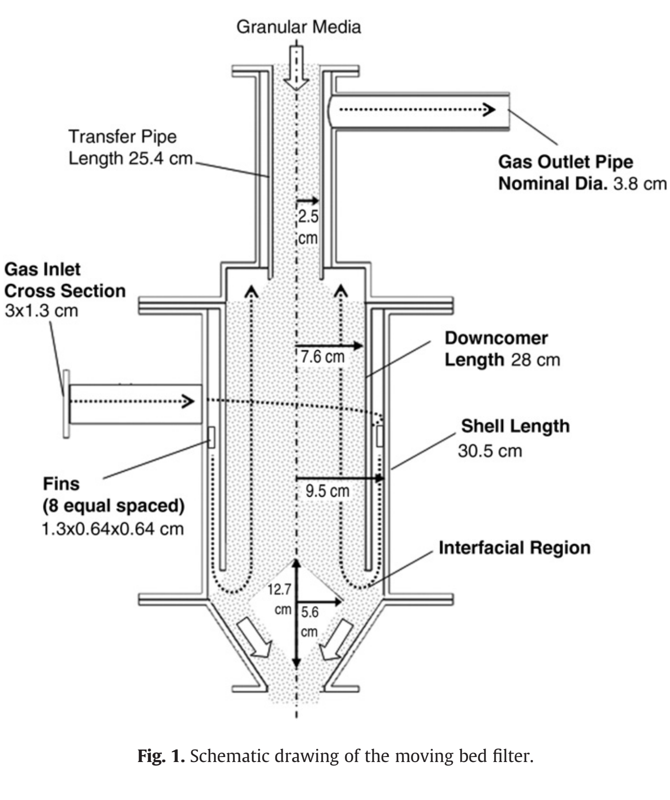

Fig. 1. Schematic drawing of the moving bed filter.

This study employs a cold flow model of a MBGF to investigate the effect of granular flow rate on dust hold-up and collection efficiency. A real-time particle counting instrument and custom-designed, in-situ pressure probes facilitate the investigation of filter performance.

2. Background

The filtration performance of a granular bed filter is expressed as the particle collection efficiency, η, which is the weight ratio of the dust removed by the filter to the dust entering the filter [16]:

$$\eta(\%) = (1 - C_{out} / C_{in}) \times 100 \quad (1)$$

where C_{in} is the concentration of dust entering the filter, and C_{out} is the concentration of dust exiting the filter.

Dust filtration involves several mechanisms including inertial impaction, interception, diffusion, straining, sedimentation, and electrostatic force [16]. Inertial impaction is considered to be the main filtration mechanism for the present application, which involves collecting dust particles smaller than 50 μm on granular particles larger than 1 mm. The effect of inertial impaction is characterized by the dimensionless Stokes number, St [16]:

$$St = 2\rho_p R_p^2 \, U C_s / 9\mu R_g \quad (2)$$

where ρ_p is particle density, R_p is particle radius, U is superficial velocity, C_s is the Cunningham factor for molecular slip, μ is gas viscosity, and R_g is the radius of granules.

The moving bed granular filter has several operating factors that contribute to its collection efficiency including superficial velocity, granular flow rate, dust feed rate, properties of gas and dust, and granule types and size [4]. This study focuses on the effect of granular flow rate because it is the easiest parameter to control in industrial practice and yet the literature is unclear on its impact. Soo [6] reported filtration efficiency to increase with increasing granular flow rates while Kalinowski [13] and Otani [14] reported just the opposite effect. Adding to the confusion, a study by Yang et al. [15] showed little effect of granular flow rate on filtration efficiency. This study attempts to resolve these contradictory reports as well as contribute to the understanding of mechanisms by which moving granular beds operate.

3. Experimental procedure

3.1. Materials used

Particulate matter simulating char dust in the gas effluent of a fast pyrolysis system is prepared from char obtained from the cyclone catch of a fast pyrolysis reactor operating with switchgrass as feedstock [17]. Very likely a MBGF will be used downstream of cyclone separators, with the result that it will be challenged with dust that is in the size range of 1–50 μm [18]. The cyclone catch, having a particle size range of 5–600 μm, required size reduction to simulate the char dust exiting the gas cyclones of a fast pyrolysis reactor. Size reduction is accomplished by screening the cyclone catch to particles finer than 300 μm and ball milling these to the desired size range. A Malvern 2000MU particle size analyzer is used to measure the final particle size distribution of the char dust as shown in Fig. 2.

The granular material used in this research is water filtration gravel obtained from Red Flint LLC. The smooth gravel has a rectangular equivalent size of 3.2 mm by 1.6 mm, which is the smallest size in the gravel classification. This granular size was previously shown to obtain high filtration efficiency [10,11].