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Continuous, dynamic and steady state simulation of the reflux classifier using a segregation-dispersion model

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ABSTRACT

A 2D continuous segregation-dispersion model incorporating a laminar- shear separation mechanism has been developed to describe the Reflux Classifier (RC). The RC, which consists of a fluidization zone, and a system of closely-spaced inclined channels, is now widely used to achieve gravity separation of a broad range of commodities. The narrow inclined channels promote the laminar-shear mechanism, leading to the selective shear-induced lift of low density particles, while allowing the fine and denser particles to deposit onto the inclined surfaces, and slide downwards. This mechanism allows a sharp density-based separation. The simulation results of this study have been validated using previously published experimental data. A total of 42 particle species were used in the simulations, corresponding to 6 different sizes and 7 different densities for each particle size, covering the particle size range of −2.0 + 0.125 mm. Simulation partition curves showed good agreement with the published experimental data, including the D_{50} and E_p values over the particle size range −2.0 + 0.25 mm. The model has also been tested to investigate the effect of high solid throughputs on the separation performance in the RC. The predictions of the fractional and cumulative ash % of the product and reject streams have been compared with the published experimental results demonstrating a good agreement and thus, the robustness of the model.

1. Introduction

Increased interest in achieving an improved beneficiation of coal and minerals has led to the adoption of new technologies such as the Reflux Classifier (RC). The mechanisms governing the RC were first investigated by Galvin and co-workers (Galvin et al., 2002; Doroodchi et al., 2004, 2006; Laskovski et al., 2006). The Reflux Classifier (RC) consists of a liquid fluidized bed with a set of parallel inclined channels located above the fluidization section (Laskovski et al., 2006), as shown in Fig. 1. The separation of particles within the fluidization section of the RC is similar to that achieved by liquid fluidized beds, governed by hindered settling, and the so-called phase inversion mechanism (Moritomi et al., 1982). Whereas, the inclined channels, which produce the Boycott Effect (Boycott, 1920; Galvin et al., 2002), provide a large effective settling area. Within the inclined channels of the RC, the denser particle species settle onto the upward facing surfaces of the inclined channels, and slide downwards towards the fluidization section, while, the lower density particle species convey along the inclined channels, reporting as overflow (Galvin et al., 2002; Amariei et al., 2014; Tripathy et al., 2015).

Prior to 2009, the inclined channel spacing varied considerably, with values of 60 mm and 120 mm in different systems, and later narrower channels of 25 mm were used. A significant breakthrough was then achieved in 2009 through the introduction of closely spaced inclined channels (Galvin et al., 2009, 2010), with the channel spacing finally set at 6 mm. For coal, over the size range of −2.0 + 0.25 mm, the overall Ecart probable, or separation error, Ep, decreased from 0.15 for the wider inclined channels (Galvin et al., 2002, 2005) down to about 0.06 for the closely spaced inclined channels in experiments (Galvin et al., 2010). The introduction of the closely spaced inclined channels led to the laminar-shear separation mechanism, and to the selective shear induced lift of coarse low density particles (Galvin et al., 2009, 2010; Galvin and Liu, 2011). This phenomenon allows fine dense particles to settle on the inclined surfaces. Therefore, the overflow mainly consists of fine and coarse particles of low density. The accumulation of the fine, denser particles in the fluidization section of the RC promotes an autogenous dense media to form, promoting the phase inversion mechanism, and hence upwards displacement of the larger and lower density particles from the lower fluidization zone. Widespread adoption of the RC followed from the introduction of the laminar shear mechanism, with improved performance in both fine coal and fine iron ore beneficiation (Galvin et al., 2010; Amariei et al., 2014).

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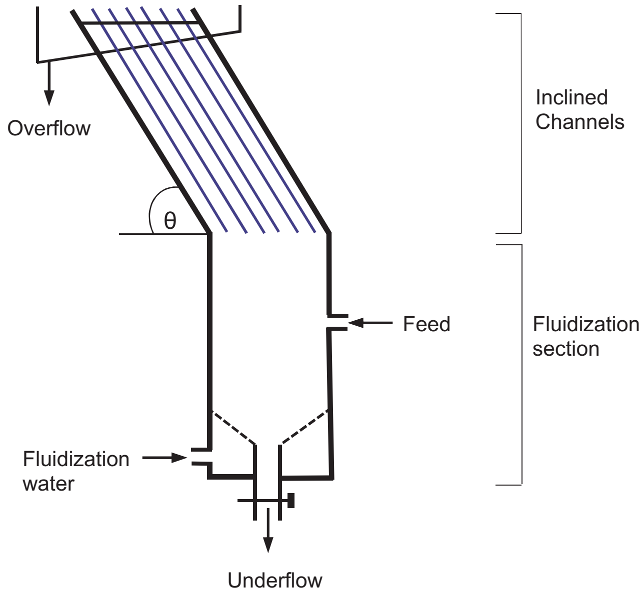

Fig. 1. Schematic diagram of the RC, comprising of a fluidization section and an inclined section.

The sedimentation and segregation of particle species of a multi-component system in different sections of the RC for a continuous process has not been studied theoretically in detail. Whereas, in the liquid fluidized beds considerable experimental and theoretical research has been undertaken on single, binary and multicomponent systems. This research has led to descriptions of the segregation, dispersion, mixing, layer inversion and sedimentation phenomena (Pruden and Epstein, 1964; Kennedy and Bretton, 1966; Moritomi et al., 1982; Van Duijn and Rietema, 1982; Asif and Petersen, 1993; Di Felice, 1995; Asif, 1997, 1998; Chen et al., 2002; Rasul et al., 2002; Asif, 2004; Ramirez and Galvin, 2005; Galvin et al., 2006; Patel et al., 2008).

Kennedy and Bretton (1966) proposed for the first time a segregation-dispersion model to study the dispersion in liquid fluidized beds under batch conditions (Asif and Petersen, 1993, Asif, 1997, Ramirez and Galvin, 2005). The model accurately predicted the movement and separation of particle species observed in experiments, showing that larger particles settle towards the bottom of the bed while smaller particles move towards the top of the bed (Kennedy and Bretton, 1966; Asif, 1998). According to the authors (Kennedy and Bretton, 1966), the transport of solid particles was the result of the combination of dispersion and segregation processes. The Kennedy and Bretton (1966) approach has been used as the basis of most of the models developed after this for liquid fluidized beds (Juma and Richardson, 1983; Asif and Petersen, 1993, Asif, 1997, Ramirez and Galvin, 2005; Galvin et al., 2006; Patel et al., 2008).

This paper is concerned with developing a model of the RC for a continuous process based upon the principles of segregation and dispersion in liquid fluidized beds (Kennedy and Bretton, 1966), coupled with an appropriate hindered settling model that provides at least some account of phase inversion. The model also incorporates the mechanism of shear induced lift to simulate the resuspension of particle species within the inclined channels of the RC.

2. Segregation-Dispersion model

2.1. Theoretical development

The segregation-dispersion model used to simulate the RC is based upon the Kennedy and Bretton (1966) approach. Accordingly, the movement of the particle species within the RC is based upon the fact that the particle species possess a net particle flux, J_i, relative to the vessel at a specific height within the vessel. The net flux of a particle species relative to the vessel comprises dispersion and segregation fluxes (Kennedy and Bretton, 1966; Juma and Richardson, 1983; Ramirez and Galvin, 2005; Patel et al., 2008). The mathematical expression of this flux balance is given as,

$$J_i = \phi_i \nu_{p,i} = -D_{p,i}\frac{\partial \phi_i}{\partial y} + \phi_i \nu_{seg,i} \tag{1}$$

where the subscript i refers to single particle species having a specific size and density, $\nu_{p,i}$ is the velocity of a particle species relative to the vessel, $D_{p,i}$ the dispersion coefficient, $\nu_{seg,i}$ the segregation velocity and ϕ_i the volume fraction of the particle species. The terms $\frac{\partial \phi_i}{\partial y}$, $-D_{p,i}\frac{\partial \phi_i}{\partial y}$ and $\phi_i \nu_{seg,i}$ represent the local concentration gradient, the dispersion flux and the segregation flux of the particle species i, respectively.

In a continuous process, the total volume flux, ν_N, through the system depends upon the zones below and above the feed points. Therefore, at the feed point and above, the total volume flux is given as,

$$\nu_N = \nu_{fs} + J_f - J_u = \nu_f \phi_f + \sum \phi_i \nu_{p,i} \tag{2}$$

and below the feed point the total volume flux is expressed as,

$$\nu_{fs} - J_u = \nu_f \phi_f + \sum \phi_i \nu_{p,i} \tag{3}$$

where J_f is the total volumetric feed flux, J_u is the underflow flux, ν_{fs} the fluidization flux, ν_f the interstitial fluid velocity and ϕ_f the volume fraction of liquid or the voidage.

In the RC, due to the inclination of the channel, the amount of material circulating through the system is expected to depend on the horizontal coordinate, hence a 2D model was developed. The x-component is taken as the component normal to the inclined surfaces and y-component is taken as the tangential component, as schematically shown in Fig. 2.

Now, the net fluxes of particle species relative to the vessel in the x

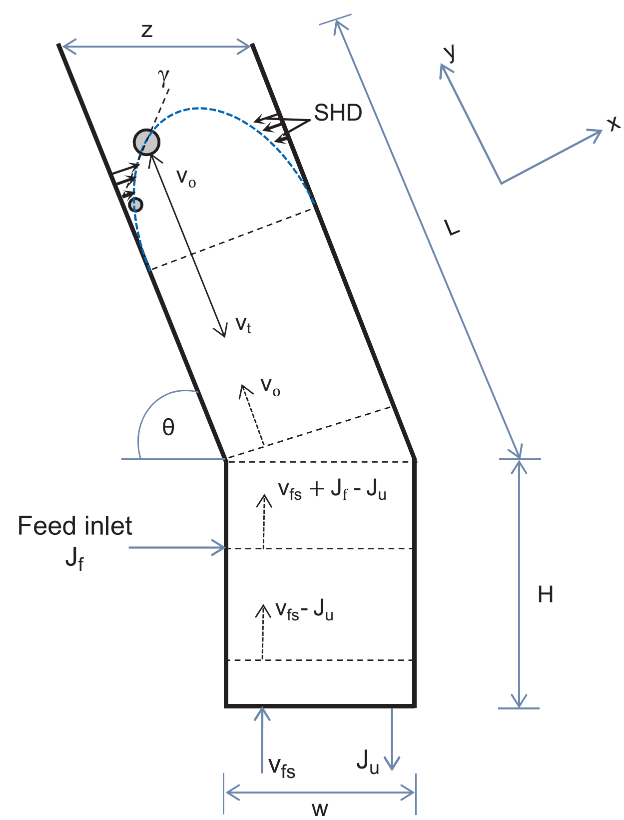

Fig. 2. Schematic diagram of the computational domain showing flux movement and parabolic profile of the liquid into the system.