Powder Technology 305 (2017) 340–346

Contents lists available at ScienceDirect

Powder Technology

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

# Elutriation of fines from binary particle mixtures in bubbling fluidized bed cold model

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ARTICLE INFO

*Article history:*
Received 28 March 2016
Received in revised form 1 July 2016
Accepted 22 September 2016
Available online 26 September 2016

*Keywords:*
Elutriation
Binary mixture, bimodal distribution

ABSTRACT

The elutriation of fine particles from a binary mixture of particles with different densities and diameters has been investigated in bubbling fluidized bed (BFB). A series of experiments were conducted in a 10 cm diameter, 170 cm tall cylindrical bubbling fluidized bed under various operating conditions. Bed materials with different particle sizes, ranging from 93 μm to 1000 μm powder, and particle densities ranging from 7.9 to 2.45 g/cm$^3$ were used in these experiments. Various combinations of these solids were mixed and fluidized at several superficial gas velocities. Solid elutriation was measured by collecting the carryover solids exiting the column with a filter. Experimental data on the effects of particle density, particle size, and gas velocity on the elutriation of particles from bubbling fluidized bed of binary mixture are examined. Influence of weight fraction of fines in the binary mixture on coarse particles was also investigated and discussed. The results indicated that the elutriation rate constant increases with increasing superficial gas velocities and weight fraction of fines in the bed. A generalized correlation for the elutriation rate constant is proposed using the ratio of $U_g/U_t$, weight fraction of fines, and fines to coarse particle density ratio.

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## 1. Introduction

The United States Department of Energy (US DOE) has set a goal to modify the existing pulverized coal-fired (PC) power plants to remove over 90% of the total carbon in the coal as $CO_2$ for use or sequestration [1]. Chemical looping combustion (CLC) is a novel technology, which has the potential to significantly reduce the energy penalty associated with carbon capture. The CLC process produces a binary mixture of $CO_2$ and $H_2O$ in the flue gas where the $CO_2$ can be separated simply by condensing the $H_2O$, similar to an oxy-fuel process. The unique characteristic of the CLC process is the use of a solid “oxygen carrier” to transport oxygen from the air to a separate fuel reactor, thus eliminating the contact between air and fuel streams [2].

Interest in chemical looping combustion (CLC) technologies has grown significantly over the last five to ten years (Lyngfelt et al. [3]; Fan [4]; Hossain and de Lasa [5]). In recent years, extensive research has been conducted on CLC of gaseous fuels. However, CLC of solid fuels is a quickly-growing area of research, particularly in the area of future clean coal power generation systems. However, direct coal CLC is a relatively novel approach that presents new research issues such as removal of ash byproducts from the CLC process.

The fuel reactor typically contains a mixture of coal, char, ash, and the oxygen carrier. The oxygen carriers typically considered are metal oxides such as $Fe_2O_3$, CuO or a mixture. The ash and char present in CLC is typically smaller and lighter than metal oxide bases oxygen carriers. Although the impact of ash on the oxygen carrier reaction kinetics is minimal (Siriwardane et al. [6]; Rubel et al. [7]), the design and operation of chemical looping combustion requires the control of ash accumulation. More importantly, char cannot enter the air reactor. If it does, the carbon will not be captured.

One approach is to drain both the carrier and the ash from the system continuously. However this requires continuous feed of fresh oxygen carrier into the system resulting in a significant operational cost. The approach investigated in this paper involves direct separation of the ash and carrier from a bubbling fluidized bed using the different aerodynamic characteristics of both particles. The benefits of an aerodynamic based solid-solid separation process include: reducing the requirement for fresh oxygen carrier make-up, reducing solid waste streams, and reducing operating costs for carrier make-up.

The optimal design of solid-solid separation and technical and economic success of chemical looping combustion requires good predictive capability of the estimation of fines hold-up in the bed and the elutriation rate of fines from the bed. Although extensive investigation on elutriation rate have been made by many researchers [8–15], nearly all of the published correlations proposed relate mainly to larger particle systems, and they do not adequately predict the elutriation of very fine particles. Furthermore, almost none of them are applicable to the multi-particle system of different densities with mixing patterns that related to particle concentration.

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http://dx.doi.org/10.1016/j.powtec.2016.09.046
0032-5910/Published by Elsevier B.V.

Recently, Chew et al. [16] reviewed a significant number of entrainment correlations in gas-solid fluidization from the literature. They have listed about 28 equations to predict the elutriation rate constant by different authors. It was concluded that the discrepancies in predicting elutriation rate constant are up to 20 orders of magnitude. Therefore, the review suggests the need for more physical understanding of the dominating factors affecting entrainment. The correlations reviewed by Chew et al. are for the elutriation of fines from a bed consisting of a single material, i.e. a single density. That is to say, they do not cover the elutriation of fines from a low density solid from a bed of high density coarse material as is the case in chemical looping combustion system applications. This being said, there is significantly paucity in the literature for binary (poly-density) data and the specific influence of density differences on elutriations rate.

In the literature reviewed by Chew et al., the elutriation rate constant are usually expressed by operating conditions and the driving force is proportional to the difference between gas velocity and terminal velocity ($U_g - U_t$) of the particle. Other relevant research in this field such as Geldart et al. [17] found that the elutriation rate increases sharply with the gas velocity close to the terminal velocity. Note that elutriation occurs at velocities less than the terminal velocity in this work by Geldart et al. Therefore, it is clear that the elutriation rate needs to be defined such that the resulting correlation covers that observation and the use of $U_g - U_t$ provides a negative value for these conditions ($U_g < U_t$).

Liu and Kimura [18] observed the fine particles controlled the elutriation of mixtures of fine and coarse particles. Geldart and Pope [19] reported that the existence of fine particles promotes the elutriation of coarse particles from a fluidized bed with mixture of fine and coarse particles. Li et al. [20] report the elutriation rate constant of group C and group A particles to be dependent on the weight fraction of the group C particles in the bed. They stated that an increased in fraction of superfine decreases the elutriation rate of the fines due to increase of interparticle adhesion. Geldart et al. [21] reported that the addition of a small quantity of Geldart-C particles caused a decrease in elutriation due to fines adhering to the large particles.

Cocco et al. [22] suggesting that the particle cluster in fluidized bed has a great influence on the elutriation rate of fine particles. In that work, Cocco et al. [22] discuss how elutriation is decreased due to the fines forming clusters and act like larger particles such that they fall back into the bed. They tested this by placing baffles near the top of the bed to break up the clusters and discovered that under high shear conditions (high superficial velocities) the elutriation was much higher when the baffles were present.

Smolder and Baeyens [23] investigated the effect of adding a small fraction of fines of different densities to a distribution of Group A powders (noted as E-Cat and zircon). They report that for these conditions, the density of the fines had little effect upon the entrainment rate. Cocco et al. [22] report that the fines density might be a factor. In the present work, Group A fine material is added to a bed of Group B material. Under these conditions, the fines density, or rather the ratio of the fines density to the coarse density clearly effected the elutriation rate.

The objective for this work was to understand elutriation of glass bead fines (a surrogate for fine ash particles generated in coal CLC applications) from a bed of larger denser material (steel shot, ilmenite and alumina as surrogates for the oxygen carrier in CLC applications). The goal of this work is to develop a general correlation that could be used to predict the elutriation rate of low density fine particles in a bubbling fluidized bed of larger dense particles, as well as to investigate the effect of fine fraction on elutriation rate.

## 2. Experimental

The experimental apparatus used in this work is shown in Fig. 1. The fluidized bed is 10 cm in diameter and 170 cm tall and constructed with a clear acrylic pipe. The 10 cm column used in this study is larger than 44% of the reported investigations in the review paper by Chew et al.

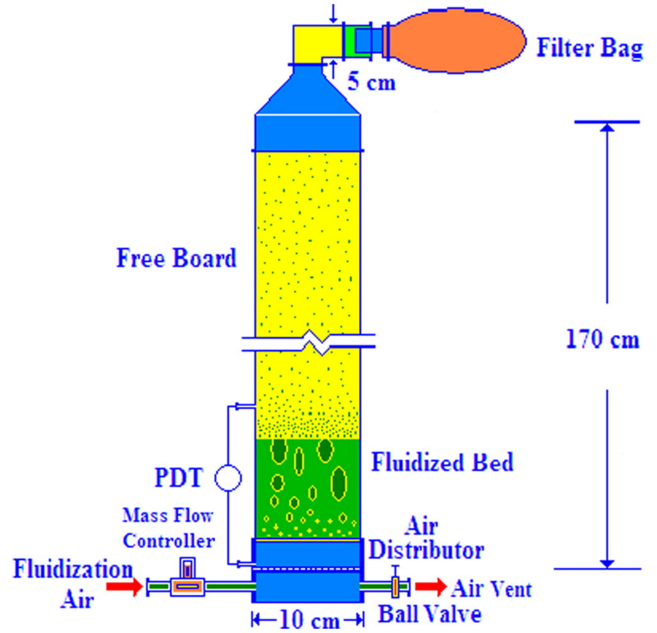


**Fig. 1.** Schematic diagram for the 10 cm diameter bubbling fluidized bed.

[16]. Additionally, it is comparable with two of the investigations in that review such that the 10 cm column used in this study is larger or comparable in size with >50% of the work discussed in the review. Furthermore, Chew et al. [16] did not report finding a systematic trend in the elutriation predictions that would be indicative of a small diameter bias.

The fines exit the bed through a 5 cm ID port at 90° at the top of the bed where a micro-sized fabric filter bag is attached and captures the fine particles being elutriated. Compressed air is used as the fluidizing gas which is controlled by a mass flow controller. A perforated plate with 25 symmetrical orifices, 1.59 mm in diameter, was used as the gas distributor. A U.S. No. 325 mesh sized (44 μm) stainless steel screen was placed at the bottom of the gas distributor to prevent material in the fluidizing bed from escaping into the plenum chamber. Experiments were performed by closing the air vent valve connected to an opening in the plenum chamber, thus directing the flow through the gas distributor and into the fluidized bed. The experiment would run for the allocated sampling time and then the air vent valve would be opened, releasing the air flow directed to the bed into the atmosphere. The filter bag was weighed after each test run to determine the weight of the material collected, as compared to the empty bag before use. The elutriated fine and coarse particles were separated by a U.S. sized 200 mesh (74 μm) sieve. Once separated, the fine and coarse particles were weighed separately to determine the mass percentages of the material that had been elutriated during the experiment. The amount of material captured in-between runs was recorded and then returned to the bed in order to

**Table 1**
Physical properties of tested materials where SMD is the sauter mean diameter.

| Material | Size range (μm) | | | | Sphericity (−) | Density (kg/m³) | $U_t$ (m/s) | |
|---|---|---|---|---|---|---|---|---|
| | Max | Avg | Min | SMD[a] | | | Largest | Smallest |
| Steel shot | 360 | 200 | 105 | 194.39 | 0.923 | 7890 | X | 1.78 |
| Ilmenite | 250 | 155 | 105 | 151.24 | 0.902 | 4457 | X | 1.24 |
| $Al_2O_3$ (small) | 500 | 309 | 149 | 293.97 | 0.821 | 3968 | X | 1.6 |
| $Al_2O_3$ (large) | 1000 | 613 | 300 | 550.56 | 0.820 | 3968 | X | 3.18 |
| Glass beads | 123 | 93 | 37 | 75.3 | 0.912 | 2464 | 0.39 | X |

[a] Sauter mean diameter.