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Numerical simulations of lateral solid mixing in gas-fluidized beds

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HIGHLIGHTS

- We model lateral solid mixing in fluidized beds using the Eulerian modeling approach.
- We quantify mixing by means of a lateral dispersion coefficient.
- We investigate how design parameters and operational conditions affect the coefficient.
- We examine the influence of frictional stress models on the numerical results.

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ABSTRACT

We investigated the influence of design parameters and operational conditions on lateral solid mixing in fluidized beds adopting the Eulerian-Eulerian modeling approach. To quantify the rate at which solids mix laterally, we used a lateral dispersion coefficient (D_{sr}). Following the usual approach employed in the literature, we defined D_{sr} by means of an equation analogous to Fick's law of diffusion. To estimate D_{sr}, we fitted the void-free solid volume fraction radial profiles obtained numerically with those obtained analytically by solving Fick's law. The profiles match very well. Our results show that D_{sr} increases as superficial gas velocity and bed height increase; furthermore, it initially increases with bed width, but then remains approximately constant. The values of D_{sr} obtained numerically are larger than the experimental ones, within the same order of magnitude. The overestimation has a twofold explanation. On one side, it reflects the different dimensionality of simulations (2D) as compared with real fluidized beds (3D), which affects the degrees of freedom of particle lateral motion. On the other, it is related to the way frictional solid stress was modeled: we employed the kinetic theory of granular flow model for the frictional solid pressure and the model of Schaeffer (1987) for the frictional solid viscosity. To investigate how sensitive the numerical results are on the constitutive model adopted for the frictional stress, we ran the simulations again using different frictional models and changing the solid volume fraction at which the bed is assumed to enter the frictional flow regime (ϕ_{min}). We observed that D_{sr} is quite sensitive to the latter. This is because this threshold value influences the size and behavior of the bubbles in the bed. We obtained the best predictions for $\phi_{min} = 0.50$. The results show that accurate prediction of lateral solid dispersion depends on adequate understanding of the frictional flow regime, and accurate modeling of the frictional stress which characterizes it.

1. Introduction

Fluidization is an operation in which a bed of granular material is made to behave like a fluid. This occurs when there is an upward flow of fluid through the granular material that makes the drag force exerted on it counterbalance its effective weight. This operation has been a winning technology, having applications in many industrial processes, such as coal combustion, biomass gasification, waste to energy conversion, sulfide roasting and food processing. Many of these processes rely on intense mixing in the fluidized bed, which creates intimate contact between the fluid and solid phases, intensifying heat and mass transfer.

To design and operate large-scale fluidized beds safely and efficiently, one needs to achieve good solid mixing in both lateral (horizontal) and axial (vertical) directions. For instance, one sees the importance of lateral solid mixing in fluidized bed combustors; in the latter, the rate at which solid fuel mixes laterally strongly influences the plant performance, affecting combustion efficiency, allocation of heat release and formation of emissions (Gómez-Barea and Leckner, 2010). It is therefore crucial to ensure that fuel

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spread homogeneously and rapidly over the whole cross-section of the bed. One way of achieving this is to feed the fuel at multiple entry points with the aid of a spreader; however, each added feed point increases the installation costs, and consequently one should aim to minimize their number. The knowledge of how fuel mixes laterally in a combustor is also crucial for minimizing excess air; the latter causes energy loss in the system and thus increases cost. Therefore, knowing how fuel mixes laterally is essential for improving the design of fluidized bed combustors. Efficient operation of the latter, naturally, also depends on how well mixing is achieved vertically.

To quantify the rate at which solids mix in fluidized beds, researchers often resort to axial and lateral dispersion coefficients; these, as we shall see in this study, are *effective* diffusivities relating to the times that solids take to spread axially and laterally over a given distance in the bed. Recently, researchers have made considerable efforts to analyze lateral dispersion coefficients more closely; this is because earlier studies (May 1956; Lewis et al., 1962; Avidan and Yerushalmi, 1985) concentrated mainly on axial dispersion. Notwithstanding, lateral dispersion is essential in the design and operation of large-scale beds, the coefficient quantifying it being a key input parameter in many models for fluidized bed reactors.

Despite the importance of lateral solid mixing, there is a dearth of research on this subject, the available works focusing mainly on the experimental methods of estimating lateral dispersion coefficients. Kashyap and Gidaspow (2011) summarized these methods as *saline* (Rhodes et al., 1991), *ferromagnetic* (Avidan and Yerushalmi, 1985), *thermal* (Borodulya and Epanov, 1982), *radioactive* (Mostoufi and Chaouki, 2001), *carbon* (Winaya et al., 2007) and *phosphorescent* (Du et al., 2002) tracing methods. These experimental approaches have their limitations: in thermal tracking techniques heat is transferred to the fluid phase and walls, making it difficult to interpret the results; in radioactive tracking methods safety of equipment and personnel are of great concern; in phosphorescence tracking methods most successful applications usually take place in dilute fluidized beds. For all solid tracer techniques, the common limitation is that repeatable results are only guaranteed if numerous runs of experiments are carried out, a condition that may not be practicable in real experiments. In addition, experiments with solid tracers are difficult to perform because of lack of continuous sampling and presence of residual tracer. Despite these experimental investigations, the understanding of how design parameters and operating conditions affect lateral dispersion coefficients is still limited, because the mechanisms governing solid mixing are complex.

In recent times, computational fluid dynamics (CFD) simulation provides a powerful tool, complementary to experiments, to investigate the dynamics of fluidized beds (Gidaspow, 1994; Mazzei and Lettieri, 2008, Mazzei et al., 2010; Mazzei, 2011, 2013). The model equations are based on first principles: the balance equation for mass, momentum and energy. Two modeling approaches are usually adopted: the Eulerian-Eulerian and the Eulerian-Lagrangian (Lettieri and Mazzei, 2009). In the former, averaged equations describe the fluid and the solid as interpenetrating continua. In the latter, conversely, one tracks the motion of each particle and solves the average equations of motion only for the continuous phase. The first approach offers the advantage of being relatively less computationally demanding, providing information of direct interest in applications (for example, average velocity fields and volume fractions). The other approach is useful in providing enormous details of the fluid bed dynamics, and is an approach of choice for researchers who are interested in gaining deeper insight into the dynamics of granular media. The CFD modeling approach has proven to be effective in studying the dynamics of fluidized beds (Coroneo et al., 2011; Tagliaferri et al., 2013), offering distinct advantages: an accurate CFD model can considerably aid in the design of the bed, saves time and improves the confidence of plant scale-up.

Despite these advantages, studies on lateral solid dispersion in fluidized beds using numerical approaches are still scanty. This has hindered the advancement of knowledge on how various design parameters and operating conditions affect fluid bed processes. To the best of our knowledge, numerical works on lateral solid dispersion in fluidized beds have only been carried out by Liu and Chen (2010) and Farzaneh et al., (2011). Liu and Chen (2010) employed the Eulerian-Eulerian approach to estimate the lateral dispersion coefficients using a micro and a macro method. The latter fits the transient particle concentration profile obtained numerically with the solution of a Fickian-type diffusion equation, while the former generates statistics of particles by using a random walk approach. Farzaneh et al., (2011), on the other hand, adopted a multi-grid Eulerian-Lagrangian approach.

In this work, we aimed to use and test a Eulerian-Eulerian model that one could employ to estimate lateral solid dispersion coefficients (we did not intend, nevertheless, to derive a numerical correlation for them). The model describes both solid and fluid phases as interpenetrating continua. It consists of the continuity equations and linear momentum balance equations written for each phase. These equations are valid for any physical and chemical system, and therefore this approach does not introduce any assumption in the model, except for the constitutive equations needed to render the equations mathematically closed. We follow an approach similar to that proposed by Brotz (1956). He used two solids of equal physical properties, but differing in color. The solids were separated by a vertical partition plate which divided the bed into two equal parts. He fluidized the bed for a certain time and then removed the partition; by measuring the rate at which the two solids mix, he estimated the lateral dispersion coefficient. With Brotz, we defined two solid phases, Solid-1 and Solid-2, with equal physical properties, differing only in the names assigned to them in the computational code. We then placed Solid-1 on the left and Solid-2 on the right of a removable partition. We fluidized the bed with air at ambient temperature, allowing it to reach pseudo-stationary conditions, and then removed the partition. From the radial concentration of the Solid-1 phase, we estimated the lateral solid dispersion coefficient at the assigned operating conditions. Before advancing further, let us briefly discuss how D_{sr} is defined in this work.

2. Lateral dispersion coefficient – definition and estimation

Sometimes one might be interested in *estimating* how fast particles mix in a fluid bed at given operating conditions, without wanting to solve complex and numerically expensive models. One way of doing this is resorting to axial and lateral *dispersion coefficients*; these, as said, are *effective* diffusivities relating to the time that solids take to spread axially and laterally over a given distance in the bed. We are going to focus on the lateral dispersion coefficient; therefore, before going any further, let us clarify how the latter is defined. Most researchers (Brotz, 1956; Borodulya and Epanov, 1982; Shi and Fan, 1984; Liu and Chen, 2010) define it through an equation analogous to Fick's law of molecular diffusion, writing:

$$\partial_t C = D_{sr} \partial^2_{xx} C \qquad (1)$$

where C represents the void-free solids concentration and D_{sr} represents the lateral dispersion coefficient. This equation, as just said, should be regarded as a *definition* of such coefficient. Let us briefly comment on the applicability of Eq. (1) to the present investigation. One might wonder how the diffusion equation above