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Numerical analysis of particle mixing in a rotating fluidized bed

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Abstract

This paper describes the numerical analysis of particle mixing in a rotating fluidized bed (RFB). A two-dimensional discrete element method (DEM) and computational fluid dynamics (CFD) coupling model were proposed to analyze the radial particle mixing in the RFB. Spherical polyethylene particles (Geldart group B particles) were used as model particles under the assumptions that they were cohesionless and monodisperse with their diameter of 0.5 mm.

The validity of the proposed model was confirmed by the comparison between the calculated degree of particle mixing and the experimental one, which was obtained by measuring the lightness of the recorded image taken by a high-speed video camera. Effects of the operating parameters (gas velocity, centrifugal acceleration, particle bed height, and vessel radius) on the radial particle mixing rate were numerically analyzed. The radial particle mixing rate was found to be strongly affected by the bubble characteristics, especially by the bubble size. The mathematical model for the rate coefficient of particle mixing as functions of operating parameters was empirically proposed. The radial particle mixing rate in a RFB could be well correlated by the three dimensionless numbers: dimensionless acceleration (Ac), bubble Froude number (Fr_b), and dimensionless radius on the surface of particle bed (β_s).

Keywords: Fluidization; Rotating fluidized bed; Particle; Mixing; Numerical analysis; Discrete element method

1. Introduction

Fluidized bed has been widely used in many industries because of its desirable characteristics such as high heat and mass transfer rates, temperature homogeneity, easy handling, and rapid mixing of particulate materials. However, in the conventional fluidized bed, it is difficult to operate at high gas velocity since the gas–solid contact becomes rather poor due to the large bubbles and slugs. It is also difficult to uniformly fluidize fine particles such as Geldart group-C particles (Geldart, 1973) due to channeling, lifting as a plug, and forming 'rat holes'.

Recently, a rotating fluidized bed (RFB) has gathered a special interest since it has the high potential to overcome the conventional limitations; RFB can fluidize particles in a high centrifugal force field, and it has many advantages that: (1) it can prevent the growth of large bubbles at relatively high gas velocities by controlling the vessel rotational speed, improved the gas–solid contact and reaction efficiency in over range of gas velocity (Nakamura and Watano, 2006); (2) it can fluidize fine particles, since it imparts high centrifugal force and drag force to particles, which are larger than the cohesive forces between them (Qian et al., 2001).

Due to the advantages, RFB has been expected to be used as advanced industrial processes, such as reactor of rocket propulsion in a micro-gravity field (Ludewig et al., 1974), the high efficiency dust filter (Pfeffer et al., 1986), removal of NO_x and soot from diesel engine exhaust gas (Tsutsumi et al., 1996), incineration of wool scouring sludges (Wong et al., 2000), granulation and coating of fine particles (Watano et al., 2003, 2004), and handling of nano-particles (Matsuda et al., 2001; Quevedo et al., 2006). In spite of many published studies, a reliable RFB process has not been established yet, because the fluidization behavior of a RFB is very complicated and its mechanism has not been well studied yet. In order to conduct better design and control of RFB, it is very important to analyze the fundamental fluidization mechanisms.

One of the attractive features of fluidized bed is a favorable particle mixing property that allows temperature homogeneity

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and high heat and mass transfer. So far, fundamental mechanism of particle mixing in a conventional fluidized bed has been well studied (e.g. Kunii and Levenspiel, 1991). Modeling of particle mixing, which was based on the bubble characteristics, has also been well conducted, since the bubble motion caused primary particle mixing in fluidized bed (Hirama et al., 1975; Lim et al., 1993). On the contrary, there are few reports of particle mixing in a RFB. Only Kroger et al. (1980) and Qian et al. (1999) investigated particle mixing behavior in a RFB. However, they only reported the effect of gas velocity on the particle mixing, and never mentioned the effect of other operating parameters. One of the reasons for few published studies is that experimental analysis is not easy in a RFB. In such a case, numerical simulation can be a powerful tool for analyzing the fundamental fluidization mechanisms. Zhu et al. (2003) reported the numerical simulation of gas flow patterns in a RFB without particles by using a computational fluid dynamics (CFD). Ahmadzadeh et al. (2003) also studied gas and particle flow in a RFB based on a two-fluid model approach. However, numerical simulation and analysis of particle mixing in a RFB have not been reported.

A discrete element method (DEM) is one of the most useful numerical analysis methods for analyzing particle mixing, since it can track individual particle motion. So far, many researchers have reported particle mixing in various particulate processes: e.g. rotary vessel mixer (Muguruma et al., 1997), tumbling blender (V-blender) (Moakher et al., 2000), and so on. In gas–solid flow systems, an incorporation model of DEM with CFD has been widely used, and it has been well known as DEM–CFD coupling model (e.g. Tsuji et al., 1993; Xu and Yu, 1997). By using this method, particle mixing in a gas–solid fluidized bed has been studied (Kaneko et al., 1999; Rhodes et al., 2001; Feng et al., 2004).

In this paper, particle mixing in a RFB with a horizontal rotational axis was numerically analyzed by using our proposed DEM–CFD coupling model for RFB (Nakamura and Watano, 2007). We here investigated the radial particle mixing rate, and the effects of operating parameters such as gas velocity, centrifugal acceleration, vessel radius, and particle bed height on the radial particle mixing rate were numerically analyzed.

2. Rotating fluidized bed (RFB)

Fig. 1 shows a schematic diagram of RFB. The RFB system has unique fluidization concept. The system consists of a cylindrical plenum chamber and a porous cylindrical gas distributor rotating around its axis of symmetry inside the fixed plenum chamber. Due to the gas distributor's rotational motion, particles are forced to move toward the rotating gas distributor by the centrifugal force, forming annular bed near to the rotating gas distributor. Air flows inward through the air distributor, and particles are balanced by drag and centrifugal forces leading to uniform fluidization in a high centrifugal force field. In this study, the dimensionless centrifugal acceleration, G_0, which corresponds to the ratio of the centrifugal acceleration on the surface of rotating gas distributor to the gravitational acceleration g, is defined as the intensity of centrifugal acceleration. It can be expressed as follows:

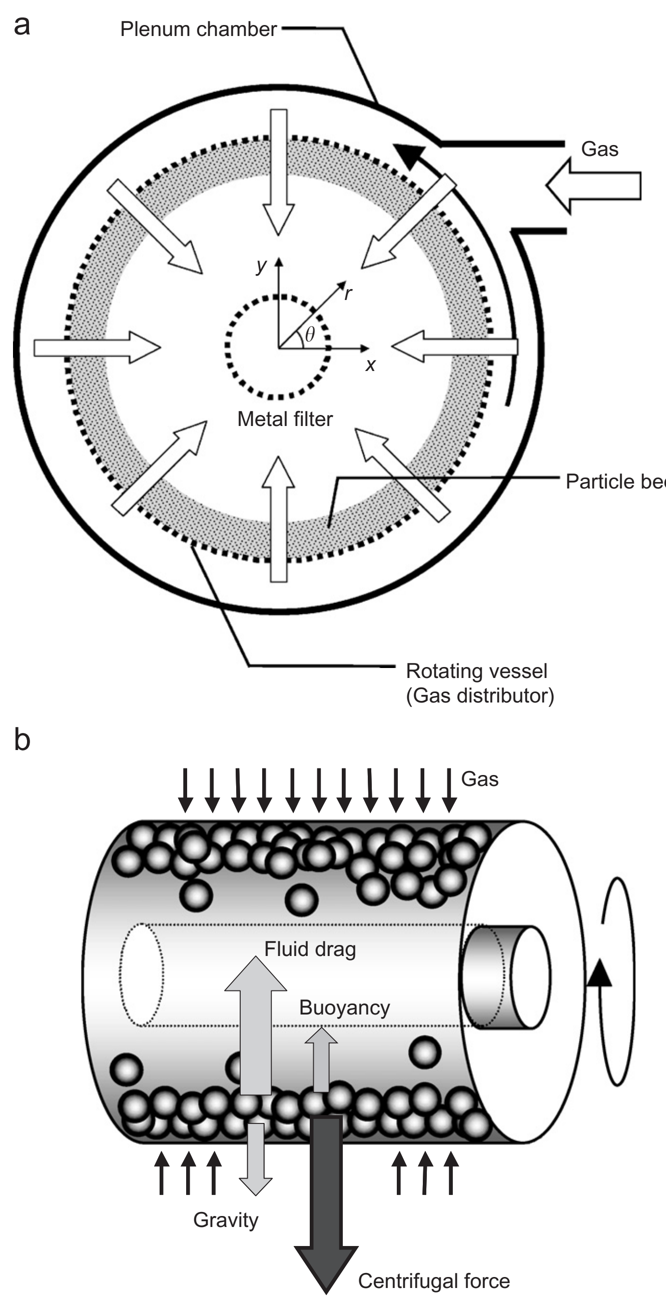

Fig. 1. Rotating fluidized bed (RFB) system: (a) front view and (b) over view.

$$G_0 = \frac{R_V \omega^2}{g}, \tag{1}$$

where R_V and ω are radius and angular velocity of rotating vessel, respectively.

3. Numerical analysis

3.1. DEM–CFD coupling model

The fluidization behavior in a RFB was numerically analyzed by using the DEM–CFD coupling model (Nakamura and Watano, 2007). The particle motion was calculated based on