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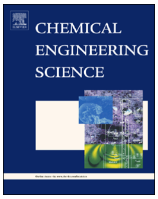


Solids velocity fields in a cold-flow Gas–Solid Vortex Reactor

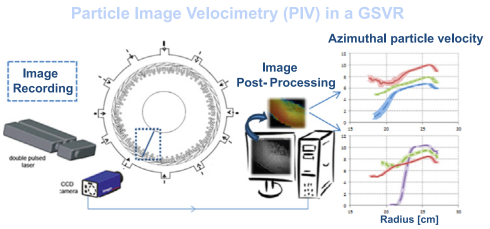
Jelena Z. Kovacevic [a], Maria N. Pantzali [a], Kaustav Niyogi [a], Niels G. Deen [b], Geraldine J. Heynderickx [a,*], Guy B. Marin [a]

[a] *Ghent University, Laboratory for Chemical Technology, Technologiepark 914, B-9052 Gent, Belgium*
[b] *Multiphase Reactors Group, Department of Chemical Engineering and Chemistry, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands*

HIGHLIGHTS

- Velocity fields and velocity profiles in a Vortex Reactor are studied.
- Lower solids density or smaller diameter results in higher particle velocity.
- Higher solids density or smaller particle diameter reduces bubbling.
- A model to calculate particle velocity at the max solids capacity is proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

In a Gas–Solid Vortex Reactor (GSVR), also referred to as a Rotating Fluidized Bed in Static Geometry, a fluidized bed is generated in a centrifugal field by introducing the gas via tangential inlet slots to the reactor chamber. Better heat and mass transfer are observed, making this a promising reactor type for Process Intensification. Developing GSVRs on industrial scale requires, amongst other, a good insight and understanding of the hydrodynamics of the granular flow. In the present work experiments are performed over a wide range of operating conditions in a cold flow pilot-scale set-up. The set-up has a diameter of 0.54 m, a length of 0.1 m and 36 tangential inlet slots of 2 mm. Different materials with solids density between 950–1800 kg/m^3 and particle diameters of 1–2 mm, at varying gas injection velocities from 55 to 110 m/s are tested between minimum and maximum solids capacities. All these operating conditions are used to follow the change of granular flow by performing PIV. The rotating fluidized bed can change from a smoothly rotating, densely fluidized bed to a highly bubbling rotating fluidized bed depending on the operating conditions. Bubbling diminishes with increasing solids density and particle diameter. Experimental measurements of azimuthal particle velocity fields in a GSVR are for the first time reported. Azimuthal solids velocity is found to decrease with higher solids density and larger particle diameter. The critical minimum fluidization velocity, that is the minimum velocity at which the complete bed is fluidized, is calculated and the centrifugal bed behavior is mapped in terms of a dimensionless radial gas velocity and a dimensionless particle diameter, as conventionally done for gravitational beds.

1. Introduction

Fluidization has been a topic of research for more than 60 years and different types of fluidization have been observed in conventional fluidized beds, depending on particle properties, particle diameter, solids density, fluid properties and fluid flow (Kunii and Levenspiel, 1969). Geldart (1973) classified particles in four groups (A, B, C, D) determined by the particle fluidization behavior in the gravitational field which depends on their mean particle size and the density difference between the particles and the fluidizing agent. Taking into account the particle classification by Geldart and the fluid properties

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* Corresponding author: Tel.: +32 9 3311753; fax: +32 9 3311759.
E-mail address: Geraldine.Heynderickx@UGent.be (G.J. Heynderickx).

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and flow rates Grace (1986) constructed a fluidization flow regime map for gravitational fluidization. Fluidized beds operating in a centrifugal field however can offer significant enhancement of heat and mass transfer due to improved gas–solid contact (Kovacevic et al., 2014), resulting in Process Intensification (PI). The concept of a Rotating Fluidized Bed (RFB) was proposed more than 30 years ago (Levy et al., 1979). A centrifugal field was generated by using a motor to make the reactor vessel rotate, while fluidization of the particle bed was realized by radial injection of gas through the side wall of the vessel. Kroger and Levy (1979) studied both packed and fluidized beds in a rotating vessel. In their experiments Kroger et al. (1980) visually observed that Geldart-B and Geldart-D particles give bubbling fluidization in a centrifugal field. Takahashi et al. (1984) and Fan et al. (1985) studied experimentally and analytically the bed pressure drop and minimum fluidization velocity in RFBs. The layer-by-layer fluidization theory developed by Chen (1987) and Kao et al. (1987) was experimentally confirmed by Qian et al. (1999) for Geldart-A particles. With increasing gas injection velocity, the bed is observed to evolve from a packed bed, to a partially fluidized bed and finally to a totally fluidized bed. When the bed is fully fluidized, bubbling behavior is reported by Qian et al. (1999). Shortly afterwards, Qian et al. (2001) showed that particles behave differently in the gravitational and in a centrifugal field. Particles observed to behave like Geldart-A particles in the gravitational field can shift to Geldart-B particle behavior in a centrifugal field. Correspondingly, Geldart-C particles shift to Geldart-A particle behavior. Nakamura and Watano (2007) experimentally and computationally reported that Geldart-B particle fluidization in a centrifugal field is bubbling in nature. Moreover, fluidization regimes in RFBs change from a fixed bed to a partially fluidized bed and to a partially bubbling bed, with increasing gas flow rate. When the gas flow rate is further increased the bubble distribution in the bed is observed to become uniform. Finally turbulent fluidization is reached. Even though the fluidization behavior of RFBs is quite extensively studied, particle velocities have not been reported, as particles are supposed to rotate with the velocity of the motor-driven rotating vessel.

An alternative approach to replace the gravitational by a centrifugal field was proposed with the design of a Gas–Solid Vortex Reactor (GSVR) (Anderson et al., 1972; De Wilde and de Broqueville, 2007, 2008; Dutta et al., 2010; Kochetov et al., 1969; Volchkov et al., 1993). No motor is used and the vessel is static. The gas is introduced in the reactor chamber, using tangential inlet slots, thus inducing tangential motion of the particles and making them rotate. Gas is continuously injected and leaves the reactor chamber through a central gas outlet. An overview of the advantages and disadvantages of the GSVR and RFB reactors over the conventional gravitational fluidized bed reactors was given by Kovacevic et al. (2014). Even though there are similarities in the flow pattern between the RFB and the GSVR, as they both comprise a rotating bed, there are also significant differences given that in the GSVR the walls are static and the air is tangentially introduced at considerably higher velocities to trigger particle rotation and fluidization. The literature available on the flow pattern characteristics in the GSVR is relatively limited. Studies of the fluidization pattern and the influence of various operating parameters are mostly qualitative. De Wilde and de Broqueville (2008) investigated the fluidization behavior of a bed of Geldart-B particles. At very low solids mass in the bed (solids capacity of the bed), channeling is observed, while with increase of mass, bubbling was found to be the main type of fluidization. For Geldart-D particles both channeling and slugging are observed at very low bed mass. With increasing solids capacity, a dense, stable and uniform bed is formed. Ekatpure et al. (2011) have experimentally studied the influence of the tangential slot thickness and the particle diameter on the bed behavior. The influence of particle diameter, particle density and gas injection velocity on the maximum solids capacity and the stability of the rotating bed was investigated by Kovacevic et al. (2014). Eliaers et al. (2014) showed experimentally that Geldart-C particles, which are difficult to fluidize under gravitational conditions, can be fluidized in a GSVR presenting Geldart-A particle behavior, as suggested by Qian et al. (2001) for RFBs. Detailed velocity data are lacking in literature. Anderson et al. (1972) measured the average flow velocity at different radii and reported a significant reduction of the angular flow velocity with increasing bed mass. This observation becomes more prominent at radii close to the end-walls. Dvornikov and Belousov (2011) measured some average particle velocities at two axial heights and reported that the particle velocity close to the wall is lower than in the center of the GSVR. Contrary to the RFBs, where the motor rotation (determining the azimuthal gas and particle velocity) and the gas injection velocity (determining the radial gas velocity) are independent, the tangentially injected gas makes the particles rotate and fluidizes the bed in GSVR. Azimuthal and radial particle velocity cannot be imposed independently. Experimental data for detailed particle velocity profiles developed in a GSVR which are of major importance to gain insight in the flow behavior of the GSVR have not been reported in literature. They are however required to optimize the GSVR geometry and operating conditions. Furthermore, validation of analytical models or numerical simulations also requires accurate experimental data. The present work determines the influence of particle diameter, particle density and gas injection velocity on the azimuthal particle velocity, as well as on the bed behavior in a cold flow GSVR pilot set-up. The experiments are performed using three materials and three particle diameters at four azimuthal gas injection velocities and with solids capacities up to the maximum capacity that can be set without particle entrainment.

2. Experimental set-up and procedure

2.1. Experimental set-up

The GSVR experimental set-up used in the present study is described in detail by Ekatpure et al. (2011) and by Kovacevic et al. (2014). A schematic diagram of the whole set-up is shown in Fig. 1(a), while the reactor main chamber is shown schematically in Fig. 1(b).

A two velocity component so called 2D Standard Particle Image Velocimetry (PIV) set-up (LaVision®) with a CCD camera of 4MP (Imager ProX4M) and a YAG Litron laser of 135 mJ is used to monitor the behavior of the rotating bed and to measure the azimuthal and radial particle velocities.

PIV is an optical method widely used in literature for studying fluidized bed flows (e.g. van Buijtenen et al., 2011). Typically PIV is used to obtain planar flow velocity fields by illuminating small (<20 microns) tracer particles following the fluid motion, with camera images having 2–3 pixels per particle. In the present study, a 2D PIV is used to measure the velocity of 1–2 mm diameter particles based on camera images having 10–40 pixels per particle. The particles used are not tracers and hence the particle velocity field will not match the fluid velocity field. The displacement of the particles and the time between two consecutive images is used to calculate the particle velocity and to obtain a 2D particle velocity vector field of the particulate flow.

Typically, in 2D PIV, particles in a fluid flow are illuminated twice, with a small time separation, by using a light sheet that is formed by passing a double pulsed laser beam through an optical arrangement including cylindrical lenses. In the present study, an evenly diffused laser light is used, instead of the light sheet. The corresponding measuring plane, near the rear end wall, is obtained with fully opened camera shutter aperture, limiting the measuring depth of the field of view. In particle free flow the total