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Bed stability and maximum solids capacity in a Gas–Solid Vortex Reactor: Experimental study

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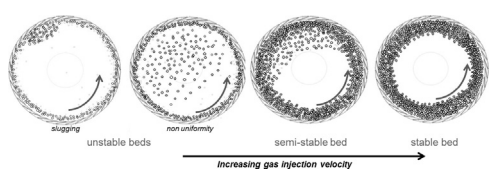
HIGHLIGHTS

- Fluidized bed stability and maximum solids capacity in a Vortex Reactor is studied.
- Lower solids density/diameter enhances stability and decreases max. solids capacity.
- Maximum solids capacity becomes almost constant for stable beds.
- Bed instabilities can be overcome by increasing gas injection velocity.

GRAPHICAL ABSTRACT



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ABSTRACT

A Gas–Solid Vortex Reactor (GSVR), in literature also referred to as Rotating Fluidized Bed in Static Geometry (RFB-SG), is a promising reactor type for Process Intensification (PI) with respect to reactor volume reduction. Although replacing gravitational by centrifugal force has been considered since the seventies, the hydrodynamics of the reactor flow and the bed behavior remain largely unknown. In the present work experiments have been carried out in a cold flow GSVR with diameter of 0.54 m, length of 0.1 m and 36 inlet slots of 2 mm. Gas injection velocities of 55–111 m/s and particles with densities of 950–1800 kg/m^3 and diameters of 1–2 mm have been applied. Depending on solids density, particle diameter and gas injection velocity the bed behavior can be considered as stable, semi-stable or unstable. For semi-stable and stable flow regimes the effect of the above process conditions on the maximum solids capacity was investigated. With increasing solids density, the bed stability considerably decreases, while the maximum solids capacity increases. By increasing the gas injection velocity, both the bed stability and the maximum solids capacity increase. Once bed stability is accomplished, a further increase of the gas injection velocity does not affect the maximum solids capacity. With increasing particle diameter, the bed stability decreases while the maximum solids capacity increases.

1. Introduction

Process Intensification has been the focus of the petrochemical industry for many years. Extensive efforts have been devoted to the improvement of Fixed Bed (FB) reactors, resulting in the development of the Static Fluidized Bed (SFB) reactor (Kunii and Levenspiel, 1991), and consequently of the Circulating Fluidized Bed (CFB) reactor. To augment the heat and mass transfer rates in SFBs and CFBs, reactors were developed in which the gravitational field is replaced by a centrifugal field (Chen, 1987). The centrifugal force was generated by rotating the reactor vessel itself, resulting in the development of the Rotating Fluidized Bed (RFB) reactor (Ahmadzadeh et al., 2008; Fan et al., 1985; Nakamura and Watano, 2007; Qian et al., 2001, 1998, 1999, 2004; Quevedo et al., 2006; Watano et al., 2003, 2004). RFBs have several advantages compared to SFBs and CFBs, as discussed by Quevedo et al. (2006). Low particle entrainment and fluidization at higher fluid velocities, resulting in a considerably higher fluid throughput per unit surface area, or in other words Process Intensification (PI), limited fluid bypassing, higher slip velocities and shorter residence times

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are some of them. Furthermore, according to Levy et al. (1979) and Saunders (1986), the problem of elutriation of the bed decreases when applying a centrifugal field. However, the over-all operational reliability of RFBs is lower than that of the conventional SFBs and CFBs (Zhang, 2009) because a rotating vessel, especially on industrial scale, suffers from severe limitations, mainly caused by vibrational problems. To avoid the need to rotate the reactor vessel itself, it was proposed to generate the centrifugal field in a static vessel by introducing the fluid phase through one or more tangential injection slots: the concept of a RFB in a Static Geometry (RFB-SG), (Anderson et al., 1972; De Wilde and de Broqueville, 2007, 2008; Dutta et al., 2010; Volchkov et al., 1993). This particular RFB-SG geometry generates a gas vortex in the reactor vessel, resulting in the alternative name of Gas–Solid Vortex Reactor (GSVR). When particles are introduced in the rotating gas phase, part of the tangential momentum of the gas phase is transferred to the particles, they start to rotate as well and a rotating annular fluidized solids bed is formed. The stability of the rotating solids bed is directly related to the forces acting on the bed as will be discussed in detail in Section 3. The high slip velocities (~1 to 10 m/s) as compared to the slip velocities in a CFB (~0.5 to 1 m/s) (Yang et al., 1992), the high solids fraction (~0.3 to 0.6) (Ekatpure et al., 2011), the short residence time (~50 ms) of the gas and the high residence time of the solid phase in a reactive flow GSVR, as shown by Ashcraft et al. (2012) allow the GSVR to promote a high throughput operation, an uniform gas–solid contacting and an enhanced heat and mass transfer, resulting in an intensified process on particle scale as well as on reactor scale (thus PI). Due to its benefits the GSVR has an extensive number of application fields, such as drying (Kochetov et al., 1969a, 1969b; Volchkov et al., 1993), in chemical technology (Kuzmin et al., 2005; Loftus et al., 1992; Ryazantsev et al., 2007) as well as nuclear technology (Anderson et al., 1972; Tang et al., 1971).

Recently, computational studies to predict the behavior of a GSVR have been performed (Ashcraft et al., 2012, 2013; Rosales Trujillo and De Wilde, 2012; Staudt et al., 2011). However, these studies are only supported by a limited number of experimental data. Furthermore, PI by using the GSVR is not limited to the effects of introducing a centrifugal field only. Other operating conditions such as reactor geometry and reactor hydrodynamics are inevitably part of the complete picture. A thorough understanding of the GSVR hydrodynamics requires an extremely extensive experimental study of the behavior and the stability of the annular rotating solids bed covering a wide range of operating conditions. In the paper of Ekatpure et al. (2011), the effect of tangential slot thickness and particle diameter has been investigated. The minimum and maximum capacities of solids in the GSVR, defining the window for stable operation, have been determined. However, the variation of solids density and diameter was limited in the previous study and further experiments have shown that within this window of stable operation, as defined by Ekatpure et al. (2011), different bed behaviors can be observed. The present work is a systematic extensive study of the effect of solids density ρ_s, particle diameter d_p and gas injection velocity through the tangential slots $v_{g,inj}$ on the bed behavior. Three polymers with different densities ρ_s are used. For each polymer, particles of at least two different diameters are applied. It was decided to use polymers as it is relatively easy to acquire polymer particles of varying density and size. Moreover, (waste) polymers could become an important energy source in the future. For example, Demirbas (2004) proposed thermal and catalytic degradation processes to produce fuel oil, as an alternative for the traditional polymer recycling processes such as pyrolysis. Lee (2012) studied the pyrolysis of widely used polymers as Polystyrene (PS) and High Density Poly-Ethylene (HDPE). Finally, up to five gas injection velocities $v_{g,inj}$ have been used.

The results of the extensive experimental study on a non-reactive cold flow pilot set-up presented in this work are basically intended to understand the GSVR hydrodynamic behavior over a wide range of operating conditions. The experimental results can be used to validate models that are intended for reliable computational GSVR studies.

2. Experimental set-up and procedure

2.1. Experimental set-up

The GSVR (Fig. 1) consists of two concentric cylinders, that is the distributor jacket and the reactor chamber. The front and rear end-wall of the cylinder are made of transparent polycarbonate

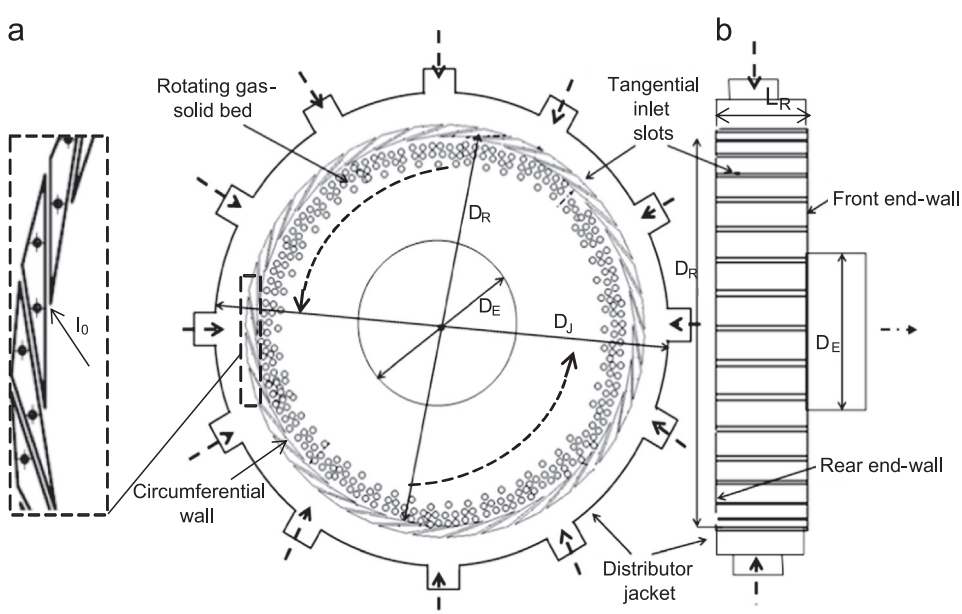

Fig. 1. Schematic presentation of the GSVR experimental set-up with tangential feed inlets, reactor diameter (D_R), exhaust diameter (D_E), reactor length (L_R) and inlet opening thickness (I_0). (a) Front view and (b) side view (Ekatpure et al., 2011).