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Influence of solids outlets and the gas inlet design on the generation of a gas-solids rotating fluidized bed in a vortex chamber for different types of particles

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HIGHLIGHTS

- The particle type determines the optimal vortex chamber design.
- A strong central vortex is essential to prevent fine particle losses via the chimney.
- Solids outlets help maintaining a strong central vortex.
- Sufficiently high velocity gas injection is essential for efficient particle retention.
- Limitations with too strong or too small gas inlet jets are demonstrated.

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ABSTRACT

Two design aspects of vortex chambers for the generation of gas-solids rotating fluidized beds are experimentally studied for different types of particles: the solids outlet(s) and the gas inlets. Efficient solids retention and minimal solids losses via the chimney are aimed at so that the gas and solids residence times can be controlled independently. The importance of a strong vortex in the central particle bed freeboard region is demonstrated. It is shown that separate, well-dimensioned and -positioned solids outlets prevent a significant presence of particles in the freeboard region, increasing the vortex strength in this region. This is found to be particularly important when fluidizing small/light particles. The ratio centrifugal force-to-radial gas-solid drag force that is generated by the gas injection is shown to also have an important impact. Theoretically it is shown that this ratio strongly depends on the particle characteristics and to what extent it can be increased by increasing the gas injection velocity, preferentially by reducing the gas inlet slot size and otherwise the number of gas inlet slots. Experiments with different vortex chambers and particles qualitatively confirm the theoretical expectations, but show that limitations are encountered. A very high gas injection velocity prevents efficient penetration of especially fine/light particles in the gas inlet jets which is detrimental for the transfer of tangential momentum between the gas and the particle bed. Slots smaller than the particle size are also shown to be inefficient, as they generate rotational motion of the particles around their own center of gravity.

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1. Introduction

Interest in gas-solid rotating fluidized beds in vortex chambers comes from the process intensification that can be achieved as a result of high-G and eventually multi-zone operation. These open perspectives for both significantly reducing equipment size and developing novel processing routes. The former was numerically demonstrated by Trujillo and De Wilde (2010, 2012) for fluid catalytic cracking (FCC), by Staudt et al. (2011) and Ashcraft et al. (2012) for biomass pyrolysis/gasification, and by Ashcraft et al. (2013) for the simultaneous adsorption of SO_2 and NOx (SNAP). Experimental demonstrations of size reduction are mainly in the field of drying (Kochetov et al., 1969a, 1969b; Volchkov et al., 1993, 2003; Eliaers and De Wilde, 2013; Eliaers et al., 2015; Pati et al., 2016). A vortex chamber device for the first-stage drying of granular materials was used at the commercial scale for agricultural applications (Volchkov et al., 2003). An example of a novel processing route based on vortex chamber technology was given by Eliaers et al. (2014) who studied the low-temperature wet coating of cohesive particles in a two-zone vortex chamber device.

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Nomenclature

List of symbols

a_c	centrifugal acceleration [m_r/s^2]
d_p	particle diameter [m]
D	vortex chamber diameter [m_r]
f	frequency [1/s]
f	factor
L	vortex chamber length [m_r]
m	mass [kg]
n	number of gas inlet slots
P	pressure [Pa]
R	radius [m_r]
s	single slot width [m_r]
S	surface area [m_r^2]
t_b	particle bed thickness (radial direction) [m_r]
u	gas velocity (interstitial) [m_r/s]
v	solids velocity (interstitial) [m_r/s]
V	volume [m^3]
β	drag coefficient [$kg/m_r^3/s$]
ε_i	volume fraction phase i [m_i^3/m_r^3]
ρ_i	density phase i [kg_i/m_i^3]
λ	Eq. (11)

Subscripts

b	bed
eff	effective/effectiveness
g	gas phase
i	inner
inj	injection
o	outer
r	radial
r	reactor
renew	renewal
s	solids
t	tangential

High-G operation allowed reducing the effect of the inter-particle van der Waals forces and treating cohesive particles. Recently, the potential of combining high-G intensified gas-solids contacting, gas-solids separation and solids segregation was recognized (De Wilde et al., 2016; Weber et al., 2017; Verma et al., 2017).

The fluid dynamics and design of gas-solid rotating fluidized beds in vortex chambers has been studied by various groups, but is still not fully understood (Kochetov et al., 1969a,b; Anderson et al., 1971, 1972; Lewellen and Stickler, 1972; Folsom, 1974; Smulsky, 1983; Vatistas et al., 1986; Volchkov et al., 1993, 2013; De Wilde and de Broqueville, 2007; 2008a,b; 2010; Sazhin et al., 2008; Dvornikov and Belousov, 2011; Pitsukha et al., 2012; De Wilde et al., 2016; Weber et al., 2017; Verma et al., 2017). The fluid dynamics is complex and shear at the end walls generates differences in rotation speed depending on the axial position. This effect is pronounced in the absence of particles, leading to strong boundary layer flows along the end walls and axial-radial circulation patterns in the chamber (Savino and Keshock, 1965; Volchkov et al., 1993). In the presence of a particle bed, the effect persists, but is dampened (Volchkov et al., 1993; Trujillo and De Wilde, 2011). Controlling the axial motion on top of the rotational motion is interesting in the context of multi-zone operation – see De Wilde (2014) for more details.

An efficient vortex chamber design must essentially guarantee efficient solids retention with minimal solids losses via the chimney. This allows building up a dense and uniform rotating fluidized bed and controlling independently the gas and solids residence times. It requires a centrifugal force that is high compared to the radial gas-solid drag force. When the centrifugal force compensates the pressure drop over the bed – the so-called cyclostrophic balance, a pseudo-fluidized concentrated particle layer can be formed. The bed is then at maximum density and tangentially, but not radially fluidized. As the superficial gas velocity in the radial direction remains smaller than the minimum fluidization velocity of the particles in the generated high-G field, bubbles are typically not formed. In other cases, the force balance is reached with a less dense and radially fluidized bed. meso-scale non-uniformities can then be formed (De Wilde and de Broqueville, 2007; 2008a,b, 2010). The unique flexibility of vortex chamber generated rotating fluidized beds with respect to the gas flow rate results from the counter-acting forces being affected by the gas flow rate in similar ways (De Wilde and de Broqueville, 2008a,b). The minimum fluidization velocity varies as such with the gas flow rate, as explained in de Broqueville and De Wilde (2009), so that a dense pseudo-fluidized rotating fluidized bed can be maintained in a relatively wide gas flow rate range.

The most important design parameters of a vortex chamber are the diameter and length, the chimney diameter and insertion length, the number of gas inlet slots and their size, and the solids inlet and outlet for operation with a rotating fluidized bed. Studying a limited number of vortex chamber designs in the context of granular material drying, Kochetov et al. (1969a) defined recommendations on ratios of dimensions to be respected. Some basic guidelines for slot design and operating conditions were given in Dutta et al. (2010). Considering the feeding of a batch of particles to a vortex chamber, Trujillo and De Wilde (2011) and De Wilde et al. (2016) showed by means of respectively Computational Fluid Dynamics (CFD) and Discrete Particle Method (DPM) simulations, the importance of a strong vortex in the particle bed freeboard region for efficient solids retention. The rotating fluidized bed is in a sense accelerated and stabilized from two sides, from the outer side by the tangential injection of the gas and from the inner side via the formation of a strong vortex. Reducing the chimney diameter was shown to increase the strength of this vortex, but comes at the cost of an increased pressure drop. The latter can eventually be reduced by making use of a dual-chimney design. The present paper focuses on the solids outlets and the gas inlet slot design. An experimental study with different vortex chamber designs and different types of particles was carried out to gain insight in the fluid dynamics and the influence of these design parameters.

2. Theoretical influence of the gas inlet slot design

A theoretical analysis on the influence of the gas inlet slot design is presented assuming a uniform and relatively thin monodisperse rotating fluidized bed. Expressing that the centrifugal force on a particle should be larger than the radial gas-solid drag force:

$$\frac{2\varepsilon_s\rho_s v_t^2}{D} > \beta u_r, \tag{1}$$

with both left and right hand side in [N/m^3 reactor] and assuming a zero radial particle velocity. Considering a solids volume fraction $\varepsilon_s > 0.2$ and turbulent flow and focusing on the region at a certain

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