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Semi-empirical drag correlation for a Gas Solid Vortex Reactor starting from the radial momentum balances

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The Gas Solid Vortex Reactor (GSVR) is a novel rotating fluidized bed reactor with a stationary geometry, in which the gravitational force in conventional fluidized bed is replaced by a centrifugal force resulting in process intensification[1]. In a GSVR a stable solids bed can be obtained for high gas flow rates thereby increasing the slip velocity between the phases. Consequently, the overall heat and mass transfer increases as to compared to a gravitational fluidized bed[2, 3]. The GSVR is a disc-like chamber where the process gas is introduced through a series of azimuthally inclined injection slots, uniformly distributed along the circumferential chamber wall. Inside the chamber the gas swirls towards the unidirectional central gas exhaust. When particles are fed inside this swirling flow field the gas transfers part of its momentum to the particles. The particles start to rotate in the chamber and form a stable, dense, rotating bed at the circumferential wall (Fig. 1). The rotational motion generates a radially outward directed centrifugal force on the particles. The injected gas flowing through the solid bed towards the unidirectional central gas exhaust generates a counteracting radially inward directed drag force on the particles. The GSVR compiles a unique set of characteristics typical for reactor technologies that combine high gas-solid slip velocities, good particle mixing and continuous operation under dense bed conditions[4]. As such, the GSVR technology has already been considered for different applications, like drying of biomass[5], biomass pyrolysis[1], SO_2-NO_x adsorption from flue gases[6] or nuclear rocket fuel propulsion[7].

As no universal understanding of the in-depth hydrodynamics of the GSVR technology is readily available, scaling and design of industrially-sized GSVRs are difficult up-to-date. An in-depth understanding of a technology often comes from a first principles approach. A first step in understanding of the multiphase hydrodynamics in the GSVR based on the radial momentum balances is aimed at in the present study.

An extensive set of experimental data has been collected by different researchers[2, 3, 8, 9] over the past years in an experimental semi-batch GSVR setup at the Laboratory for Chemical Technology. The investigated range of operations spans a wide range of gas flow rates, particle sizes, particle densities and bed masses. The experimental data is used to verify the assumptions made and to determine the model parameters of the semi-empirical drag formulation.

Following some simplifying assumptions, like neglecting the weight of the gas, the wall force and particle-particle interaction, the radial solids and gas momentum balances are combined to:

$$\frac{\Delta p}{h_{bed}} V_{bed} = m_{bed} \frac{v_{s,\theta}^2}{R} \tag{1}$$

The resulting one-dimensional, averaged equation shows that the pressure drop over the bed height balances the centrifugal force of the bed. Here h_{bed} describes the radial height of the bed, v_{bed} the overall volume of the bed, m_{bed} the mass of the bed and R the outer radius of the unit. The azimuthal solids velocity $v_{s,\theta}$ is averaged over the height of the bed.

Pressure drop over a conventional fluidized bed is usually estimated using semi-empirical correlations for the drag force[10, 11]. In the present work a semi-empirical correlation for the radial drag force on the GSVR bed is developed, starting from the well-known correlations for single-particle drag[12]. The resulting correlation is:

$$F_{Drag,r} = 282\,\frac{(1-\varepsilon)}{d_p}\rho_g v_{g,r,sup}^{1.6}\ V_{bed} \tag{2}$$

Here ε is the void fraction, d_p the particle diameter, ρ_g is the gas density and $v_{g,r,sup}$ the radial superficial gas velocity in the unit. Equations 1 and 2 are combined and written in dimensionless form:

$$Ar_c = 282Re_{rad}^{1.6} \tag{3}$$

The correlation parameters are obtained through linear regression of the available experimental data sets. The parity plot for equation 3 is shown in Figure 3. The radial Reynolds number and the centrifugal Archimedes number are calculated from equations 4 and 5, where μ_g is the gas viscosity.

$$Re_{rad} = \frac{v_{g,r,sup}\rho_g d_p}{\mu_g} \tag{4}$$

$$Ar_c = \frac{(\rho_g - \rho_s)\rho_g d_p^3 \frac{v_{s,\theta}^2}{R}}{\mu_g^2} \tag{5}$$

Using this modeling approach a more fundamental understanding of the interaction between gas and particles in a dense rotating bed is obtained. The absence of the void fraction as a classic modeling parameter, states that the gas interacts with every particle in the same way and that particle-particle interaction is minimal. In this respect the GSVR differs from conventional fluidization technologies operating in the dense bed regime, confirming the appropriateness of the GSVR for innovative industrial applications.

Acknowledgments

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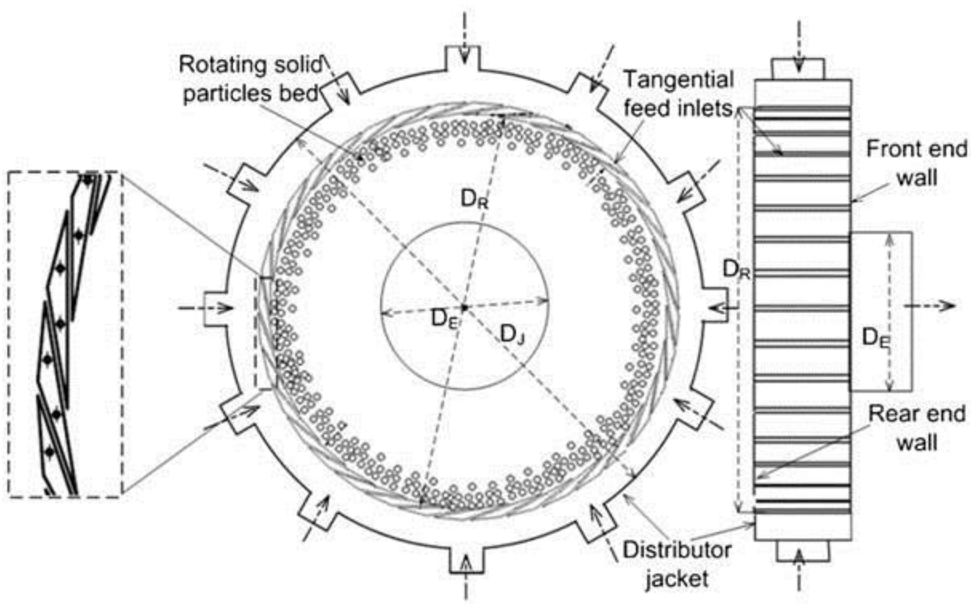

Fig. 1. A schematic representation of the Gas-Solid Vortex Reactor

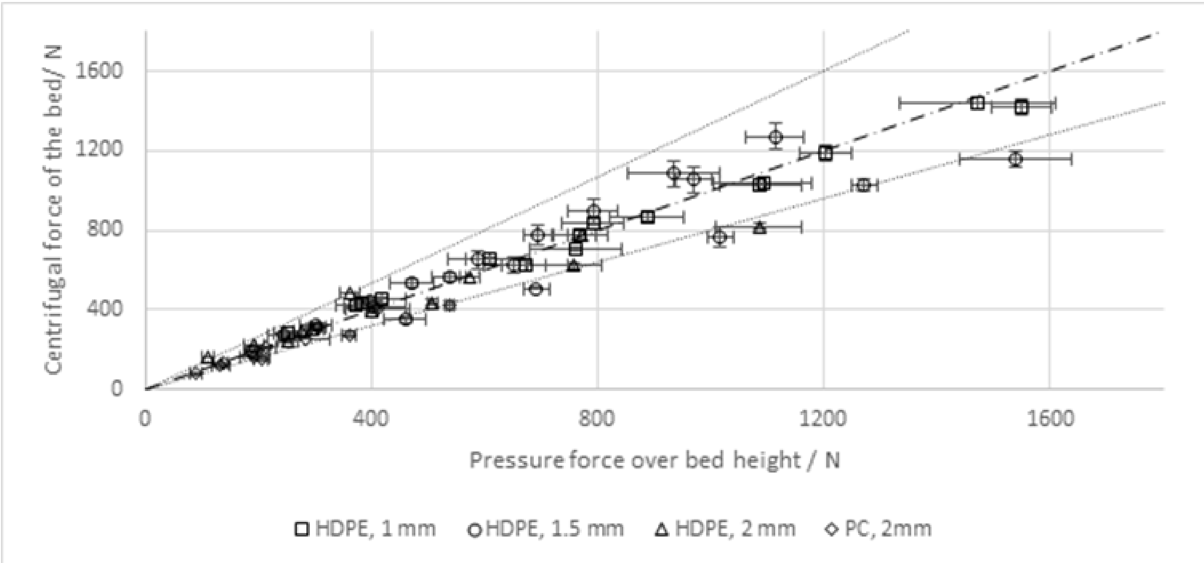

Fig. 2. Plot for the centrifugal force of the bed and the force exerted by the pressure on the bed (Equation 1).

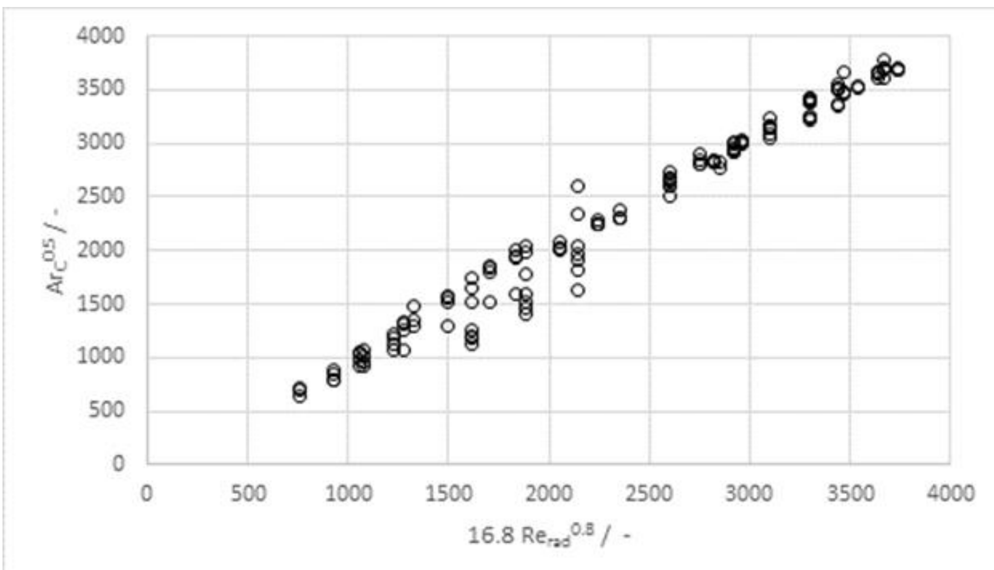

Fig. 3. Parity plot for the semi-empirical correlation for the particle-gas interaction in the GSVR (Equation 3).