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# Experimentally validated numerical study of gas-solid vortex unit hydrodynamics

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ABSTRACT

A three-dimensional numerical analysis of the flow in a Gas-Solid Vortex Unit (GSVU) is carried out. The numerical model is first validated by comparing the bed pressure drop and solids velocity with experimental data. Next, the influence of gas flow rate, solids density, and particle diameter on the pressure drop, solids velocity, bed void fraction and slip velocity between the two phases is studied. A stable, solids bed is achieved for the entire range of gas flow rates tested (0.1–0.6 $Nm^3/s$). No particle entrainment is observed when varying the solid density (1800–450 $kg/m^3$) or the particle diameter (2–0.5 mm). A shift to bubbling fluidization regime is observed for small particle diameters (0.5 mm). The observed changes in the GSVU flow patterns are discussed by analyzing the changes in the cumulative centrifugal to drag force ratio over the bed.



## 1. Introduction

Gas-solid Fluidized Beds (FBs) are widely used in chemical industry as they enhance heat and mass transfer and solids mixing. The applications range from physical operations such as drying of solids [1], adsorption of dilute components from carrier gas [2] and particle coating [3] to reactive operations such as fluid catalytic cracking of hydrocarbons [4] and polymerization of olefins [5]. Heat and mass transfer efficiency in FBs is determined by the relative velocity between both phases, the so-called slip velocity. In conventional gravitational FBs, where the drag force is balanced by the gravitational force, the slip velocity cannot exceed the terminal free-falling velocity of the particles in a uniform bed operation [6]. Higher gas velocities in gravitational beds results in the formation of bubbles and slugs. Extensive gas bypass decreases gas-solid contact and thus the corresponding heat and mass transfer drops. Further increase in gas flow rate causes particle entrainment [7] and may affect the compactness of the industrial-scale fluidization setups [8].

Centrifugal force can reach much higher values than the gravitational force allowing feasible operation in the 7–40 g regime, which is suitable for high gas throughput, more uniform fluidization, higher slip velocities and, hence, much higher heat and mass transfer [9–13]. Centrifugal FBs cause a shift in the Geldart classification of particles [14] and have been successfully used in fluidization of cohesive particles [15,16]. Consequently the centrifugal bed technology is more energy efficient, increasing the gas flow rate per reactor volume and making the fluidization process more compact. Hence, a centrifugally fluidized bed is an ideal candidate for Process Intensification (PI).

A centrifugal FB can be achieved in two ways: by setting the particles in motion by rotating the operating vessel itself, known as Rotating Fluidized Bed (RFB) [13,17,18] or by introducing the particles in a swirling flow field of azimuthally injected gas in a static vessel (Gas-Solid Vortex Unit) (GSVU) [10,19–21]. In the RFB, the independent control over the rotational velocity of the vessel and the injected gas flow rate imply that the azimuthal and radial velocity components can be varied in a decoupled manner [13]. However, RFBs involve mechanically moving parts and are prone to mechanical abrasion. In GSVU's on the other hand, the fluidizing gas is injected from a number of azimuthally inclined rectangular slots at the circumferential wall. Azimuthal momentum is transferred from the swirling gas to particles fed into the unit, which start rotating and experience an outward centrifugal force. The particles rotating in a GSVR achieve a 'fluidized state' when the radially inward drag force exerted by the gas overcomes the apparent weight of solids in the centrifugal field [22]. Unlike the RFB, in the GSVU the particle velocity components cannot be independently controlled. However, the absence of mechanically moving parts significantly reduces the abrasion in the GSVU and makes the device more suitable for scale-up [19,23].

As the centrifugal force in a GSVU is a function of reactor geometry, operating conditions and solids properties, it can be tailored to establish a desired fluidization regime [17]. The latter cannot be achieved in gravitational FBs, as gravitational force is constant. All these features make the GSVU a potential device for PI of selected processes such as combustion of hydrocarbon fuels [24,25], drying of fine pored materials like food grains, pharmaceutical products or polymers [26,27], biomass pyrolysis [28] and $SO_2$-$NO_x$ adsorption [29]. Excellent reviews of GSVU

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**Nomenclature**

| | |
|---|---|
| $A_P$ | cross-sectional area of a particle ($m^2$) |
| $d_p$ | particle diameter (m) |
| e | dissipation of turbulent kinetic energy ($m^2/s^3$) |
| $e_{ss}$ | restitution coefficient |
| $F_c$ | cumulative centrifugal force over bed (N) |
| $F_d$ | cumulative radial drag force over bed (N) |
| $G_M$ | gas flow rate ($Nm^3/s$) |
| g | acceleration due to gravity ($m/s^2$) |
| k | turbulent kinetic energy ($m^2/s^2$) |
| L | GSVU length (m) |
| P | static pressure (Pa) |
| $P_{gauge}$ | static gauge pressure (Pa) |
| $\Delta P_{bed}$ | bed pressure drop (Pa) |
| r | radial coordinate (m) |
| *Re* | Reynolds number |
| U | velocity (m/s) |
| $U_{slip}$ | slip velocity (m/s) |
| $V_P$ | volume of a particle ($m^3$) |
| $V_T$ | total volume of particles ($m^3$) |
| z | axial position (m) |
| Greek letters. | |
| $\beta$ | gas-solid drag coefficient ($kg/m^3$ s) |
| $\delta$ | angle of internal friction |
| $\varepsilon$ | volume fraction |
| $\varepsilon_{s,max}$ | maximum packing limit solids volume fraction |
| $\gamma$ | dissipation of granular temperature by collisions ($kg/m\ s^3$) |
| $\lambda_s$ | solids bulk viscosity (Pa s) |
| $\mu$ | granular viscosity (Pa s) |
| $\mu_{col}$ | solids collisional viscosity (Pa s) |
| $\mu_{fr}$ | solids frictional viscosity (Pa s) |
| $\mu_{kin}$ | solids kinetic viscosity (Pa s) |
| $\varphi$ | specularity coefficient |
| $\Theta$ | granular temperature (J/kg) |
| $\rho$ | phase density ($kg/m^3$) |
| $\theta$ | angular coordinate (rad) |
| $\tau$ | wall shear stress ($N/m^2$) |
| Subscripts. | |
| g | gas phase |
| s | solids phase |
| t | turbulent |
| col | collisional |
| fr | frictional |
| kin | kinetic |
| c | circumferential wall |
| e | end-wall |

design as well as potential applications of single phase and multiphase vortex devices reference can be found in literature [16,30].

Reports on experimental studies carried out in GSVU setups to investigate the cold gas–solid hydrodynamics, i.e. in the absence of reactions, have improved the understanding of the nature of the flow field in the unit [11,12,19,31,32]. Kochetov et al. [33] ran experiments with varying length-to-diameter ratios of the GSVU and prescribed optimal values for its construction. Anderson et al. [19] performed experiments on GSVU bed hydrodynamics with talc, tungsten and zinc particles using X-ray absorption techniques to measure solids volume fractions in the bed and using a paddle wheel to measure angular bed velocities at various radii. Heat and mass transfer intensification when drying wheat grains in a GSVU was demonstrated by Volchkov et al. [34]. Particle entrainment close to the end-walls of the GSVU was observed as gas and solids centrifugal acceleration decrease in the wall boundary layers. Their work thus demonstrated the need for a 3D description of the GSVU bed hydrodynamics. Volchkov et al. [12] studied changes in the GSVU bed porosity behavior in the GSVU with varying gas flow rate and concluded that the bed becomes more dense with increasing gas flow rate. The authors also found the centrifugal force to be larger than the radial drag force in the GSVU under given flow conditions, indicating that, if centrifugal force and drag force do not balance each other, particles are pushed towards the wall resulting in increased wall shear stresses. De Wilde and de Broqueville [10,11] experimentally demonstrated by fast digital camera image analysis that the GSVU shows different fluidization behavior for different Geldart classified materials. Kovacevic et al. [31,32] used Particle Image Velocimetry (PIV) and pressure probing techniques to measure the pressure drop and solids velocity in a cold flow GSVU. The authors observed higher solids velocities with increasing gas flow rate and decreasing solids density. Depending on the solids loading, the GSVU bed exhibited bubbling characteristics for smaller sized particles.

Although the experimental work carried out by different researchers highlighted important GSVU flow characteristics, two major drawbacks of the experimental data acquisition remain. Firstly, the range of operating conditions is limited by equipment design. More importantly, the non-intrusive measurements techniques employed limit experimental data collection to locations near the end-walls due to the dense nature of the bed [32]. However, for a complete description of the GSVU bed hydrodynamics various interactions at multiple scales (viz. at particle scale, bubble/slug scale and reactor scale) need to be accounted for [34–36]. The lack of complete information on the internal bed hydrodynamics of centrifugal FBs necessitates the need for a numerical study [13]. de Broqueville and De Wilde [37] performed two-dimensional (2D) numerical heat transfer studies in a GSVU. The authors theoretically demonstrated an increased heat transfer thereby achieving a more uniform heat distribution and a higher bed-averaged heat transfer rate compared to the conventional gravitational bed riser. Rosales and De Wilde [36] captured the appearance of slugs and non-uniformities in the bed for small sized catalyst particles (80 μm) in a 2D numerical study. Ashcraft et al. [28] implemented 2D simulations for biomass pyrolysis and demonstrated PI in a GSVU. These numerical studies although highly insightful, are 2D in nature and cannot capture the effect of a unidirectional gas exhaust or the presence of the end-walls on bed hydrodynamics. Moreover, bubble formation and slugging in fluidized beds may possess 3D propagation tendencies [38]. Hence, in order to properly investigate the bed (non-)uniformity in the GSVU, 3D simulations are needed. Preliminary 3D simulations using various geometrical designs of the GSVU have been carried out by Dutta et al. [23]. However, elaborate studies on the effect of gas flow rates and different solids properties were not performed. Furthermore, the validation of the applied CFD model was purely qualitative, requiring further calibration of the numerical model.

In the present work, the commercial Computational Fluid Dynamics (CFD) code FLUENT® 14.0 is used to perform a three-dimensional (3D) numerical study of the hydrodynamic behavior of the GSVU. First, the CFD model is validated by comparing simulated pressure and velocity data with experimental data. Next, the validated numerical model is used to study the gas-solid hydrodynamics in the GSVU over a wide range of conditions. Gas flow rate, particle diameter and solids density are individually varied to estimate their effect on various flow variables such as pressure drop, solids velocity, bed-averaged solids volume fraction and slip velocity.

## 2. Methodology

### 2.1. GSVU setup

A photographic view of the experimental GSVU setup, simulated in this work, is shown in Fig. 1(a). A schematic of the setup, shown in