Powder Technology 338 (2018) 702–715

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Operational range of a Gas-Solid Vortex Unit

Maximilian Friedle, Guy B. Marin, Geraldine J. Heynderickx *

Ghent University, Laboratory for Chemical Technology, Technologiepark 914, B-9052, Gent, Belgium

ARTICLE INFO

Article history:
Received 22 January 2018
Received in revised form 25 May 2018
Accepted 17 July 2018
Available online 22 July 2018

Keywords:
Gas-Solid Vortex Unit
Dimensional analysis
Maximum capacity
Multiphase flow

ABSTRACT

The Gas-Solid Vortex Unit is an advancing fluidization technology with the potential to overcome the limitations of conventional fluidized beds. The conditions for stable fluidization are investigated, that are the upper and lower limit, i.e. minimum and maximum capacity ($W_{s,min}$ and $W_{s,max}$). Based on dimensional analysis three non-dimensional groups are identified, governing the fluidization phenomena: the superficial radial particle Reynolds number $Re_{p,R}$, the swirl ratio S and the unit loading λ.

Data from different authors is gathered for minimum (42 datasets, 3 geometries) and maximum (251 datasets, 8 geometries) capacity and used in regression analysis. Parameters are estimated for different proposed functional dependencies of the identified dimensionless groups. The model equations describing the minimum and maximum unit loading best, including their 95% confidence intervals, are:

$$\lambda_{max} = (4.0 \pm 0.4)\ 10^{-3}\ Re_{p,R}^{(0.443 \pm 0.011)} S^{(0.454 \pm 0.018)}$$
$$\lambda_{min} = (1.15 \pm 0.05)\ 10^{-4}\ Re_{p,R}$$

The two equations describe the limits of the operational range of a GSVU for which stable fluidization is possible. The applicability of the model equations is verified against a wide range of data taken from different publications.

1. Introduction

The Gas-Solid Vortex Unit (GSVU) is a technology used for intensified gas-solid contact. As such it has been investigated for a wide range of different applications, including drying [1], combustion [2, 3], biomass gasification [4] and biomass pyrolysis [5, 6]. Applications that highlight its applicability on a purely hydrodynamic level include milling [7, 8] and particle separation [9, 10]. As fluidization in the centrifugal field allows higher forces than in the gravitational field, the Geldart classification has also been shown to change with the use of a GSVU [11]. The radial force balance on fluidized particles is made up by the equilibrium of drag and centrifugal force. This use of the centrifugal force makes the GSVU more versatile compared to gravitational fluidized beds, where gravitational force has a fixed value and the drag force is thus limited [12]. The limitations of gravitational fluidized beds, like particle entrainment or bed instabilities (clusters, slugs, channeling) can be overcome in the GSVU if the operational range is set accordingly.

A schematic of a GSVU is given in Fig. 1. The gas enters a distribution jacket (not shown) before it is injected into the cylindrical GSVU chamber through a number (I_N) of azimuthally inclined inlet slots with a slot thickness (I_0). The injection angle for the gas is set to the value of α with respect to the tangent at the circumference of the cylinder. The projection of the injection area of one slot on the r-z-plane multiplied with the number of injection slots gives the azimuthal injection area A_θ. The gas flows through the particle bed, that is, rotating along the circumferential wall of the cylinder. It transfers a part of its azimuthal momentum to the solid phase and thus keeps the particles rotating. The particles form a dense fluidized bed close to the circumferential wall of the chamber. The gas flows radially inward towards the central gas exhaust and exerts drag on the bed. The radial drag force balances the centrifugal force on the particles in stable or semi-stable Condition (13). Finally the gas leaves the unit through the central gas exhaust.

The minimum and maximum bed capacity in a GSVU are closely linked to the bed stability, marking the boundary towards instabilities and particle entrainment. Consequently, bed stability is discussed first.

Kovacevic et al. [14] described different phenomena that are linked to bed stability, as shown in Fig. 2. Depending on operating conditions and particle characteristics, the bed stability may increase or decrease from a slugging over a non-uniform to a semi-stable and finally to a stable particle bed. Important variables include the gas injection velocity, the particle density and mass, and the particle diameter.

The phenomena of maximum and minimum capacity are linked to the pressure in a GSVU [15]. The static pressure at a GSVU

* Corresponding author.
E-mail addresses: geraldine.heynderickx@ugent.be (M. Friedle), guy.marin@ugent.be (G.B. Marin), Geraldine.Heynderickx@ugent.be (G.J. Heynderickx).

https://doi.org/10.1016/j.powtec.2018.07.062
0032-5910/

Nomenclature

Latin symbols

a–f	Parameters in regression analysis	–
Ar	Archimedes number	–
A_θ	Azimuthal injection surface area	m^2
d_p	Particle diameter	m
G_M	Gas mass flow rate	kgs^{-1}
L	GSVU chamber length	m
I_N	Number of slots	–
I_0	Inlet slot opening width	m
n	Number of dimensionally bound quantities	–
p	Number of linear independent non-dimensional groups	–
P	Pressure	Pa
r	Number of linear independent variables; radial coordinate	–
R	GSVU radius	m
$Re_{p,R}$	Superficial radial particle Reynolds number	–
S	Swirl rato	–
u_{inj}	Azimuthal gas injection velocity	ms^{-1}
$u_{r,sup}$	Superficial radial velocity at the circumferential wall	ms^{-1}
V_s	Solid particle volume	m^3
V_U	GSVU volume	m^3
$\dot{V}_{cr}$	Critical volumetric gas flow rate	$m^3\ s_{-1}$
$W_{s,max}$	Maximum capacity	kg
$W_{s,min}$	Minimum capacity	kg
z	Axial coordinate	m

Greek symbols

α	Slot inclination	°
μ_f	Fluid dynamic viscosity	Pas
ρ_f	Fluid density	kgm^{-3}
ρ_s	Solid density	kgm^{-3}
λ_{max}	Maximum unit loading	–
λ_{min}	Minimum unit loading	–
λ	Unit loading	–
θ	Azimuthal coordinate	rad

Abbreviations

AIC	Akaike Information Criterion
FCC	Fluid Catalytic Cracking
GSVU	Gas-Solid Vortex Unit
HDPE	High Density Poly Ethylene
PC	Polycarbonate
PVDF	Polyvinylidene Fluoride
RSE	Residual Standard Error
Sn	Chemical element: tin

circumferential wall when adding particle mass to an established gas-only flow is illustrated in Fig. 3 for a constant solids feeding rate.

Fig. 3 shows that the pressure in the unit is highest for gas-only flow. The validity of the cyclostrophic balance [16] and the of secondary flow phenomena [17, 18] for pure gas flow in a GSVU have been investigated. The addition of particles breaks down the swirling gas structure, which reduces the pressure drop and leads to a very dilute solid-gas flow. With further feeding, the majority of the gas bypasses the particles, which is called channeling. Here the particles rotate on specific r-θ planes, while the gas bypasses the particles axially. In one special case, e.g. the particles rotate close to one end wall, while the main gas flow happens at the other one [19]. In gravitational fluidized bed reactors, channeling is seen as the result of aggregation effects in the presence of cohesive particles or a non-uniform gas-distribution [20]. In the case of a GSVU an insufficient mass of particles has a clear correlation with this effect. With further addition of bed mass, the particles build up to clusters, introducing slugging effects in the GSVU. At a bed mass of minimum capacity further addition of particles makes the pressure in the unit increase. A stable bed is formed, as a result of particle-gas-interaction. Further addition of particles makes the pressure increase linearly with the bed mass. At a bed mass, referred to as maximum capacity, the pressure remains constant, as the added particles are entrained and follow the gas out of the unit.

Several researchers have described the phenomenon of maximum capacity, while only one [15] was concerned with minimum capacity. Authors have described qualitative trends and postulated correlations to determine maximum capacity values in a GSVU. Some of the presented correlations were developed based on theoretical considerations, some through the assembly of various variables influencing GSVU behavior. At times [21–24] the experimental setup did not meet the criteria to be considered a GSVU setup and could not be further integrated into this work. Apart from Prashant et al. [25], using water, all researchers used air as medium for fluidization.

The following gives a chronological overview of the postulated theories for GSVUs and similar devices on maximum capacity. Remark, that different correlations and findings of different authors are at times contradicting. They are described here for the sake of completeness.

Kochetov et al. [23] proposed a correlation for the maximum capacity based on experimental data with poppy seeds, millet grains, styrene polymer beads and quartz sand.

$$W_{s,\ max} \propto \rho_f \frac{\left(\frac{G_M}{\rho_f}\right)^3}{(I_N I_0 L)^2}\ I_0^{0.15}\ (2R)^{-0.55} \tag{1}$$

The experimental setups they used were flexible, e.g. the distribution of inlet slots on the circumference of the chamber could be altered. The correlation is highly dependent on the inlet flow rate, the number of slots, the total slot inlet surface area, the gas density, and the radius and height of the unit. The proportionality constant proposed is highly material-dependent.

Anderson et al. [26] did experiments in a GSVU using talcum, tungsten and zinc powders in the micrometer range. The maximum capacity was recorded in a fully continuous operation. It was found that the maximum capacity does not depend on the length/radius ratio $\frac{L}{R}$ of the unit. Instead the maximum powder load linearly increased with the gas flow rate, independent of material size and density. Under similar conditions, Turman et al. [27] operated different GSVU geometries using talcum powder with an average diameter of 18 μm. Setups with different geometries were used to determine the maximum capacity for different gas flow rates. It was concluded that the maximum capacity depends on the gas flow rate as shown in Eq. (2).

$$W_{s,\ max} \propto (G_M)^{\frac{1}{3}} \tag{2}$$

Akulich et al. [21] developed a correlation for the maximum capacity for drying applications in a GSVU, based on the force balance for a single particle in equilibrium. Experiments in two setups using different disperse materials (polyethylene, millet grains, lactose, potato starch, malachite) showed that the maximum capacity increased with increasing gas flow rate. Based on these experiments a correlation for the maximum capacity as a function of different dimensionless groups was developed based on a volume ratio, the ratio of unit length to unit