Experimental and Modelling Studies of Gas Solid Vortex Reactor Hydrodynamics

Inês Paiva

Supervisors: Prof. dr. ir. Kevin Van Geem
Prof. Dr. Vítor Geraldes

Coach: Shekhar R. Kulkarni

The concept of centrifugal fluidization is studied since the 1960's[1]. Although many decades of research have passed, several characteristics of GSVR's, one of the reactor types where centrifugal fluidization happens, are still unknown amongst the scientific community. To better understand some hydrodynamic aspects of it, experimental trials and a model work were done. The maximum loading of solids was compared using different configurations of the setup. It was concluded that this variable achieves values which are approximately 3 times higher when the exhaust is orientated against gravity than when placed with gravity. The degree of particle segregation/mixing during the fluidization on a GSVR was also evaluated, experimentally. Particle segregation could only be achieved using different sizes of particles. Lastly, a modelling work was developed, to better understand the properties of the materials which could be processed in the unit. This model strives to estimate the minimum particle diameter of a certain material which can be fluidized in a GSVR. It was successfully developed and applied to alumina and aluminium particles. Even though the model has its limitations, it can provide a realistic estimation of the critical particle diameter. With this work, the knowledge on how to process solids in GSVRs and its behavior under centrifugal forces was deepened. The usage of GSVR's on an industrial level is becoming closer to be a reality as more studies like this arise.

Key Words: Gas Solid Vortex Reactor; centrifugal fluidization, particle segregation, critical particle diameter.

I. Introduction

A Gas-Solid Vortex Reactor is a relatively new technology that allows the gas fluidization of solid particles in the form of a rotating fluidized bed in a static unit. Although its worth has been proven in literature, its industrial use is still narrow, mainly because there is still a lack of knowledge on how to do a scale-up of these devices. The lack of correlations to describe accurately the main aspects of such units, related to heat and mass transfer, also contributes to its limited use[2]. The segregation of particles by their size and density is a promising feature of GSVR's which still needs to be explored. This advantage can be applied in processes during which the particles suffer a decrease of size or density or new ones are formed during the ongoing process. If the segregation of particles is proven to be a successful and feasible way to separate particles, the GSVR can also be included in the category of process intensifying methods. The use of hybrid technologies which allow to combining operations or processes into single equipment to minimize the unit operation size, lower the energy use and cost and reduce the operation time is one of them. Using alternative energy sources as a magnetic field, microwaves or ultrasound are being studied. Lastly, anti-fouling techniques are being considered, since Process Intensification is close-banded with miniaturization which in an extreme point will lead to problems related to fouling and blockage.

II. Setup Description

Figure 1 gives an overview of the reactor setup. A heater heats up the mass flow controlled gas flow (air in the current work) coming from the compressor. This is then inserted in the jacket of the reactor. Here, the gas travels through the narrow, tangentially inclined injection slots (Figure 2), into the reactor volume and finally leaves through the exhaust that is installed in the reactor top plate. The reactor height is 2.5cm, the exhaust diameter is 4 cm and the reactor dimeter is 13.9 cm. The reactor is installed with the exhaust pointing vertically upwards. The collecting system represented in Figure 1 has a cartridge filter, a cyclone and a two-valve system. All three allow the separation of the gas from the solid phase.

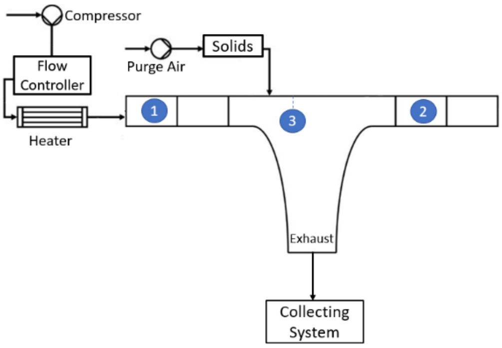


Figure 1. Schematic description of the reactor setup. 1: reactor jacket region. 2: position of the vanes. 3: Top plate.

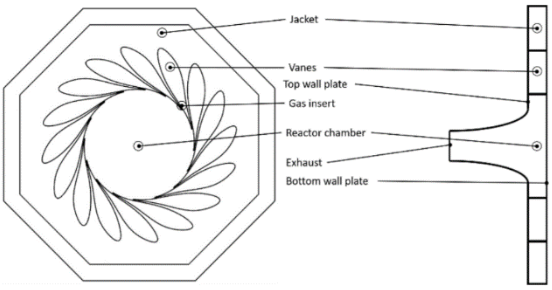


Figure 2. Top view and cross section of the reactor.

Sixteen vanes with a 1mm slot opening are installed for the majority of the experiments done in the current work. Solids can be added to the reactor volume via a small opening in the bottom plate with the help of pressurized air.

III. Maximum Loading

The maximum loading can be defined, for a given flow rate, as the mass of solids in the bed/reactor beyond which there will be particles leaving through the exhaust. Experiments have been done to understand the influence of the position of the exhaust in the hydrodynamics of the setup. The experiments with the exhaust orientates against gravity (same direction and opposite way as this force) were done by another student and reported in his thesis[3]. Both experiments are compared in Figure 3.

Alumina particles of 0.7-0.8 mm of diameter were fed to the reactor, where a preset gas flow rate was passing through. A waiting time of 5 minutes was required for bed stabilization. After that time, with the two-valve system, the particles which were entrained from the chamber are collected. That portion is called 'Entrainment quantity'. After that collection, the gas flow rate is turned off to allow the rotating solids to fall in the exhaust. After cleaning the remaing portion with pressurized air, those particles are collected. That amount has the name of 'retained quantity'.

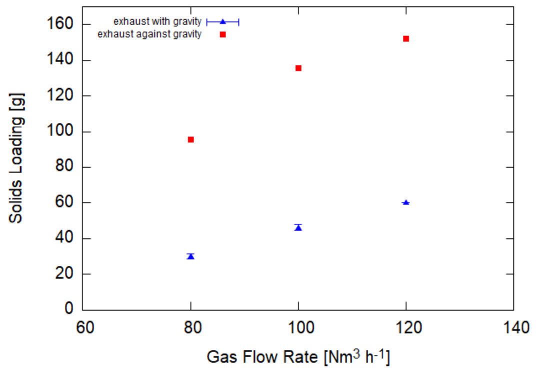


Figure 3. Maximum Loading of Alumina (0.7 – 0.8 mm) for several air flow rates.

Observing Figure 3, it is clear that the higher maximum loading (or maximum solid loading) is achieved for the previously studied configuration. In the current arrangement, the particles are pulled through the exhaust because of gravity. It is observed that even minor changes to solids rotating closer to the exhaust, brought about by either collisions or miniscule changes to the gas flow rate, the particles tend to leave via exhaust, under the added influence of gravity. This effect does not happen in the previous configuration when the exhaust is against gravity. When the exhaust is oriented vertically downward, gravity effects start to dominate in the freeboard zone as well as in the backflow zone. As a consequence, the presence of freely rotating particles in the freeboard are no longer observed in this mode of operation. The lack of loosely rotating particles in the unit suggests that all the solids are accommodated in the bed, unlike in the previous configuration. Furthermore, deposition of particles on the bottom plate is not possible due to strong gravitational effects on heavy particles such as Alumina. As a combined effect of both, the maximum solid loadings are substantially lowered when operating with an exhaust aligned with gravity. With all other operating conditions being unchanged, roughly half the amounts of solid can be retained in the configuration with downwards exhaust. Smaller error bars on the solid loadings across all the flow rates is also resultant from the lack of solid lingering on the bottom plate, as opposed to the previous configuration.

IV. Particle Mixing/Segregation

Particles with different mass, due to their diameter or density differences, will assume different radial positions inside of the chamber, since they experience different values of centrifugal and drag forces. This phenomenon is called particle mixing/segregation. Hence, in a GSVR, the probability of particle entrainment will be higher for particles for which radial position is smaller, e.g. closer to the exhaust. Therefore, lighter particles are more likely to leave the reactor, in opposition to the heavier particles. To study this phenomenon, the composition of the bed was examined by analyzing the entrained and retained quantities and their composition. During operation, some characteristics of the bed were also studied, such as the bed height (which are present in solid volume fraction form) and the pressure drop across the entire reactor.

To study this phenomenon, aluminium and alumina particles of different sizes (0.7-1mm diameter), were used. Mixtures of two different sizes and several compositions (0, 25, 50, 75 and 100 % of a certain size) were fed to the reactor. The total mass of the fed mixtures is always kept at 100 g. Three main air flow rates are used: 80, 100 and 120 Nm^3.h^{-1} and the purge air pressure was kept at 500 mbar.

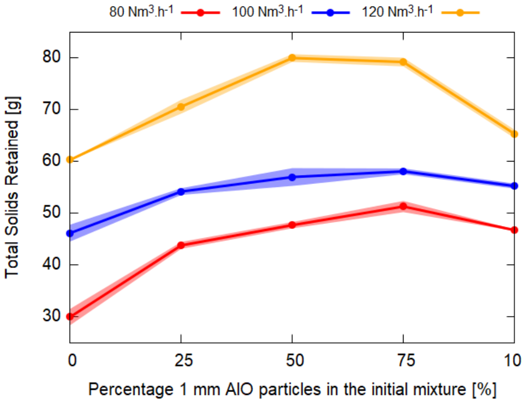


Figure 4. Total solids retained for several gas flow rates (particle sizes: 1 mm and 0.7-0.8 mm). Colored areas represent respective error region.

Figure 4 is perhaps the figure from where we can extract more information. This plot can be used backwards. An Alumina mixture with an unknown composition can be fed to the reactor and the retained percentage will give information regarding its composition, in terms of particle sizes. However, this figure does not reveal any information related to particle segregation. It only shows that for different compositions of the fed mixture, the maximum capacity of the reactor shifts in a non-linear way, without any information about the composition of the bed in each case. As of yet, it was believed that particle segregation in a GSVR was due one of two reasons – different particle diameter or different particle density, or the combination of those. Now, that hypothesis is at stake. It is believed that the bed packing might influence the particle segregation/mixing.

The spaces left empty by larger particles can be occupied by smaller particles, preventing the latter to occupy a smaller radial position inside of the chamber, as it would happen if the bed was only constituted by smaller particles. The fact that the total solids retained is higher for the composition studied which includes the larger quantity of bigger particles gives some positive indication. The outcome arrangement of this mixture provides a higher amount of free spaces for the small particles.

Despite such conclusions, the presented hypothesis can only be confirmed using optical techniques, such as PIV or high-speed camera.

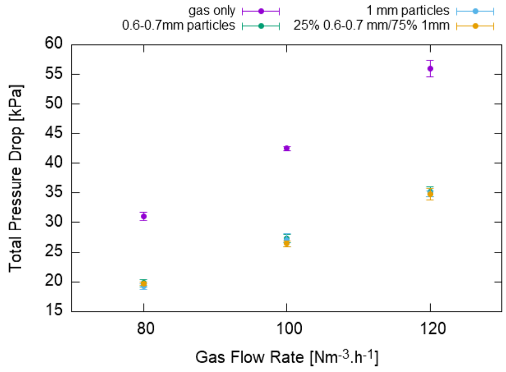
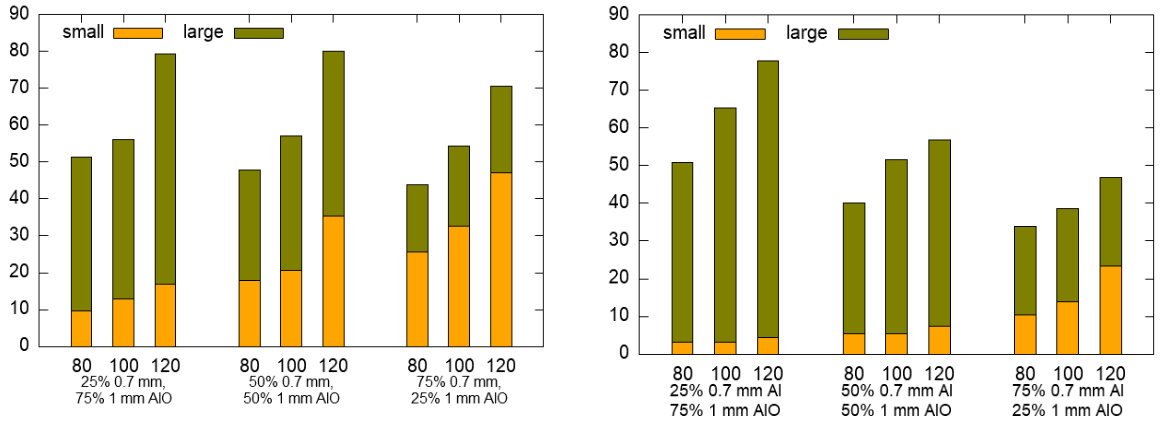


Figure 5. Total pressure drop measured and its errorbars for multiple bed compositions and gas flow rates.

The total pressure drop in a GSVR can be defined as $P_{inlet} - P_{outlet}$, with pressures being measured before and after the reactor, respectively. Hence, there are two major pressure drop sites to be accounted: the slots and the bed. Because of the reduced width of the slots and the large velocity of the gas through those, the gas loses a lot of momentum, which is converted into a pressure drop for the entire system[2]. The bed is only responsible for a small contribution of the pressure drop.



(a) (b)

Figure 6. Composition of the bed in grams for each air flow rate and initial fed mixture. (a) Mixture of alumina of different sizes. (b) Mixture of alumina and aluminium of different sizes.

Therefore, the results described in Figure 5 – the total pressure drop being equal for all the analyzed mixtures – does not lead to a particular conclusion, because of the inherently smaller contribution of pressure drop across the bed to the overall pressure drop. Initially, the hypothesis of the same total pressure drop being related with the same packing was considered but after a careful analysis, it got compromised. Hence, by only looking to the data displayed in Figure 5, it is not possible to conclude anything about the degree of mixing or segregation in the bed.

Although such differences, the residence time of the gas phase does not change according to the number of phases present inside the unit. What changes is the residence time distribution of the gas.

Figure 6 (a) and (b) have represented a lot of information, which should be carefully analyzed. As mentioned before, the total mass fed to the reactor was always kept constant, at 100 grams, which corresponds to 100%. Hence, the plots should be read according to that principle. If the reader wants to know how much alumina can be fluidized in the GSVR at 80 Nm3.h-1 in a mixture of alumina and aluminium, they should look at the initial composition of the fed mixture and correlate the points (which can have different colors, expect for the case of a binary mixture of 50% each). The results presented are always relative to the initial mass quantity fed from a certain material. Therefore, the red circles and triangles, which correspond to 25 grams of a certain material, will always be found bellow the horizontal line of 25 grams in both graphs.

As already concluded by the percentage plots presented before, when the mixture is composed by particles with different densities and sizes, the maximum loading is larger. These new plots help to understand that the larger the quantity of a certain material in the initial mixture, the larger is the increase of the total mass fluidized, for an increasing air flow rate. This conclusion is clearly seen in Figure 6**Erro! A origem da referência não foi encontrada.** (a). In Figure 6 (b), the suggested trend is less notorious, especially for smaller percentages in the initial composition, where the total mass of the material fluidized is practically independent of the gas flow rate.

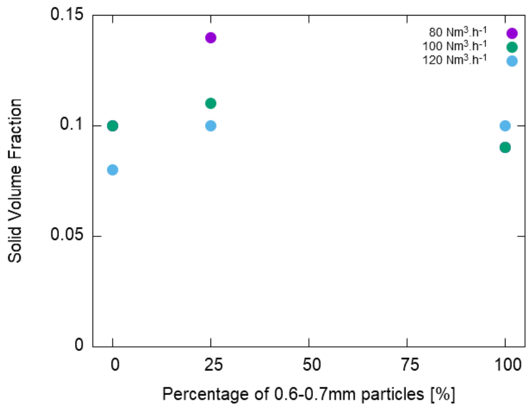


Figure 7. Solid Volume Fraction in the bed under various air flow rates.

By analyzing Figure 7, the void fraction is influenced by the gas flow rate and the nature of the fed mixture. The higher the gas flow rate, the larger will be the solid volume fraction.

Higher flow rates will lead to smaller heights of the bed, which is linked to having higher maximum solid capacities in the reactor for those cases. A higher flow rate will also carry more momentum, which can be distributed to more particles. If those particles achieve the minimum velocity necessary to stay in the bed, the bed will become denser, leading to lower bed lengths and higher solid volume fractions. Although having higher maximum loadings for higher gas flow rates, the expansion of the bed has a bigger effect on the solid volume than the extra amount of particles that can be retained in that case. That is the reason why the solid volume fraction is higher for higher air flow rates. Being the solid volume fraction higher for the mixture between small and large particles, one can assume that the bed is denser in that case and therefore that the packing is more efficient.

V. Modelling

The design aspects of a GSVR greatly influence the possible operating conditions associated with the unit. The swirl ratio and the dimensions of the unit cannot be easily changed during operation. For that reason, a GSVR has the disadvantage of narrowing the diversity of processed materials and operating conditions (e.g. the main gas flow rate). Hence, a necessity of understanding which materials can and cannot be successfully fluidized in a certain reactor arises. For that purpose, a mathematical model was constructed and presented in this section. Besides the presented objective of the model, it can also be employed in a more preliminary stage of the setup, namely during its design and construction. If a certain set of materials are to be studied, with a particular particle diameter and density, a unit can be built to match the desired operating conditions. The model will give a preliminary idea of what is possible to process in a certain unit, without the need for experimental trials.

This model was applied to three different materials – aluminium ($\rho_{Aluminium}$= 2700 kg.m^{-3}), alumina ($\rho_{Alumina}$= 4000 kg.m^{-3}) and high density polyethylene (HDPE; ρ_{HDPE}= 950 kg.m^{-3}) – and two different setup configurations – with swirl ratios of 30.94 and 27.27 – and it is based on a force balance made to a fluidized particle inside of a GSVR. This model strives to find the smallest particle diameter, of a certain material, that can be retained inside a certain GSVR, with a specific swirl ratio and dimensions. Henceforth, that variable will be called the critical particle diameter.

The critical particle diameter is the diameter that emerges from the balancing of centrifugal to drag force at a given radial position in a GSVR. Particles smaller in size than the critical diameter will be entrained from the specific radial position as the drag force will surpass centrifugal. As it was mentioned in the previous chapters, there are three main forces acting on a particle which is rotating in a GSVR: gravity, centrifugal – equation 1 – and drag force – equation 3. Gravity effects are assumed to be invalid for the present study (considering a vortex unit with a vertical central axis and placed horizontally). Hence, the force balance takes only into account drag (F_d) and centrifugal (F_c) forces, as presented below. As a rule of thumb, centrifugal force is believed to be the stabilizing one and drag to be destabilizing force for a vortex unit.

$$F_c = m_p \frac{v_{s,\theta}^2}{r} \tag{1}$$

$$F_d = \frac{1}{2}\rho_g g A_p C_d u^2 \tag{2}$$

Balancing both forces, three possible scenarios arise. In an ideal situation, drag and centrifugal forces will assume the same value, which results that the particle will keep a certain radial position inside of the chamber. However, during the operation of the GSVR, two more cases can happen. If the drag force exceeds the centrifugal force, the radial position of the particle will decrease and consequently, the particle will get entrained. If the centrifugal force exceeds the drag force, the particle will assume a larger radial position. Hence, for a particle to stay inside of the reactor, the centrifugal force should be equal or higher than the drag force. That situation implies a minimum particle diameter, which is called the critical diameter since it is the smallest diameter a particle can assume in order to stay and rotate inside of the reactor. Equaling the drag and the centrifugal force and isolating the particle diameter in one member of the equation, equation (3) is obtained.

$$D_{cut} = \frac{3}{4} C_d \frac{\rho_g}{\rho_p} \left(\frac{v_{g,r}}{v_{s,\theta}}\right)^2 r \tag{3}$$

Equation (3) is the core of the presented model. A description on how to determine each parameter will follow.

C_d is the drag coefficient which depends on the flow regime, and therefore on the particle Reynolds number– i.e., equation (5). A similar approach was used by the works of Weber et al[4] in their study of segregation in a GSVR.

$$C_d = \frac{24}{Re_p} + \frac{2.6\left(\frac{Re_p}{5}\right)}{1+\left(\frac{Re_p}{5}\right)^{1.52}} + \frac{0.411\left(\frac{Re_p}{263000}\right)^{-7.94}}{1+\left(\frac{Re_p}{263000}\right)^{-8}} + \frac{0.25\left(\frac{Re_p}{10^6}\right)}{1+\left(\frac{Re_p}{10^6}\right)}, 0.1 < Re_p < 10^6 \qquad (4)$$

$$Re_p = \frac{\rho_g d_p v_{g,r}}{\mu_g} \qquad (5)$$

The velocities present in equation (3) – $v_{g,r}$ is calculated from equation (6) – while the $v_{s,\theta}$ values are taken from PIV trials reported by Gonzalez-Quiroga et al.[5] done with Aluminium particles with 500 µm. Because the reported azimuthal solid velocities are local ones, and not averaged, it was decided that the values should be approximated using a linear regression. Thus, the outcoming results will be an average of all the particle diameters found at a certain radial position in the chamber.

$$v_{g,r} = \frac{G}{2\pi r L} \qquad (6)$$

Since C_d also depends on the particle diameter, the presented equation cannot be simply solved. Therefore, an iterative process was employed to determine the critical diameter for each case. First, a particle diameter was chosen for each evaluated material. For aluminium, the initial value is the same as the used by Gonzalez-Quiroga et al.[5] (500 µm). For alumina, the value chosen was 600 µm, a typical particle size. Then the particle Reynolds – equation (5) – and the drag coefficient – equation (4) – were calculated with that value. Finally, a new particle diameter was calculated using equation (3). The procedure was repeated for several gas flow rates, radial positions and materials. The results are shown in the next figures – Figure 8 and Figure 9. Since it is an iterative process, it must have a stop criterion. For both materials, it was decided that the iterations could be stopped when, for two consecutive calculations, the outcoming particle diameters differ by 5 µm or less.

The data in Figure 8 can be interpreted as follows: the minimum aluminium particle diameter that can be retained inside a reactor with the same characteristics and using 35 Nm^3.h^{-1} of air is approximately 70 µm. And if the largest bed length formed by aluminium particles that can be retained is 4.5 mm, then the smallest particle diameter that is possible to retain in the bed, under the same air flow rate, is approximately 170 µm.

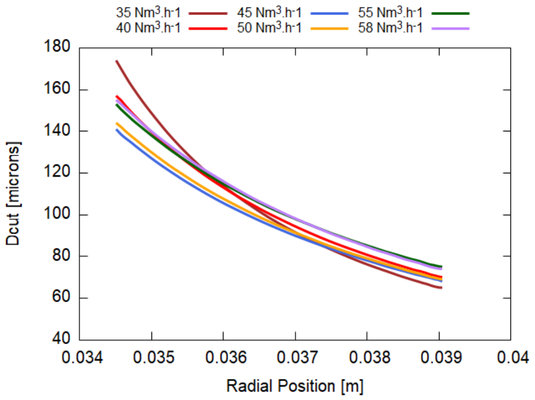


Figure 8. Critical aluminium diameter along the chamber for several gas flow rates.

To apply the same method to other materials, an assumption has to be made. For alumina, a momentum balance is necessary, since there is no data available regarding the azimuthal velocities of such materials in a GSVR. The momentum transfer from the gas phase to the solid phase in a GSVR depends on the swirl ratio, the main gas flow rate and the gas properties. Thus, maintaining such conditions, e.g. using the same reactor, the same gas phase, and the same gas flow rate, the momentum balance associated to the solid phase can be described by equation (8).

$$(v_{s,\theta} m_p)_{Aluminium} = (v_{s,\theta} m_p)_{material} \qquad (8)$$

Since the properties (density and size) of the particle are known, it is possible to calculate the azimuthal solids' velocity of that material and therefore determine the critical particle diameter for each radial position and gas flow rate – Figure 9.

The momentum balance described in equation (8) is not valid for all the materials. When the compared materials differ in terms of fluidization classification under centrifugal forces, then equation (8) cannot be applied. What is known is that the momentum transferred by the gas is always the same, since the air properties and the gas flow rate used remain unaltered. But each material receives that momentum in a different way, which is thought to be correlated to its fluidization patterns and behavior. That momentum can be converted into azimuthal velocity (remark that in a GSVR, it is assumed that the solid phase does not have radial velocity) or it can be lost through friction – mainly between the particle and the circumferential walls).

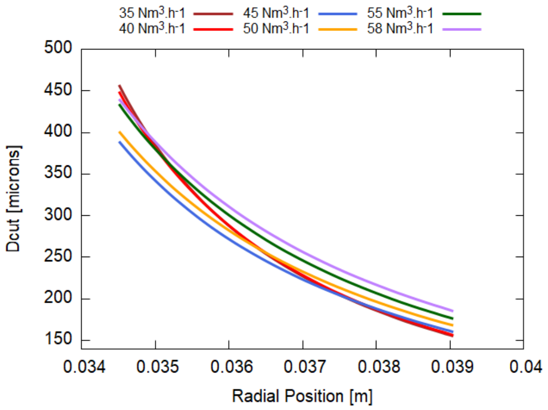


Figure 9. Critical alumina diameter along the chamber for several gas flow rates.

Figure 9 can be analyzed in the same way as Figure 8. If the unit is empty and a flow of 35 Nm^3.h^{-1} of air is fed to the chamber, an alumina particle with 160 µm is the estimated minimum particle size that can be retained in the reactor. As the operator feeds more particles, a fluidized bed starts to form and to expand. If the maximum bed length that is possible to achieve in this reactor and using the same air flow rate has approximately 5 mm, the biggest alumina particle that can be kept inside is estimated to have around 450 µm.

Comparing both materials, alumina presents values for the critical diameter larger than aluminium. That difference has mainly to do with the difference of densities between the two materials. The denser the material, the heavier the particles (while keeping the size unaltered) and harder is to keep them inside of the chamber. A heavier particle will have a higher mass, and, for that reason, it would be expected for that particle to sense a stronger centrifugal force. But the azimuthal solid velocity will decrease for denser particles[6]. And since that variable is squared, it influences more the outcoming value for the centrifugal force then the mass of the particle, which is only directly proportional. Therefore, the centrifugal force will not increase, but decrease, causing the particles to assume a smaller radial position, being closer to the exhaust and therefore, more likely to be entrained from the chamber. To balance that drop on the azimuthal solid velocity, the particle must assume a higher size, which results in higher mass but also higher projected area, increasing the drag force. The whole set of reasons explained in this paragraph justifies why a denser particle has to be bigger in size to be able to stay inside a GSVR. Besides density, there are other variables that have an impact on the resulting critical particle diameter. Therefore, a sensitivity analysis is performed and presented in **Figure 10**.

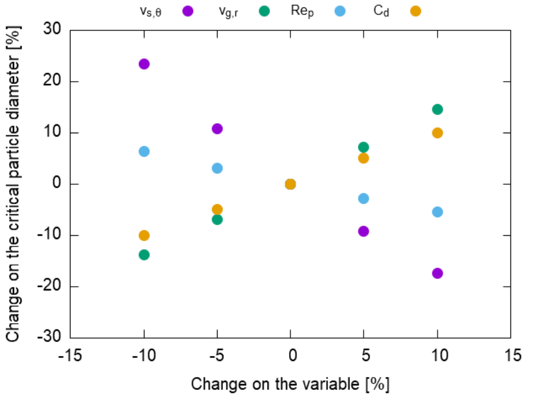


Figure 10. Sensitivity analysis on the particle diameter.

A sensitivity analysis was performed for aluminium – Figure 10 – , choosing one radial position – 0,0345 m – and one gas flow rate – 35 Nm^3.h^{-1} – in order to evaluate which parameter influences greatly the critical diameter. For that purpose, positive and negative changes were done in the variables present in equation (4) and the outcoming results compared with the initial scenario. Using such process, it is possible to conclude that the particle Reynolds does not influence significantly the particle diameter (the changes induced by modifying the variable on the evaluated range are always smaller than 10%), while the azimuthal solid velocity has a greater influence on the particle diameter, in the studied range – a change of -10% on this variable causes the particle diameter to increase in more than 20%.

While evaluating the robustness of the mathematical model, the reader can already perceive that its range of applications is limited, mainly for mathematical reasons, as it is expressed by the sensitivity analysis and the application of the method to an experimental set of values.

The main reason for the results given by the sensitivity analysis is that the model is developed based on only one set of conditions, obtained in one setup with a constant swirl ratio, for a specific material and a certain range of gas flow rates. For it to have a broader range of applications, it was necessary to base the method in more experimental values, retrieved from several setups and fluidizing different materials with different sizes. During the next paragraphs, several limitations associated with the model will be depicted.

The model and its further iterations were performed using Microsoft Excel, which has a limited capacity when it comes to iterative processes. There were some mathematical problems with convergence, since the model tended to converge to a trivial solution. During each iteration, a new air of values for the particle Reynolds and the particle diameter where calculated. As the iterations continued, the particle diameter would converge to zero and the particle Reynolds would increase to extreme high values, e.g. converge to infinite.

Another aspect to account is that since the model is based on aluminium azimuthal velocities it can only be extrapolated for materials which centrifugal fluidization classification is the same as aluminium. Otherwise, the momentum balance stated in equation (8) can no longer be valid, since the fluidization mechanisms are also different. Thus, the model can only be applied to other materials if 1) they have the same centrifugal fluidization classification or 2) when there is available data, namely radial positions vs. azimuthal solid velocities for a certain particle size of such material.

There are some approximations done between iterations. The azimuthal solid velocities should change between each iteration, since a new step on the iterative process leads to a new particle size. Something else that also changes with the particle size is the bed height that should be evaluated. As the particle decreases in size, the bed height expands radially inwards (the centrifugal force will decrease for a smaller particle because its mass will also decrease). This approximation is supported by Weber et al., who presented the same reasoning but contradicted by Kovacevic et al., whose results show a significant difference between the azimuthal solid velocities of particles with different velocities from the same material. As we change the size of the particles, the solid volume fraction also changes, as shown in **Figure** 7. This change will produce a variation of the bed height, which is also not accounted in the model.

The model was designed to a specific reactor, with a certain swirl ratio (the geometry of the reactor was kept constant during all the trials), since all the experimental data was retrieved from the same setup. Applying the model to other GSVR can lead to erroneous results. The same problem exists when it comes to the valid range of gas flow rates.

Lastly, the preformed force balance was done on a single particle. Interactions between particles or particle-wall were not accounted, nor its effects. Although the entire bed height has been accounted for, the existence of more particles (which are the reason why the bed grows inwards radially) are not taken into account. This approximation can influence the drag coefficient, which is probably underestimated.

VI. Conclusions

The first reported experiments demonstrate the flexibility of the setup in terms of various operating modes, ease of feeding and recovering solids (in accurate fashion, for quantification purposes) and stable operation over long time periods. It also shows that for achieving a larger solid loading, the studied unit should be orientated with the exhaust against gravity.

All the results and conclusions regarding the mixing/segregation work are in agreement with a published article in the same matter[4]. Weber et al. present several sets of experiments where different materials, with different sizes, are fed to a GSVR and the segregation and mixing degrees are evaluated. That evaluation accounts with visual technique, namely PIV, but only for the case where segregation occurs. The conclusions retrieved from that work are similar to the ones already mentioned before.

The modeling work developed under the scope of this master thesis resulted in a successful mathematical model which can preliminarily estimate the minimum particle diameter of a certain material that can be fluidized in an empty GSVR. The method has several limitations, but it can safely be extended to materials which have the same fluidization behavior as aluminium, under centrifugal forces.

This model can be used for designing purposes and for studying theoretically which materials of which size can be processed in an already existing unit. For achieving accurate results, a great quantity of data, namely azimuthal solid velocities, should be provided to the model. This variable has the highest influence on the accuracy of the critical particle diameters. This model gets the scientific community one step further to comprehend the hydrodynamics of the GSVR.

Finally, this is a work which includes a significative amount of subjects regarding the GSVR technology. In this scientific article, a lot of information is collected, which can be useful for it to be implemented on an industrial level, in a wide range of industries.

VII. References

(1) Gel'perin, N.; Ainstein, V.; Gakman, I. Rate of inception of fluidization and expansion of a fluidized layer in a centrifugal force field. *Khim. Mash.* **1964,** (5), 18.

(2) Kulkarni, S. R.; Gonzalez-Quiroga, A.; Nuñez, M.; Schuerewegen, C.; Perreault, P.; Goel, C.; Heynderickx, G. J.; Van Geem, K. M.; Marin, G. B. An experimental and numerical study of the suppression of jets, counterflow and backflow in vortex units. *AIChE Journal* **2019**, e16614.

(3) Schuerewegen, C.; Heynderickx, G. p.; Van Geem, K. c. "Experimental Heat Transfer Studies in a Hot Flow Vortex Reactor," University of Gent, 2018.

(4) Weber, J. M.; Stehle, R. C.; Breault, R. W.; De Wilde, J. Experimental study of the application of rotating fluidized beds to particle separation. *Powder Technology* **2017,** *316*, 123.

(5) Gonzalez-Quiroga, A.; Kulkarni, S. R.; Vandewalle, L.; Perreault, P.; Goel, C.; Heynderickx, G. J.; Van Geem, K. M.; Marin, G. B. Azimuthal and radial flow patterns of 1g-Geldart B-type particles in a gas-solid vortex reactor. *Powder Technology* **2019**.

(6) Kovacevic, J. Z.; Pantzali, M. N.; Niyogi, K.; Deen, N. G.; Heynderickx, G. J.; Marin, G. B. J. C. E. S. Solids velocity fields in a cold-flow gas–solid vortex reactor. *Chemical Engineering Science* **2015,** *123*, 220.