PARTICLE AGGLOMERATION IN CYCLONES: PACYC MODEL

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Abstract: The purpose of this work is to build a model to predict in a more realistic way the collection efficiency of a gas cyclone recirculating system (Chibante et al., 2007; Salcedo et al., 2007). These systems consist in an optimised reverse-flow cyclone combined with partial recirculation of uncaptured particles via a straight-through cyclone concentrator, with very high collection efficiencies for very fine particles.

As a first approach, in this paper a reverse-flow gas-cyclone without recirculation was studied. The model starts by solving the particle trajectory in a turbulent flow field inside the cyclone, and by employing a fixed set of parameters, it determines if a collision or an agglomeration occurs. In case of agglomeration, the initial particles will have a dynamic behaviour inside the cyclone as a newly formed agglomerate, thus having a different collection efficiency from that of the original particles. In fact, the observed efficiency will increase above theoretical predictions and this can be observed in various experimental results, usually referred as "hook-like" grade-efficiency curves.

The hypothesis of particle agglomeration within the cyclone turbulent flow seems a sound justification for the higher than predicted collection efficiencies observed for smaller particles in a gas-cyclone, being expectable with recirculation that this effect will become even more significant.

Keywords: Optimised Cyclones; Turbulent Dispersion; Particle Agglomeration

1 INTRODUCTION

Collection efficiency models currently developed for reverse-flow gas cyclones, such as the Mothes and Löffer's model (Mothes and Loffler, 1988), can predict with high accuracy the collection efficiencies of particles with diameters above about 3-4 μm.

Experimentally, it was observed at laboratory, pilot and industrial-scales that cyclone systems with or without recirculation can have complete collection below about 150 nm, viz. the grade-efficiency curves have a hook-like shape, showing a minimum in collection at an intermediate particle size (from about 0.8 to 2 μm).

However, no model, to the authors' knowledge, can correctly predict this behaviour. Muschelknautz's model (Hoffman and Stein, 2002) predicts, at high solid loadings, a fairly constant value of collection efficiency for the smaller particles. In this case, this is achieved because it is postulated that a portion of the feed is separated unclassified. However, this model is not able to predict the abnormal high collection for very fine particles that occurs even at low solid loadings.

In this work, this abnormal behaviour for very fine particles is attributed to agglomeration within the cyclone turbulent flow field (Salcedo et al., 2007), much as it happens in recirculating fluidised beds (Mao et al., 2002; Sommerfeld, 2001).

Thus, this work concentrates on modelling this phenomena, by considering the particles' trajectories inside the cyclone and studying possible interparticle interactions. The probability of collision and effective particle agglomeration are considered, and their direct implication in the particle size distribution actually processed by the gas cyclone. This particle size distribution will be different from the feed size distribution at the inlet to the cyclone and will consequently affect the grade-efficiency curve.
In fact, upon impaction and agglomeration of fine particles by larger ones, the smaller particles will be

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captured as much larger particles, viz. with a much higher collection efficiency than that predicted by any of the currently available models. If the cyclone is highly efficient above about 4-5 μm, as it indeed happens with very high efficiency cyclone systems, then the finest particles will also be collected with these high efficiencies, and this could explain the minima observed in the grade-efficiency curves.

2 MODELLING

A model was developed to predict the agglomeration inside a gas-cyclone, which has a fully-developed turbulent flow field. Afterwards, the model can reconstruct the history in terms of agglomeration of each particle, and take that into account to rebuild the effective efficiencies of the initial (unagglomerated) particles.

The proposed model was obtained by combining the Mothes and Loffler (1988) model which predicts collection efficiencies in reverse-flow gas-cyclones, the Salcedo *et al.* (2007) model which is an extension to the Mothes and Loffler (1988) model to recirculating reverse-flow gas-cyclones, and the Sommerfeld (2001) model which predicts the agglomeration of particles in turbulent flows.

2.1 Particle behaviour in turbulent flow

In this work, agglomeration was estimated using a stochastic Lagrangian approach of the binary inter-particle collisions in a turbulent field as proposed by Sommerfeld (2001) and Ho and Sommerfeld (2002). This is a complex method to predict the evolution of each particle inside a control volume, hence, its simplified structure is presented in Fig. 1.

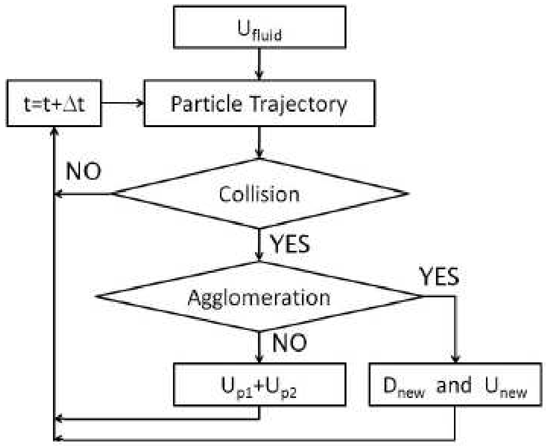

Fig. 1. Scheme of the agglomeration model

Inducing a primary flow field in the control volume, particles' trajectories are calculated by integrating the following system of equations:

$$\frac{dx_{p,i}^{N}}{dt} = u_{p,i}^{N} \tag{1}$$

$$\frac{du_{p,i}^{N}}{dt} = \frac{3\rho_F c_D}{4\rho_p D_p^N}\left(u_{F,i} - u_{p,i}^{N}\right)\left|\overrightarrow{u_F} - \overrightarrow{u_p^N}\right| + g_i \tag{2}$$

Equation 1 solves the particle trajectory explicitly while Equation 2 calculates the particle velocity. This is directly related to some physical parameters such as the fluid and particle specific gravities but mainly to the relative particle/fluid velocity.

Solving these equations in a predetermined flow field (in our case with radial and tangential components given by the Mothes and Loffler model (1988)) leads each particle to have a deterministic behaviour in the control volume. To introduce turbulence into the system, the fluid velocity is changed, in consecutive time steps and at the same position, according to Equation 3.

$$u_{F,i}^{n+1} = u_{F,i}^{n} R_p + \left|u_{F,i}^{n}\right| \sqrt{1 - R_p^2} \times N(0,1) \tag{3}$$

The parameters associated with turbulence are taken into account in the variable R_p which is bounded to [0, 1]. As a short explanation of the impact of this variable in the final fluid velocity field, if R_p has a value near one, the fluid velocity is highly auto-correlated, so the turbulence is low and the fluid velocity has almost a deterministic behaviour. However, if R_p has as value near zero, the fluid velocity shows practically no autocorrelation, implying a strong turbulent flow and consequent almost random behaviour of the fluid velocity components between consecutive time steps.

After obtaining the particles' trajectories in turbulent flow, a statistical criteria proposed by Sommerfeld (2001) is used to determine if a collision occurs between two particles. In the case where a collision occurs, using a momentum criteria the decision is made whether the result of the collision is an agglomerate or on how the collision affects the velocities of the two particles. The formation of an agglomerate is determined by a number of parameters but has high dependency on the relative velocities of the particles. The process repeats itself, analysing all the binary interactions, until the final time of interaction is reached. No simultaneous three-particle or higher level interactions are considered.

The results of this part of the model are the final number distribution, which has stored the resulting number of particles after interaction (in their respective original class diameter), and the particle agglomeration history, which contains the time evolution of each resulting diameter.

2.2 Control volume specification

To apply the agglomeration model to our case-study, a cylindrical control volume was created according to the one used in the Mothes and Loffler (1988) model, taking into account that it must have the same total height of the cyclone and a pseudo-radius to force the volume of the cylinder to be equal to that of the cyclone. As an improvement to the model, this cylindrical control volume was sliced with several slices with height that, in principle, are equal to the height of the cyclone gas inlet.

The classical Mothes and Loffler model is then applied to the entire cyclone, and the slice grade-efficienciy curves are obtained from Equation 4, where it was assumed that each slice has the same efficiency, independent on the axial position. In this approach, one of the major consequences is that the outflow of particles of one slice is different to the inflow in the next slice, since particles are removed between slices according to the theoretical slice-efficiencies.

$$\eta_i^{Slice} = 1 - \left(1 - \eta_i^{Final}\right)^{\frac{1}{N_{Slices}}}, i = 1 \ldots N_{classes} \quad (4)$$

This slicing enables the chance to study the cyclone as a sequential separation unit, allowing refined experimental studies of this separation unit in future work.

2.3 *Final particle decomposition*

After obtaining the final number distribution the purpose is to follow the time dependent history of each of the resulting particles and/or agglomerates, taking in account that each agglomerate is a result of at least two particles, in order to build the particle size distribution that the cyclone actually "sees".

Taking into account the information on the constitution of each new particle and of the final number of particles, it is possible to build an information matrix (INFO matrix). This matrix allows to follow the path of each initial particle up to the final agglomerates, and to calculate (backtrack) the effective efficiency of each class of initial particles.

In Equation 5 the new class efficiency is calculated using the referred information matrix. The matrix has dimensions $N_{classes} \times N_{diameters}$ and each $N_{diameters}$ has a corresponding efficiency (η_j) calculated by the Mothes and Loffler (1988) model for the cyclone or by the Salcedo et al. (2007) model for the recirculating system, whatever the case.

$$\eta_i^{new} = \frac{\sum_{j=1}^{N_p} INFO_{i,j} \times \eta_j}{\sum_{j=1}^{N_p} n_{i,j}}, i = 1 \ldots N_{classes} \quad (5)$$

3 MODEL INPUTS/OUTPUTS

In this section we present some results obtained using the proposed model. As a first remark, the results presented were obtained with the cyclone geometry proposed by Salcedo and Candido (2001), with internal diameter = 447 mm and inlet mean velocity of 15 m/s, without partial recirculation of gases and particles.

To better visualize the idea behind this model, some trajectories of random particles inside a slice with turbulent flow are presented. Afterwards, the effect of the agglomeration in terms of the number and mass distribution is presented, closing with a sensitivity analysis of some of the major parameters of the model, and of preliminary model results

By solving Equations 1, 2 and 3 to obtain the trajectories of each particle and using this information, their behaviour is calculated inside the control volume. Fig. 2 and 3 present some of the basic steps of the model as an example of two intersecting trajectories and the corresponding generation of an agglomerate.

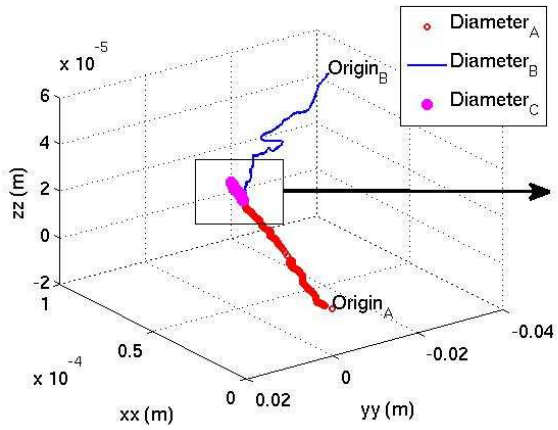

Fig. 2. Trajectories of two colliding particles and of generated agglomerate

Fig. 2 presents the trajectories of two particles with different diameters. The larger particle has a more deterministic trajectory while the smaller particle has a more random trajectory.

If the particles collide in their trajectories resulting in a formation of a new agglomerate, the model has the ability to calculate the new agglomerate trajectory by solving the momentum equations. The resulting agglomerate has a tendency to follow the trajectory of the larger particle, fact that is pictured in Fig. 2.

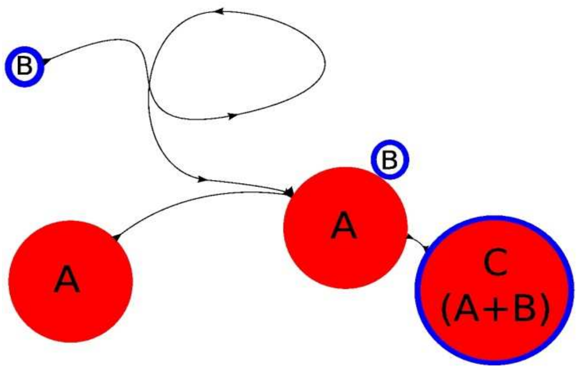

Fig. 3. Diagram of formation of a new particle with mass conservation

Fig. 3 illustrates the calculation of the new diameter of the agglomerate, which must take into account mass conservation of the particles.

The mass distribution is an input to the model and the model converts the information stored in this distribution to a number distribution. After completing the part of the model presented in Section 2.1, the model calculates the final number distribution and recalculates the corresponding mass distribution. Fig. 4 and 5 show a typical example of the initial and final number and mass distributions before and after particle interaction/agglomeration.

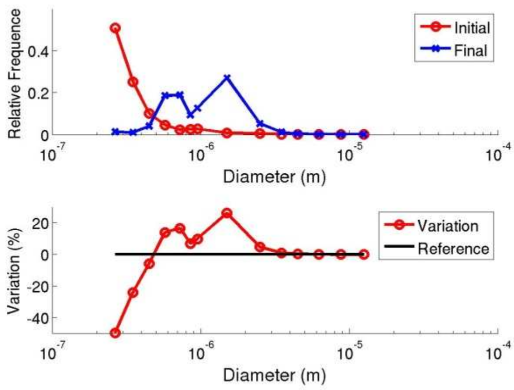

Fig. 4. Changes in the number distribution

Fig. 4 shows that the modal class in the beginning corresponds to the first class (corresponding to a diameter around 0.3 µm).

Analysing the result of the model, there is a displacement of the modal size towards larger diameters. This shows that the smaller particles are disappearing (the variation of the first three classes is negative) and that there is formation of larger particles (the variation of the next five classes is positive).

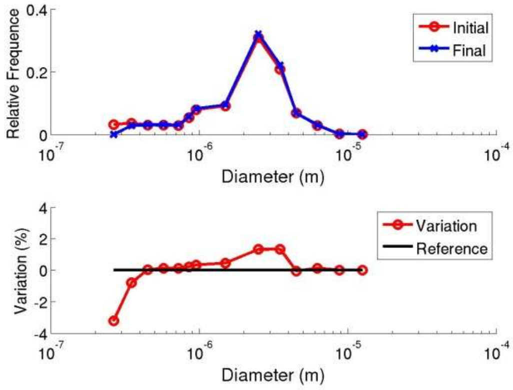

Fig. 5. Changes in mass distribution

Fig. 5 shows the corresponding implications for the initial and final mass distributions. The reduction in the mass of the smaller particles and the increase in the mass of the particles above 1 µm is clearly seen.

Fig. 6-10 show the grade-efficiency curves and the sensitivity to some model parameters. The chosen parameters were the time of interaction, the particle specific gravity, the particle concentration, the cutoff-diameter of the initial distribution, viz, the maximum allowable particle present in the original distribution, and the number of slices that represent the control volume.

In each situation, the reference case has the following values: time of interaction (**10** ms), particle specific gravity (**1500** kg/m^3), concentration (**700** mg/m^3), cutoff-diameter (**12** µm) and number of slices (**5** slices).

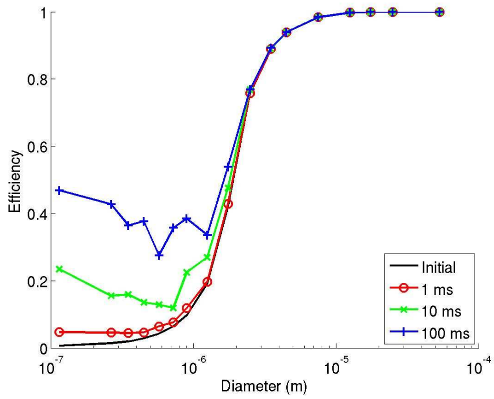

Fig. 6. Time influence: 6 µm, 1500 kg/m^3, 700 mg/m^3, 5 slices

Synthesising the information obtained in the sensitivity analysis of the model, we can observe that as the residence time of the gas increases (Fig. 6), higher efficiencies are obtained for the smaller particles.

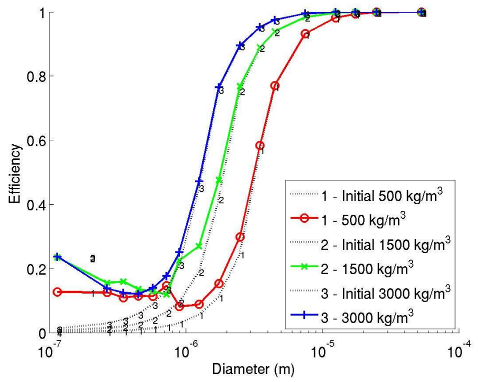

Fig. 7. Specific gravity influence: 10 ms, 6 μm, 700 mg/m^3, 5 slices

Fig. 7 presents the initial efficiency without agglomeration, and the grade-efficiencies obtained by varying the particle specific gravity.

The predicted grade-efficiencies increase with the specific-gravity as expected. In terms of agglomeration, the agglomeration model leads to higher efficiencies as we increase this parameter, due to the initially higher theoretical efficiency for the larger particles, which act as targets to the finer ones.

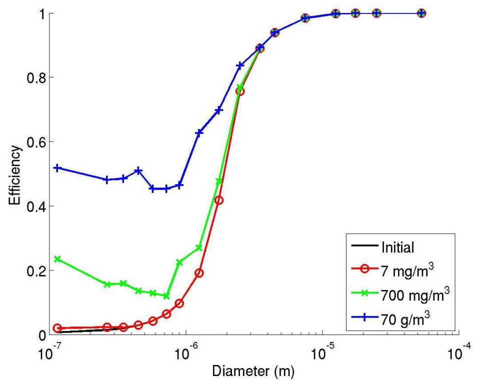

Fig. 8. Concentration influence: 10 ms, 1500 kg/m^3, 6 μm, 5 slices

Another important parameter of the model is the particle concentration, and Fig. 8 gives the effect of this parameter. If the concentration is very low, the collision and consequent agglomeration will be two phenomena with almost no significance due to the small number of particles present in the control volume.

Therefore, as expected with low concentration, the results after agglomeration are almost those initially predicted by Mothes and Loffler (1988). On the other hand, for the higher concentrations, the agglomeration phenomena has increasing relevance, so the final efficiency of the smaller particles increases substantially over the base-case.

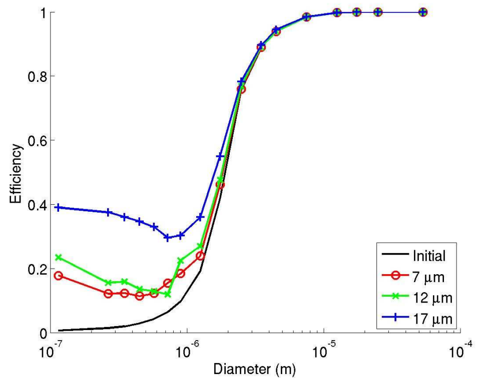

Fig. 9. Cutoff-diameter influence: 10 ms, 1500 kg/m^3, 700mg/m^3, 5 slices

Fig. 9 shows the influence of the cutoff-diameter on the initial distribution. This parameter determines directly the initial highest diameter available for collision and as this parameter increases, higher efficiencies are obtained for the smaller particles.

This is justified by the fact that, as we increase the cutoff-diameter, we have more larger particles to interact, and injecting more quantity of larger particles implies that there are more target particles available, with collection efficiencies around 100 % to collect the smaller ones. In this case we can observe that the results are also much smoother, which means that the "noise" of the results has been reduced, as more particles were injected in the control volume.

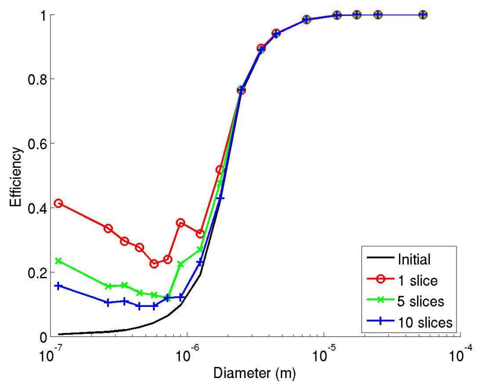

Fig. 10. Number of slices influence: 10 ms, 1500 kg/m^3, 6 μm, 700 mg/m^3

In Fig. 10 we can observe that as we increase the number of slices, the efficiency of the smaller particles decreases.

In the case with only one slice (viz, the entire cyclone volume), the larger particles are always available to collide in this control volume, while in the five or ten slices cases, as the larger particles have high collection efficiencies, these are removed between slices, not being present along the axial downward displacement in the cyclone to collide and/or agglomerate in the final slices of the control volume.

4 PRELIMINARY EXPERIMENTAL RESULTS

Fig. 11 shows two cumulative particle size distributions. The dashed-line corresponds to an undisclosed pharmaceutical chemical (ρ=800 kg/m^3, inlet concentration=1.6 g/m^3) while the solid line corresponds to a commercial-grade PVC (ρ=700 kg/m^3, inlet concentration=10 g/m^3).

In both cases, a cyclone with internal diameter = 447 mm and inlet mean velocity of 28 m/s, without partial recirculation of gases and particles was used.

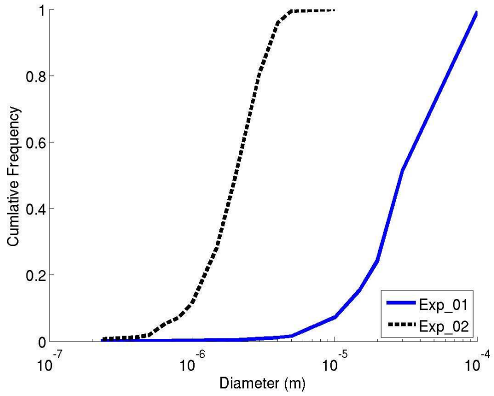

Fig. 11 – Cumulative Particle Size Distributions

The experimental collection efficiencies and model predictions are presented in Fig. 12, where it is seen that the PACYC model predicts fairly well the experimental data.

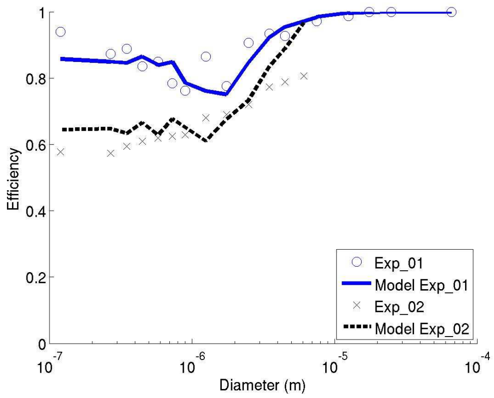

Fig. 12 - Experimental Data and PACYC preditions

5 CONCLUSIONS

The agglomeration model presented in this work has yet some parameters which must be further studied, like the collision properties or the influence of the material under study, but at the present moment, the model can predict in qualitative manner the increased efficiencies for the smaller particles, fact experimentally observed by several authors.

The agglomeration phenomena seems to be a good justification of the large observed collection efficiencies obtained experimentally for fine particles using cyclones. and we conclude that this model may lead to results closer to reality.

The PACYC model is an improvement of the existing models developed to predict grade-efficiency curves in gas-cyclones. It is expected that, after further studying the model parameters, theoretical results may better represent the experimental ones, allowing a more correct design and optimisation of reverse-flow gas-cyclones. This work is currently under development.

6 ACKNOWLEDGEMENTS

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