Hurricane® and ReCyclone® systems: Modelling and application to emission control and value added product recovery

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Abstract

The development of high efficiency Hurricane® and ReCyclone® systems allows their application either to emission control or to value added product recovery. The purpose of this paper is to present not only the performance of these systems, but also a model to predict in a more realistic way the collection efficiency of a gas cyclone with or without partial recirculation.

ReCyclone® systems consist in an optimized reverse-flow cyclone (collector) combined with partial recirculation of un-captured particles via a straight-through cyclone (concentrator). As in improvement of the ReCyclone, it is possible to include a DC electric field in the concentrator to enhance even further particle recirculation to the cyclone collector, leading to higher collection efficiencies.

To model the system, a computer program (PACyc - **P**article **A**gglomeration in **Cyc**lones) was developed. which starts by estimating the collection efficiency of a system without agglomeration, relying on previously published models to predict collection efficiency either for isolated cyclones or for cyclones with mechanical/electrostatic recirculation.

Some experimental results obtained in emission control and value added product recovery are presented, together with the corresponding PACyc predictions on grade and global collection efficiencies.

Keywords: Optimized Cyclones; Turbulent Dispersion; Particle Agglomeration; Recirculation Systems; Emission Control; Value Added Product Recovery

1 Introduction

Cyclones are gas-solid separation devices used in a wide variety of industries, mainly for the recovery of raw or process materials, as collectors for compliance with particulate emission limits, and as primary collectors to decrease the burden on more expensive secondary collectors. Cyclones are essentially attractive for operation at high temperatures and/or pressure, and the development of highly efficient cyclones, especially for fine particles below 2-3μm in diameter, could have a significant impact in the chemical processing industries.

Upon obtaining a numerically optimized cyclone geometry (referred as Hurricane®) [1–4], in order to increase even more the system performance, partial recirculation of gases to the cyclone has been adapted [5; 6].

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Taking into account the three major options available to build such a system, Wysk et al. [7] have built a straight-through gas cyclone placed upstream of the reverse gas cyclone.

This information was taken into account and Salcedo et al. [5] have shown that by placing the reverse-flow cyclone (collector) upstream form the concentrator, higher efficiencies could be obtained. These of systems have very high collection efficiencies at laboratory, pilot and industrial scales (these kind of systems are referred as ReCyclone® MH). These authors have also proposed a model to predict the overall collection efficiency of this system, derived from the Mothes and Löffer's model [8] to predict isolated gas cyclone collection efficiency.

Finally, the inclusion of an electrostatic field in the recirculation system will increase the amount of recirculated particles and consequently the global efficiency. Combining all these steps, the Recyclone® EH was developed which as been proven as a good alternative to filters and electrostatic precipitators, obtaining, at moderate loads, very high collection efficiency even for submicrometric particles.

Previous work [1; 4–6; 9–13] has shown at laboratory, pilot and industrial-scales that these systems can have much higher collection for fine particles (below about 3μm) than predicted by classical models, viz. grade-efficiency curves show a minimum in collection at an intermediate particle size (ranging from about 0.8 to 2 μm). In spite of these hook-like curves not always occurring [5; 12], this abnormal behavior for fine particles is attributed to agglomeration within the cyclone turbulent flow field, as initially postulated by Mothes and Löffler [14], much as it happens in recirculating fluidized beds [15; 16].

This phenomenon inside the isolated gas cyclone has been studied by Paiva et al. [17], culminating in the PACyc model. This model considers that upon collision/agglomeration of fine particles by larger ones, the smaller particles will be captured as much larger particles, viz. with much higher collection efficiency than that predicted by any of the currently available models.

This agglomeration effect is even more noticeable if the cyclone is highly efficient above about 2-3 μm, i.e., above 90-95% collection, as it indeed happens with numerically optimized cyclones [1; 3; 4], and especially with recirculation systems (with or without an electric field) [5; 6].

2 Modeling

Figure 1 presents the system studied in this work, composed by a numerically optimized reverse-flow gas-cyclone and a straight-through cyclone (referred here as concentrator).

To use the PACyc model to predict the collection efficiency of the system with partial recirculation, it is not only necessary to know the geometrical parameters of the system but also the operating conditions and several simulation parameters. To predict each system efficiency, several models are used.

2.1 Reverse flow cyclones efficiency estimation

There are several models available to predict the collection efficiency in reverse flow gas-cyclones. As referred before, previous work [9; 18; 19] has shown that the Mothes and Löffler model [8] gives, on average, the best agreement with available data. Thus, this model was retained as the model used to predict grade-efficiency in isolated cyclones, in the absence of particle collision/agglomeration, viz., the baseline curve for isolated cyclones.

In order to determine the collection efficiency, a mass balance is established between the region of escaping particles (upstream flow) and the entry area.

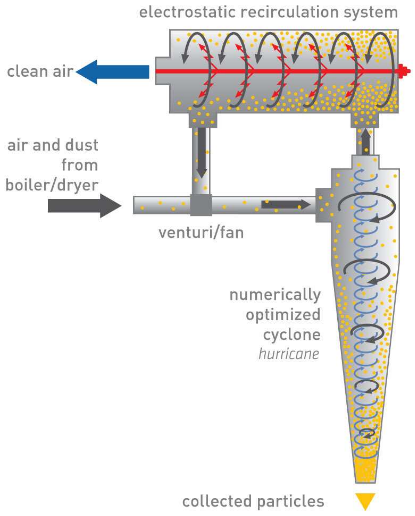


Fig. 1: System studied in this work

2.2 Straight-trough cyclone (concentrator)

In order to predict the behavior of the system with recirculation, the model developed by Salcedo et al. [5] is considered.

The main hypothesis assumed are adapted from the ones in the Mothes and Löffler [8] model, considering also that the processed particle size distribution (PSD) is updated in an interactive procedure, until the change in the particle size distribution is less than a specified error. This process is shown in Figure 2.

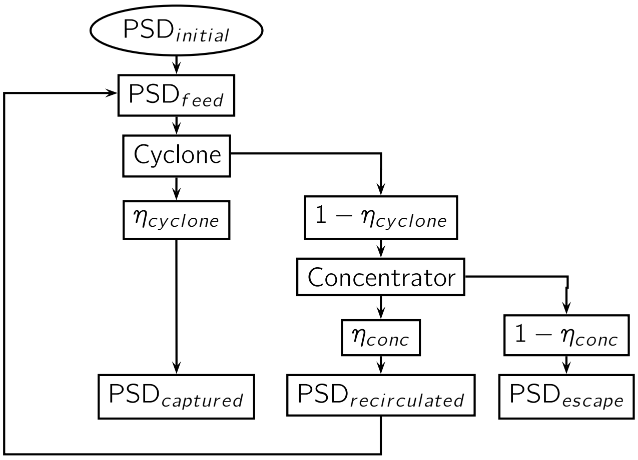


Fig. 2: Iterative process concerning the processed particle size distribution

Finally, and similarly to isolated cyclones, in order to determine the collection efficiency of a systems with recirculation, a mass balance is established between the inlet and outlet of the recirculator.

2.3 Particle charging and collection in electric fields

Concerning this subject, several authors proposed different approaches to this matter, but the combination of classical models [20–22] leads to a good enough approximation of the reality occuring in the electrostatic recirculator.

Figure 3 is a visual representation of the major steps involved in this procedure, where the circles stand for input/output to/from the model, while the boxes stand for mathematical operations.

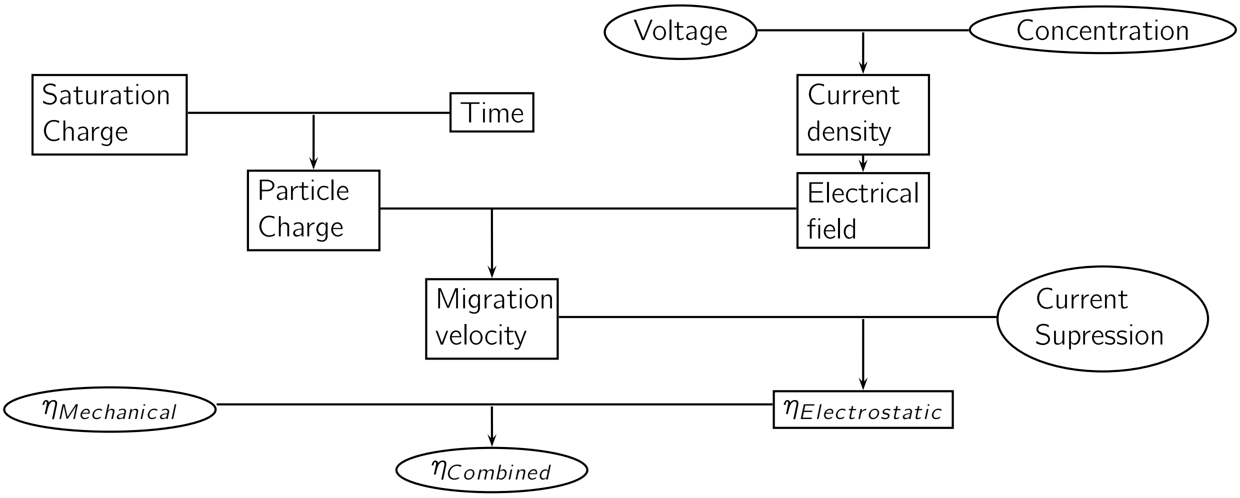


Fig. 3: Information flow diagram to illustrate the internal operations of the electrical model

2.4 Interparticle Agglomeration Highlights

The agglomeration effect taken into account in PACyc [17] is based on the Sommerfeld model [15; 23] of particle agglomeration in turbulent flows.

The intrinsic procedures of the PACyc model are shown in Figure 4. The model starts by calculating the fluid velocity in the control volume, and next the trajectories of each individual particle injected in this control volume. Using a probabilistic criteria, the model defines if particles collide and in case of collision, using an energetic criteria defines if the collision results in agglomeration.

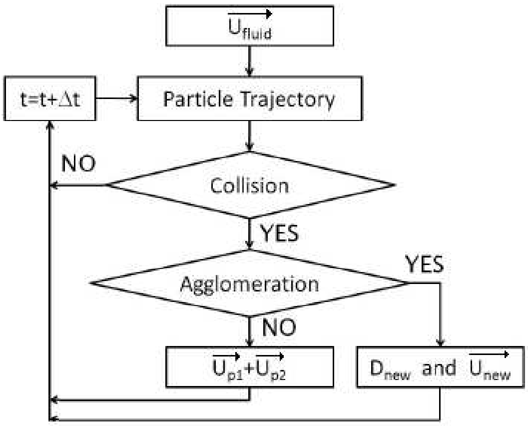


Fig. 4: Representation of interparticle agglomeration model

2.5 Model integration

In order to easily understand integration of the various models, Figure 5 is a simple representative outline of the connection of the major constituents of PACyc applied to systems with recirculation, as presented in this work.

It is possible to see four different decision zones (marked by diamonds) and each of the global procedures is assembled in the rectangles. With this configuration, it is possible to obtain: cyclone,

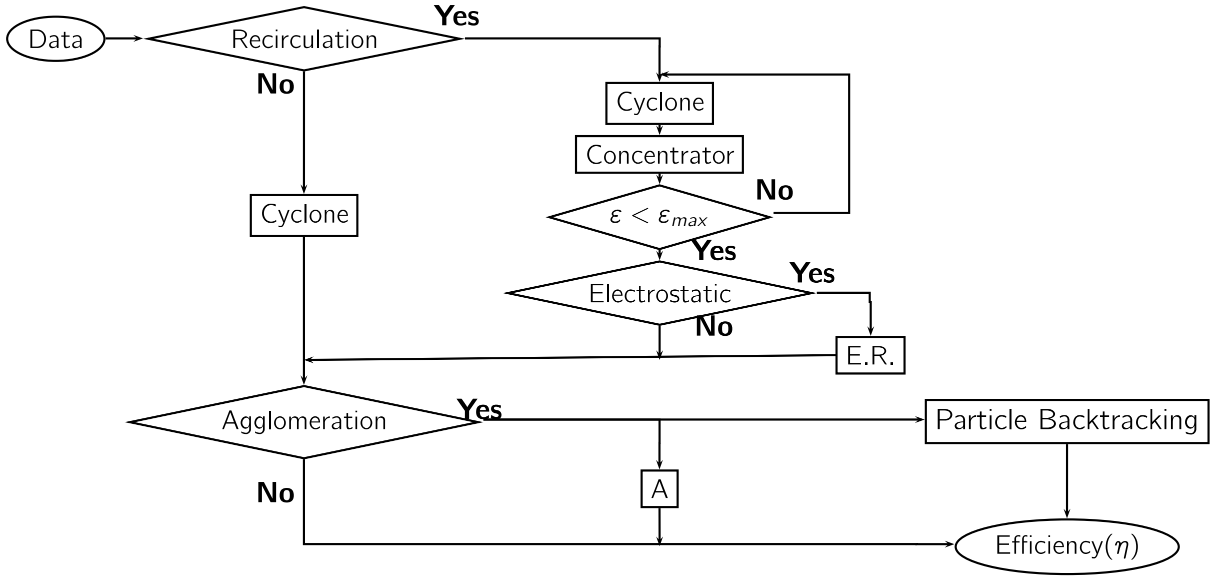


Fig. 5: Representation of the different models integration

cyclone with recirculation (with or without electric field) and in all cases, it is possible to consider or neglect particle agglomeration.

However, it is important to refer that PACyc is more than a model integration, since PACyc can rebuild the grade efficiency curves of the several systems configurations, considering particle agglomeration and respective backtracking to the originally injected particles (history rebuild). This subject is extensively shown for cases with isolated cyclones in Paiva et. al [17].

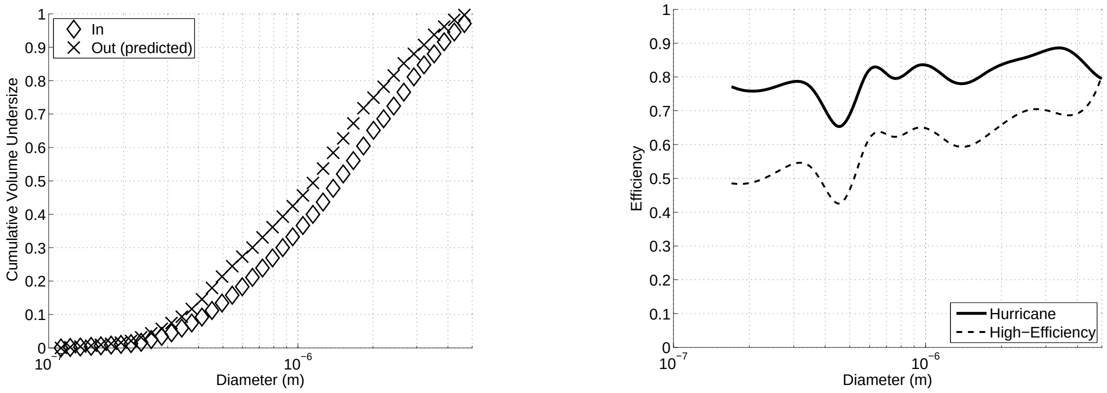
3 Experimental results and model prediction

In this section three case studies are presented. For the first case, a pilot-scale numerically optimized cyclone [3; 4] with internal diameter of 450 mm without partial recirculation of gases and particles is used. For the second case (experimental with mechanical recirculation), a similar cyclone was fitted to a concentrator of the same diameter at the industrial site, and particles were fed directly from the industrial process. For the case with electrically enhanced separation in the concentrator, a set of cyclones with internal diameter of 1850 mm and concentrators of 800mm was simulated by PACyc. For a more direct and valid comparison, in all cases, the cyclone inlet mean velocity was $\approx 15{-}20 m.s^{-1}$. Finally, as a reference, the experimental grade-efficiency curves were obtained with simultaneous inlet/outlet isokinetic sampling using constant volume samplers (Techora Bravo), in GFA glass fiber filters.

Figures 6 refer to a case of calcined kaolin. Figure 6a shows off-line measurements using a Coulter LS230 laser sizer and emissions using the grade efficiency curves predicted by PACyc ($\rho_p = 2677 kg.m^{-3}$, inlet concentration $\approx 500\ g.m^{-3}$ at 650 °C). Figure 6b presents the comparison between the predicted grade-efficiency curve for Hurricane cyclones and another high-efficiency cyclone.

Figures 7 refer to a case of value added chemical product recovery. Figure 7a shows off-line measurements using the Coulter laser sizer ($\rho_p = 1471 kg.m^{-3}$, inlet concentration = 7.73 $g.m^{-3}$ at 120 °C), while Figure 7b presents the comparison between the predicted grade-efficiency curves (worst and probable cases) and the obtained experimentally for both measuring methods.

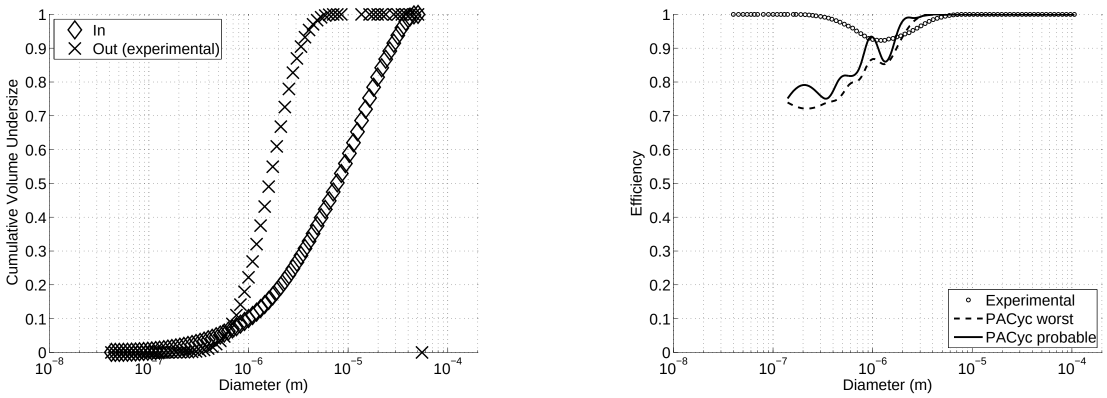
Figures 8 refer to a case of excess air of clinker cooler. Figure 8a shows off-line measurements using a Coulter LS230 laser sizer and emissions using the grade efficiency curves predicted by PACyc (ρ_p



(a) PSD at the inlet of the system and in emissions (predicted by PACyc for Hurricane®)

(b) Grade-efficiency Curves

Fig. 6: Case 1 - Hurricane® application example: simulation of calcined Kaolin

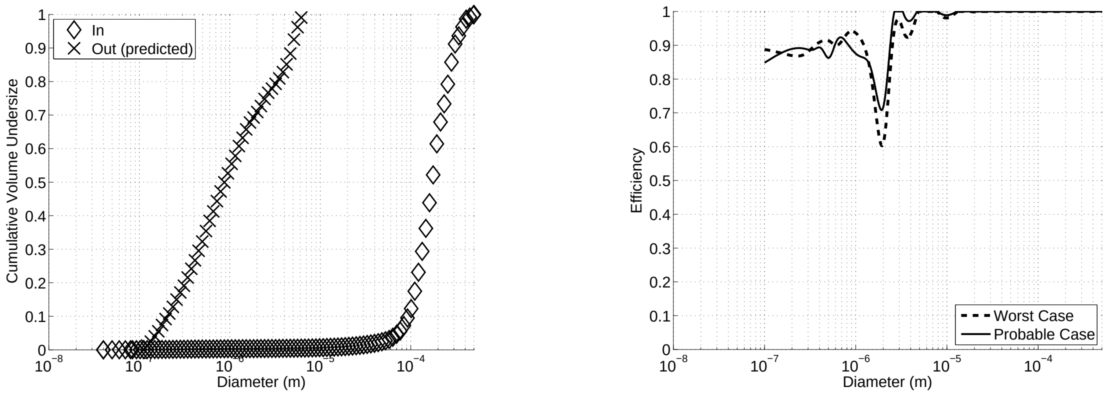


(a) PSD at the inlet of the system and in emissions (experimental)

(b) Grade-efficiency Curves

Fig. 7: Case 2 - ReCyclone® MH application example: value added product recovery

= 3110 $kg.m^{-3}$, inlet concentration $\approx$ 50 $g.m^{-3}$ at 120 °C). Figure 8b presents the predicted grade-efficiency curve for the studied ReCyclone EH system.



(a) PSD at the inlet of the system and in emissions (predicted by PACyc)

(b) Grade-efficiency Curves

Fig. 8: Case 3 - ReCyclone® EH application example: excess air of a clinker cooler

Figure 9 shows the global efficiency as a function of concentration either for the PACyc predictions either for the experimental case, and it noticeable that:

- Hurricane® geometry leads to significantly higher efficiency than other high efficiency cyclone geometries;

- PACyc leads to overall collection efficiencies very similar to the ones obtained experimentally;
- PACyc has very high precision, hence the worst and probable cases show very similar results;

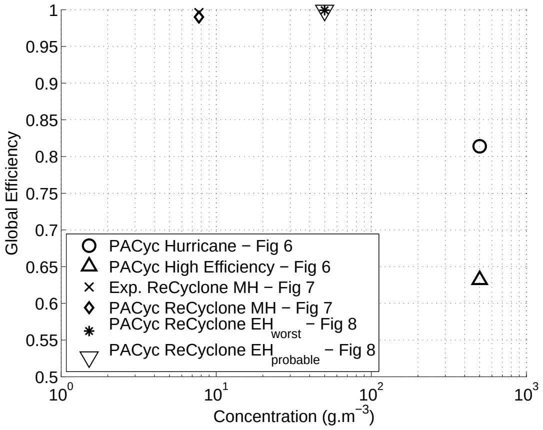


Fig. 9: Global efficiency for each of the cases: experimental and predictions

Considering all the figures shown in this section, it is possible to state that the presented technologies are well suited for decreasing particle emission of fine particles. In terms of prediction/simulation, the PACyc model seams to be a good tool in order to design optimal systems for each situation, since it predicts reasonably well the experimental data, predicting global efficiencies near to the experimentally obtained.

4 Conclusions

Numerically optimized cyclones and ReCyclone® systems were designed by solving appropriate optimization problems. The abnormal high collection of fine submicrometric particles often observed with these systems is attributed to particle agglomeration within the turbulent cyclone flow field, and the PACYC model leads to good predictions of overall efficiency of all these systems.

This model was developed based on the Ho and Sommerfeld [15; 23] particle agglomeration model, superimposed on the Mothes and Löffler [8] particle collection model in isolated cyclones or on the Salcedo et at. [5] model for mechanical recirculation systems. Coupling these with electrostatic precipitator classical models [20–22] enables the predictions of these recirculation systems with a superimposed electric field.

On average, Hurricanes® can reduce emission of comparable pressure drop high efficiency cyclones by about 40-60%, mechanical ReCyclones® by about 75-80% and ReCyclones® EH by about 90-95%. Their effectiveness has already been shown at laboratory, pilot and industrial scales for a variety of very fine dusts (relevant for mineral and chemical industries), including dusts as calcined kaolin, value added chemical product or excess air from clinker coolers.

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