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Cyclones' Project Optimization by Combination of an Inequality Constrained Problem and Computational Fluid Dynamics Techniques (CFD)

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The cyclone is, in its most basic form, a stationary mechanical device that utilizes centrifugal force to separate solid particles from a carrier gas. The collection efficiency, one of the most important performance parameters at a cyclone project is directly related to operational conditions and geometric relations. However, in most cases, only the geometric relations of cyclones are possible to change, being necessary to do an optimization study to obtain the best geometric configuration. The optimization problem proposed in this paper aims to obtain a cyclone with collection efficiency higher than those presented by the Lapple and Stairmand cyclones, under the same operational conditions and with pressure drop less than those cyclones. The used methodology basically consists in coupling the CFD code CYCLO-EE_5 (an “in-house” simulator of gas-solid flows in cyclones) in the optimization algorithm COMPLEX, with nonlinear objective functions and inequality constraints.

1. Introduction

The cyclones are widely used for separating particles from a gas stream due to its wide range of operation and simplicity in constructive form, which makes it a device with a low investment cost and maintenance. However, it should be noted that the collection efficiency of cyclones is directly related to operating conditions and geometric relations. Despite this geometrical simplicity, the fluid dynamics of turbulent flow in cyclones is very complex, with various phenomena including recirculation zones, high-intensity turbulent, high conservation of vorticity, among others. As the principles that govern the operation of cyclones have not changed since its inception in the late nineteenth century, more than a century of interventions through research and industrial applications resulted in projects of cyclones with significant improvements. Before the 1960’s, the optimization methods and equipment designs were empirical, based on experiments, intuition or semi-empirical calculations, which were used in the similarity laws and testing models. Those empirical and semi-empirical methods, due to their simplicity, are still widely used in the design and evaluation of cyclones. The objective of this work is to develop a methodology for optimizing the geometric relations of the cyclone separators, in order to operate with high collection efficiency and low pressure drop through CFD techniques coupled with optimization methods.

2. Mathematical Formulation

By studying the vorticial flow of fluid dynamics in cyclones, it is necessary to model both the gas phase and the particulate phase. The particulate phase is presented as an additional complication to the modelling and can be treated through two distinct approaches: the Eulerian or Lagrangian approach. The Eulerian approach considers the phases as interpenetrating and continuous, differentiated by a volume fraction in each control volume and has heterogeneous velocity fields, obeying their own transport equations. In the Lagrangian approach, the solid particles are treated as discrete, and Newton’s law is

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solved for each particle, making it possible to track the particles throughout the fluid. The problem is that the tracking of the total number of particles is still an impractical task due to high demand of computer processing, so stochastic approaches are considered, in which each particle stochastically represents a larger group of particles. The application of CFD techniques in the study of cyclones began in the 80s with the pioneering work of Boysan et al. (1982). In this paper, an Eulerian-Lagrangian model was used in a two-dimensional system, where one phase is gaseous and the other is solid. Even after three decades of studies, this setup is still widely used in studies of cyclones. However, the use of Eulerian-Eulerian models for gas-particle flows have been widely studied in the multiphase flow community, and have become practical for the design and scale-up of industrial systems, since they allow to balance the computational cost of the simulations with the accuracy in the description of the flow (Passalacqua and Fox, 2011). Some researchers also propose new numerical models in the presence of *n* solid phases representing more faithfully the multiphase flow. Among them, are Ibsen et al. (2007) and Meier et al. (2011).

In this work it is assumed the Eulerian-Eulerian six-phase model, which composes the dedicated code for the vorticial flow into cyclones CYCLO-EE_5, and also an extension of the four-phase model proposed by Meier et al. (2011).

2.1 Eulerian-Eulerian six-phase model

From the Navier Stokes equations, it is possible to obtain the Eulerian-Eulerian six-phase model (a gaseous phase and five solid phases) used in this work. The constitution of this model, requires some simplifying assumptions: (a) presence of a real fluid phase (gas phase) and five hypothetical phases (solid phases); (b) the five different solid phases may be represented by each particle diameter, density and volume fraction; (c) the flow is diluted or, inviscid for the solid phases, and the Reynolds tensor of the particulate phase can be neglected; (d) The flow becomes symmetrical soon after the asymmetric entry of the cyclone, making it possible to admit the symmetry of the axial axis and the 3D-symmetrical model; (e) the flow is incompressible and isothermal; (f) pressure force acts only on the gas phase; (g) transfer of momentum at the interface between the phases is predicted by drag force model.

As a starting point, it was used the volumetric fraction of gaseous phase (f_g) for developing the model. This fraction is the ratio of the volume of the gaseous phase and the total volume of flow in the spatial domain, and can be expressed by:

$$f_g=\frac{Q_g}{Q_g+\sum_{j\neq i=1}^{5}\lambda_{i,j}Q_{si}}\quad ;\text{ with } (i=1,\ldots,5)\qquad \text{being,}\quad \lambda_{i,j}=\frac{|\mathbf{v}_i|}{|\mathbf{v}_j|} \tag{1}$$

In Eq(1), f_g, Q_g and Q_{si} represent the fraction of total volume occupied by the gaseous phase, the volume of the gas phase and the solid phase *i*, respectively; $\lambda_{i,j}$ is the ratio between the modules of the velocity vector of the phases *i* and *j* (if the relationship between modules of the velocity vector of the phases *i* and *j* is unitary, the flow is considered homogeneous, otherwise it is considered heterogeneous); $|\mathbf{v}_i|$ and $|\mathbf{v}_j|$ are the modulus of the velocity vector in phase *i* and *j*, respectively. In the multiphase flow, it is necessary to consider the influence of solid phases on the flow. This can be accomplished by introducing the volume fraction of each phase. The equations of mass and momentum for the gas and solid phases, in Eulerian approach, can be written as follows.

Mass conservation in the gas phase:

$$\frac{\partial}{\partial t}\left(\rho_g f_g\right)+\nabla\cdot\left(\rho_g f_g \mathbf{v_g}\right)=0 \tag{2}$$

Mass conservation in the solid phase:

$$\frac{\partial}{\partial t}\left(\rho_{si} f_{si}\right)+\nabla\cdot\left(\rho_{si} f_{si}\mathbf{v_{si}}\right)=0\quad ;\text{ with } (i=1,\ldots,5) \tag{3}$$

Momentum conservation in the gas phase:

$$\frac{\partial}{\partial t}\left(\rho_g f_g \mathbf{v_g}\right)+\nabla\cdot\left(\rho_g f_g \mathbf{v_g}\mathbf{v_g}\right)=-f_g\nabla\cdot\left(\mathbf{T}_g^{eff}\right)+\rho_g f_g\mathbf{g}-\nabla p+\sum_{i=1}^{n}\left(\mathbf{F}_{drag}\right)_{g,si} \tag{4}$$

Momentum conservation in the solid phase:

$$\frac{\partial}{\partial t}\left(\rho_{si} f_{si}\mathbf{v_{si}}\right)+\nabla\cdot\left(\rho_{si} f_{si}\mathbf{v_{si}}\mathbf{v_{si}}\right)=\rho_{si} f_{si}\mathbf{g}-\left(\mathbf{F}_{drag}\right)_{si,g}+\sum_{j=1\neq i}^{n}\left(\mathbf{F}_{drag}\right)_{si,sj}\quad ;\text{ with } (i=1,\ldots,5) \tag{5}$$

In Eq(2) to Eq(5), f, ρ and $\boldsymbol{v}$ represent, respectively, the volume fraction, the density and the velocity. The subscripts g, si and sj indicate the gas phase and the solid phases i and j. In Eq(4) and (5), $\boldsymbol{T}_g^{eff}$, $\boldsymbol{g}$, p and $\boldsymbol{F}_{drag}$, represent, respectively, the effective stress tensor in the gas phase, the acceleration of gravity, the thermodynamic pressure and the drag forces acting between the phases. The equations for turbulence closure, numerical methods, the initial and the boundary conditions used by the CYCLO-EE_5 code can be found in Meier et al. (2011).

3. Methodology

The proposed methodology is an extension of Sgrott Jr. et al. (2012), and consists in coupling of the simulator of gas-solid flow in cyclones CYCLO-EE_5 code, in the optimization algorithm COMPLEX. The CYCLO-EE_5 code is the result of improvement of earlier versions developed by Meier (1998). The good results obtained with the Eulerian-Eulerian model in the works of Meier and Mori (1998, 1999), Vegini et al. (2008) and Meier et al. (2011) were crucial for this approach to be adopted as standard in the CYCLO-EE_5 code. The finite volume methods have been used to discretize the partial differential equations of the model using the SIMPLEC (SIMPLE Consistent) method for pressure-velocity coupling in a 3-D-space domain with a 3-D symmetric cyclone inlet. The modelling of turbulence is formulated by combining the k-ε model for radial and axial components of the Reynolds stress, and the mixture Prandtl theory for the tangential components. More details about this model are described by Meier and Mori (1999).
The optimization algorithm COMPLEX (Box, 1965) used in this work, consists of maximizing an objective function subject to inequality constraints (Figure 1-a), and in this case, it means the maximization of the collection efficiency (η) establishing a maximum limit for the corresponding pressure drop (ΔP). As manipulated variables, seven of the eight basic geometric relations of a cyclone (Figure 1-b) were chosen, and each of the seven variables had a restriction for upper and lower limits. The geometric constrains imposed on the manipulated variables were chosen considering as reference the geometric relations of Lapple and Stairmand cyclones, using 20 % increase for the upper constrains and 20 % decrease for the lower ones. As a restriction for pressure drop it was used the value obtained by the Stairmand cyclone (η=93.29 % ; ΔP=2,150 Pa), because it presents a better collection efficiency when compared to the Lapple cyclone (η=88.43 % ; ΔP=1,810 Pa).

(a)

$$\begin{cases} \text{Maximize } F_{\text{Objective}} = \eta, \text{ if } \Delta P \le \Delta P_{max} \\ \text{Maximize } F_{\text{Objective}} = \dfrac{\eta}{\Delta P}, \text{ if } \Delta P > \Delta P_{max} \\ \text{Subject to the Geometric Restrictions,} \\ \qquad \begin{cases} (Ds)_{Lower} \le Ds \le (Ds)_{Upper} \\ (Dl)_{Lower} \le Dl \le (Dl)_{Upper} \\ (Ls)_{Lower} \le Ls \le (Ls)_{Upper} \\ (Lc)_{Lower} \le Lc \le (Lc)_{Upper} \\ (Lco)_{Lower} \le Lco \le (Lco)_{Upper} \\ (Le)_{Lower} \le Le \le (Le)_{Upper} \\ (b)_{Lower} \le b \le (b)_{Upper} \end{cases} \end{cases}$$

(b)

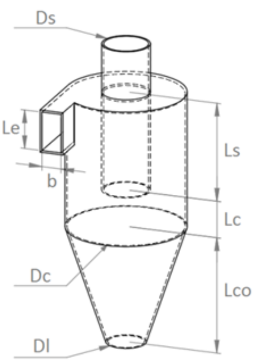

Figure 1: (a) Objective functions subject to inequality constraints, where η is the collection efficiency and ΔP is the pressure drop; (b) Geometric relations of a cyclone.

The optimization method consists in building a geometric figure with a number of dimensions at least equal to the number of manipulated variables plus one. In this particular case, there were eight variables, and from those, a sixteen-dimensional optimization algorithm COMPLEX (twice the number of geometric relations) was chosen. The generation of those sixteen points is conducted by a random number generator, in which each point represents one different geometric configuration of a cyclone according to Figure 2. The procedure starts with the generation of the initial condition, which corresponds to the sixteen initial geometry of the first iteration of the system. All of the sixteen initial geometries are simulated through the CYCLO-EE_5 code, and the results of collection efficiency and pressure drop are subjected to evaluation of the objective function and constraints. The cyclones that present the worst performance in terms of the objective function are discarded and a new one is generated by the optimization algorithm COMPLEX. This procedure is repeated until the objective function is maximized, while the standard deviation obtained on the average of the collection efficiency or pressure drop of the iteration is minimized.

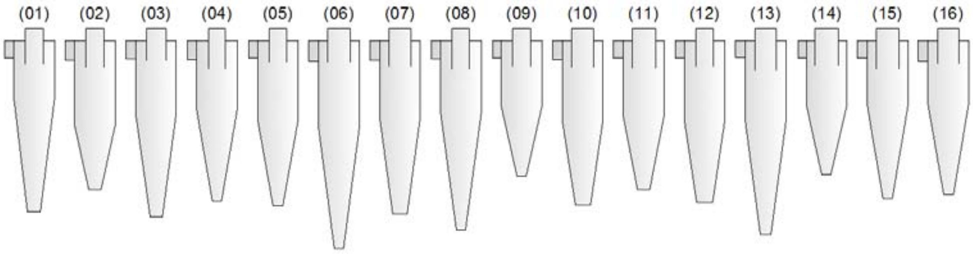

Figure 2: First iteration of optimization algorithm COMPLEX, where each point represents one different geometric configuration of cyclone.

The operational condition used for gas flow is 2,200 m^3/h at 25 °C with a loading ratio of 15,000 mg of particles per cubic meter of gas (diluted flow). The properties of the five particulate phases are shown in Table 1.

Table 1: Properties of the particulate phases.

	Solid phase 1	Solid phase 2	Solid phase 3	Solid phase 4	Solid phase 5
Size	12 μm	10 μm	8 μm	6 μm	4 μm
Density	1,400 kg/m^3	1,400 kg/m^3	1,400 kg/m^3	1,400 kg/m^3	1,400 kg/m^3
Fraction	15.87 %	17.13 %	34.00 %	17.13 %	15.87 %

4. Results and Discussions

As a first analysis, it is possible to observe the maximization of the objective function through graphics of collection efficiency and pressure drop for the cyclones of the first and last iteration (80^{th}). In the first iteration (Figure 3), it can be seen a great variety of cyclones, some operating with a high collection efficiency, and consequently high pressure drop, while others have very low efficiency of collection, with a low pressure drop. This diversity was caused by the random generation of cyclones within the geometric constraints imposed. However, when analysing the results obtained in the last iteration (Figure 4), it is possible to see a great homogeneity of the results, besides maximizing the collection efficiency (more than 93.29 %) with pressure drop within the constraints imposed on the method (less than 2,150 Pa).

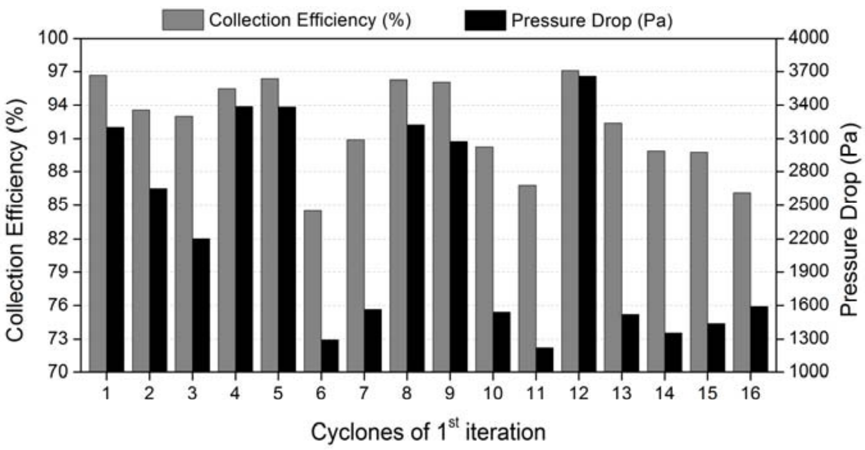

Figure 3: Collection efficiency (left axis) and pressure drop (right axis) obtained at the first iteration.

Another way to analyse the optimization is by making an average of all the results obtained for the collection efficiency and pressure drop for each iteration. In Figure 5, it is possible to notice that at the beginning of the method, there is a decrease in average efficiency, reaching lower values in the ninth iteration. This behaviour can be explained due to the restrictions imposed on the objective function, since the method tends to eliminate the cyclones that are presenting pressure drop exceeding the maximum one pre-established ($\Delta P_{Stairmand}$=2,150 Pa). After eliminating the cyclones with greater pressure drop, the method begins to search the greater objective function possible within the restrictions imposed.

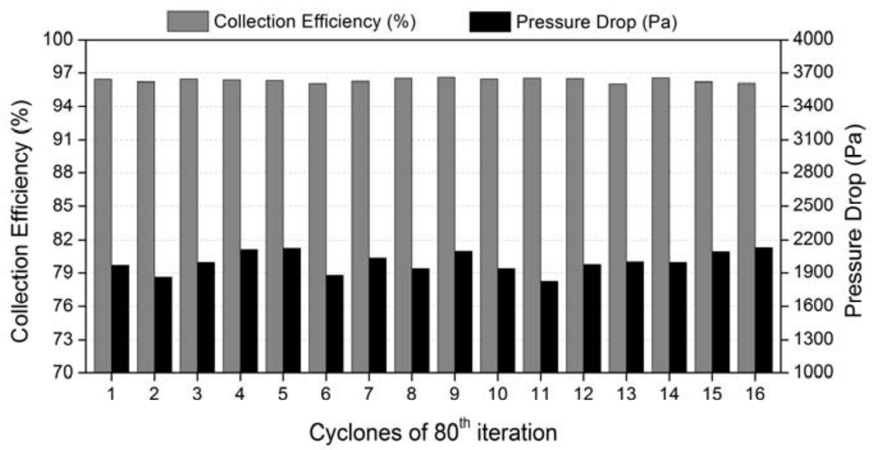

Figure 4: Collection efficiency (left axis) and pressure drop (right axis) obtained at the last (80th) iteration.

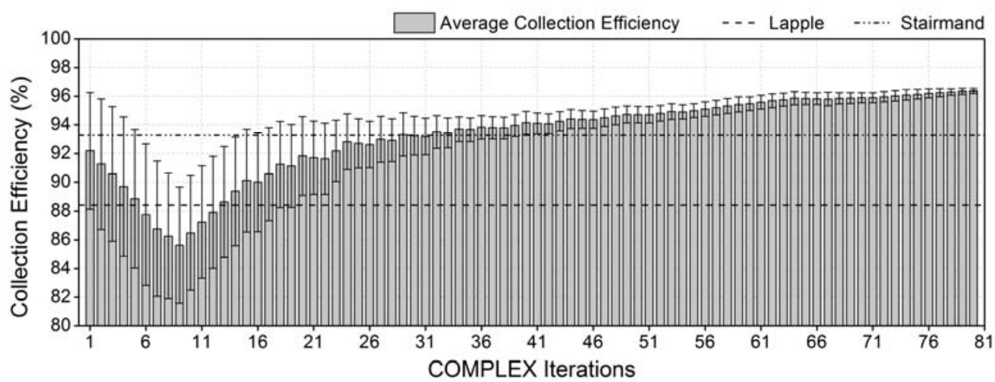

Figure 5: Evolution of the average collection efficiency along the iterations.

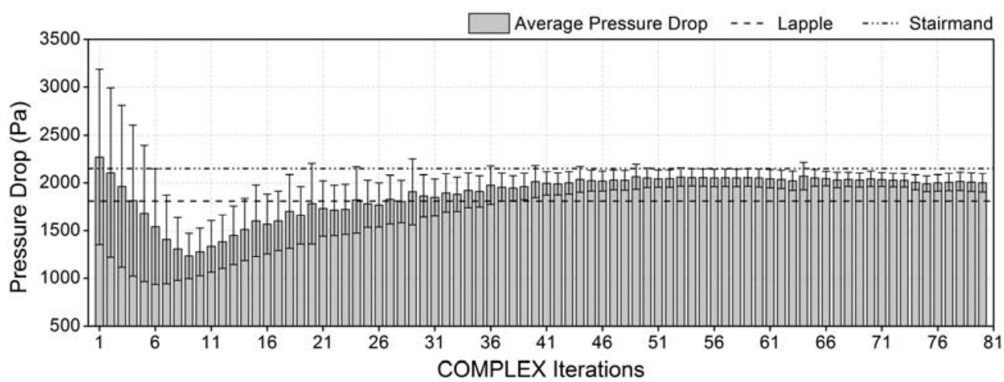

Figure 6: Evolution of the pressure drop average along the iterations.

In Figure 6, it is observed that during the iterative process, some cyclones with high pressure drop are still generated, but in the following iteration they are replaced by a corresponding one with lower pressure drop. Another factor that can be highlighted in the last iteration (80^{th}) is the great value of average collection efficiency (96.36 % with ±0.17 % of standard deviation) and the average pressure drop was 2,000 Pa with ±95 Pa of standard deviation. Another evidence that proves the efficiency of the optimization method is the steady decline of the standard deviation along the iterations. Finally, the last analysis of the optimization process is the geometrical evolution of the cyclones. In Figure 7, it is possible to observe that the geometries become more similar at the last iteration of the optimization process, in comparison with the first one (Figure 2), confirming the search for a maximized objective function with a common geometry.

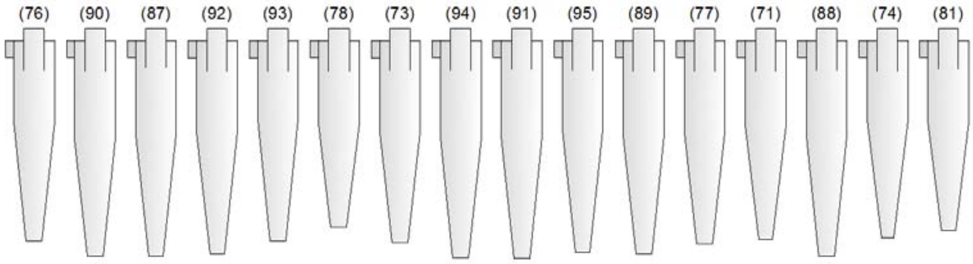

Figure 7: Last iteration (80th) of optimization algorithm COMPLEX, in which each point represents one different geometric configuration of cyclone.

5. Conclusions

From the results presented in this work, it is possible to state that the proposed methodology for the geometric optimization of cyclones showed satisfactory results within the operational limits established. The results show that with a small level of geometric change of the Lapple and Stairmand cyclones, it is possible to achieve results of collection efficiency superior to those presented by such cyclones, with a cost of lower pressure drop. It is also worth emphasizing the importance of using CYCLO-EE_5 code for simulation of cyclones, as it presents reliable results at a computational much lower cost than that required by current commercial software. The next step of this work is to reduce the pressure drop using internal accessories as can be seen in Noriler et al. 2004.

6. Acknowledgement

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