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Effects of the gas outlet duct length and shape on the performance of cyclone separators

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ABSTRACT

In most published studies regarding the numerical simulation of cyclone separators, the gas outlet duct is usually treated as a short straight duct, differing considerably from the experimental apparatus, in which a relatively long duct followed by a curve, or vice versa, is generally used. This work focuses on the influence of length and shape of the outlet duct on the grade efficiency and pressure drop inside a small cyclone separator. The results are obtained through Large Eddy Simulation of the fluid flow inside the separator, coupled with a concomitant Lagrangian description-based on Newton's second law-of the dispersed phase. More than thirty different outlet duct configurations, including different lengths, curves, curves positions and curvature radii were simulated. The results show that the cyclone gas outlet duct may affect the cyclone performance: the pressure drop initially decreases with duct length until a minimum is reached, and from this point on it monotonically increases with duct length. As for the cut off diameter, the relation showed itself much more complex.

1. Introduction

The first cyclone patent was grant to John M. Finch back in 1885 [1]. Although it was a considerably different piece of equipment, it was based on the same physical principles of all cyclone separators. By the early 20s most of the reverse flow cyclone separators already had similar characteristics to today modern cyclones [1]-presenting the typical cylinder on cone geometry. This shows the fast development of this particular class of separators device, indicating its importance in an industrial environment. Currently cyclone separators are probably the most widely used separator devices in industrial environments, being applied in many industrial branches, ranging from food and pharmaceutical industries to mining and petrochemical industries [1–49]. In spite of the great development in its early days, until the 80s basically all obtained development was based in simplified models and/or on empirical correlations, because despite their deceitful simplicity, cyclones are complicated to design and hardly optimized, since the flow field within them is extremely complex.

In the 80s computational power allowed the two-dimensional simulations, through the use of CFD (Computational Fluid Dynamics), of such equipment [2–4]. These early studies demonstrated the potential of the methodology and the importance of turbulence modeling, showing that traditional turbulence models, i.e. κ–ε model, were not applicable to cyclone simulations. Considering the numerical simulation of cyclone separators, a breakthrough point was the use of Large Eddy Simulation in three-dimensional simulations, with the initial works by [5,6]. Derksen and van den Akker [5] were able to correctly reproduce not only the average and RMS velocity components but also, the PVC (Precessing Vortex Core) phenomena, and the operating conditions in Slack et al. [6] included a relatively high Reynolds number. Over the last few years LES simulations have became more common in the study of cyclone separators [5–18], mainly because most RANS models, except for the Reynolds Stress Model or other anisotropic models, cannot predict the Rankine vortex and are therefore not suitable for cyclone simulation. Although turbulence modeling inherently embeds errors, the underlying simplifications are less severe in the LES approach than in the RANS one. RANS models contain constants calibrated for canonical flows, such as jets and wakes, and may not applicable to arbitrary flows. On the other hand, most LES models, such as dynamic model, do not contain any calibration constant, being universally applicable.

As the flow field inside such equipment is complex, some works tried to correlate the influence of operating parameters and geometrical modifications, while most works considered only one or another variable. Considering the geometrical modifications, we can highlight: the inlet duct entrance [10,32,33,52,53]; the outlet duct for the dispersed phase-including changes in the cone apex diameter [20,23,36,54–56]; and changes in the diameter and

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length of the vortex finder [16,22,29,57], just to name a few. A specific parameter which has not received much attention is the overflow duct. To the best of the authors knowledge only [19] were concerned to hold a work devoted, only, to the study of different configurations for the overflow duct.

Schmidt et al. [19] performed several numerical simulations, using the DES (Detached Eddy Simulation) turbulence modeling approach, covering seven different gas outlet duct configurations. They found that even slight modifications in the outlet duct, as an increase in the gas outlet duct length, was able to produce large modifications in the flow field inside the equipment. Unfortunately, although [19] highlighted that some modifications in the outlet duct may considerably reduce the swirl intensity in the separation space, the authors considered only the gas phase in their work. Thus there is virtually no information, in the open literature, regarding the influence of gas outlet duct configurations in the performance of cyclone separators.

In the current work our goal is to assess the influence of the gas outlet duct length and shape in a small cyclone separator performance. Over thirty different Large Eddy Simulations of the fluid flow inside the separator, coupled with a concomitant Lagrangian description-based on Newton's second law-of the dispersed phase were performed. In each of those a different modification in the gas outlet duct, including different lengths, curves, curves positions and curvature radii, were assessed. Some marginal effect of the bend beginning position and radius are expected on the pressure drop. Since the inlet mass flowrate was kept constant in all cases, and the relation $\frac{\text{Bend radius}}{\text{overflow duct diameter}} \geqslant 1$ [58], a larger bend radius will require more pumping pressure, as more energy is needed for the gas to flow through the bend. As for the cut-off diameter, normally a higher pressure drop is associated with higher swirl. This trend was observed for most of the cases investigated. Regarding the bend beginning position, in general the pressure drop variations associated with this variable were rather small, but it is expected that the closer it is to the cyclone body, the higher the pressure drop will be, except for the cases where the bend starts at the cyclone top.

The results show that, unlike [19], although the pressure drop was substantially affected, the mean and RMS velocity and pressure profiles do not show significant differences in most cases. The tested modifications have not produced considerable changes for this particular cyclone operating at the configurations investigated, in the grade efficiency curves and cut off diameter.

2. Mathematical models

2.1. Cyclone geometry and grids

The dimensions of the cyclone are displayed in Fig. 1 and Table 1. This cyclone was investigated experimentally by R. Xiang et al. [49].

The models for both the fluid flow and particle motion were described in a previous publication and are summarized in the Appendix A section.

2.2. Numerical grids

One of the major concerns when performing numerical simulations, especially when performing large eddy simulations, of fluid flow is to produce mesh independent results. In a previous study [15], cyclone 1 from Table 1 was simulated and it was found that, for this particular cyclone operating at the Reynolds number 21,900, a numerical grid with nearly 400,000 hexahedral elements was sufficient to produce mesh independent results for the gas phase, as shown in Fig. 2, and the correct tendency for the dispersed phase, Fig 3. Although 400,000 elements may seem too coarse for an LES, as stated by [16], it must be kept in mind that another important factor concerning numerical simulations is the mesh quality. Aiming the highest quality possible, the authors decided, as in [15], to use only hexahedral elements, i.e., avoiding the use of automatic generated meshes with quad dominant elements or tetrahedral elements, which may require a larger number of elements, due to numerical diffusivity. Although more laborious, this method allows, considering the simulation of this specific device, to obtain numerical grids with a overall higher quality. This, in turn, enables the use of fewer elements.

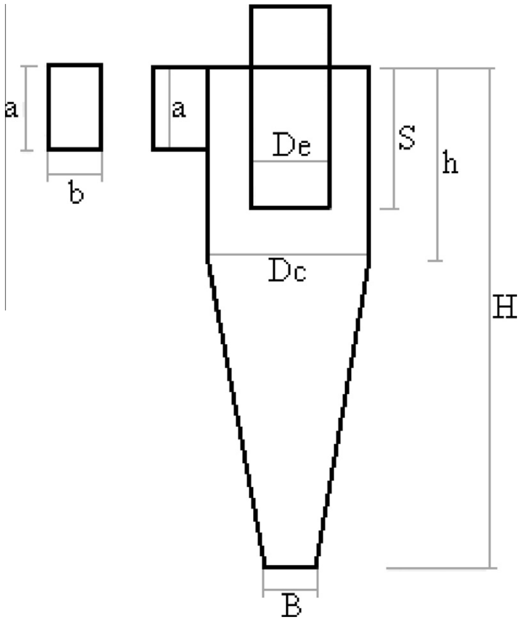

Fig. 1. Cyclone geometry.

Table 1
Dimensions of the cyclones simulated.

Dimension	Cyclone 1 (m)	Cyclone 2 (m)
Body diameter, Dc	0.031	0.031
Gas outlet diameter, De	0.0155	0.0155
Inlet height, *a*	0.0125	0.0125
Inlet width, *b*	0.005	0.005
Cyclone height, *H*	0.077	0.077
Cylinder height, *h*	0.031	0.031
Gas outlet duct length, *S*	0.0155	0.0155
Cone bottom opening, *B*	0.0194	0.0116

Elsayed and Lacor [14] also performed a large eddy simulation of cyclone 1. The authors used the GCI (Grid Converge Index) in order to evaluate the mesh refinement. [14] concluded that a mesh with approximately 800,000 elements was sufficient to produce mesh independent results, but decided to use a numerical grid with approximately 1,000,000 elements in order to exclude any uncertainty. The results for the cut-off diameter obtained in [14] differ by approximately 49% compared with the experimental data [49]. This illustrates the difficulty associated with the LES simulation of a cyclone separator, and exposes that the number of elements used in the numerical grid is not responsible, by itself, for the simulation quality, i.e., the grade efficiency curves in Fig. 3 show cut-off diameters differing from 22% and 12% when compared with [49] results. The main point in the above discussion is that, even with a relatively coarse numerical grid, representative values, in a qualitative point of view, for the cyclone performance may be obtained.