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Multi-objective optimization of cyclone separators in series based on computational fluid dynamics

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ABSTRACT

The pressure drop and collection efficiency are generally the most relevant parameters when evaluating the performance of gas-solid cyclone separators. In optimization procedures, mathematical cyclone models are used to find the best possible compromise between the pressure drop and the collection efficiency, based on the design preferences. Although several geometry optimization studies on single cyclone configurations have been reported, multiple cyclones in series remain relatively unexplored in this regard. Highly sophisticated models are described in the literature, but researchers mostly use lower fidelity models due to the shorter computational times involved. Also, when more sophisticated models are used, the authors tend to employ surrogate modeling approaches, which reduce the computational times but add another layer of uncertainty. In addition, several authors have optimized either the efficiency or the pressure drop, usually by adding a constraint on the other parameter. In contrast, herein, we describe the multi-objective optimization of three cyclones in series based on high fidelity computational fluid dynamics (CFD) cyclone modeling. A fully automated methodology solving this problem is evaluated, with the COBYLA optimization method and an Eulerian-Eulerian six-phase two-way gas-solid CFD approach simultaneously minimizing the pressure drop and maximizing the efficiency. No surrogate modeling is used here, which means that the results of the CFD simulations are directly used in the optimization procedures. The results obtained indicate that the optimized trios of cyclones outperform the conventional Stairmand (high efficiency) and Lapple (moderate pressure drop) geometries. The minimization of the emission resulted in 30 times less solids being emitted compared with the Stairmand trio. When minimizing the energy consumption, the pressure drop was 50% that of the Lapple geometry. When balancing the pressure drop and emission several results were considerably better than both geometries simultaneously (e.g. 33% less emission than Stairmand combined with 30% less pressure drop than Lapple). This demonstrates that the multi-objective optimization of cyclones in series delivers excellent results and is highly feasible in industrial timescales without compromising the fidelity of the mathematical cyclone model used.

1. Introduction

In the class of gas-solid separators, cyclones are the most widely used equipment in industry [1]. These separators mainly rely on centrifugal forces to separate solid particles from gaseous streams. The main advantages of cyclones are that they can be designed for a wide range of operating conditions, and are economical in terms of investment and maintenance costs due to their simplicity of construction.

Two conventional geometries are frequently cited when benchmarking new cyclone geometry proposals: the Stairmand [2] and Lapple [3] geometries. The former is a high efficiency and high pressure drop design, while the latter sacrifices efficiency for a lower pressure drop. In the literature, cyclone geometrical variables (Fig. 1) are usually shown in the form of dimensionless relations as a function of the barrel diameter (Dc) which is also known simply as the cyclone diameter. The ratios of the Stairmand and Lapple geometries are shown in Table 1. These designs were obtained through physical experimentation and empirical models which predicted the pressure drop and cut-off diameter as a function of the geometrical variables.

Cyclones are generally operated in series when the efficiency of a single cyclone is not high enough for the process being studied, with the main drawback being an increased pressure drop and therefore higher energy consumption (in addition to installation costs). The literature on cyclones operating in series is relatively scarce. The main studies focused on this issue are not optimization studies but

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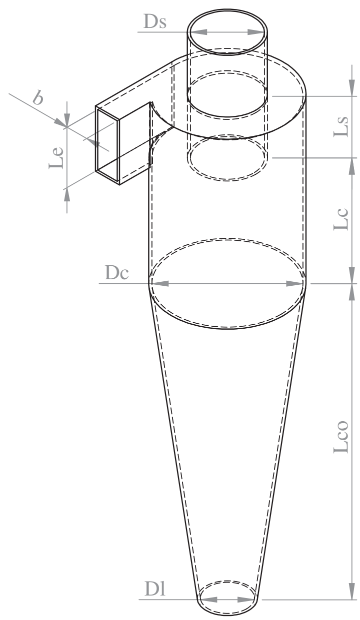

Fig. 1. Variables of the tangential cyclone separator geometry.

either validation studies [4] or comparison studies [5–8]. The latter are based on physical experimentation tests, and up to four conventional geometries in series, with specific ratios of barrel and cone lengths to body diameter, were evaluated. Some of the conclusions drawn by the authors were that the cyclones in series provided substantially higher collection efficiencies (and shifted the particle size distribution toward smaller sizes) while also increasing the pressure drop, but not linearly (e.g. two cyclones in series did not double the pressure drop). Whitelock and Buser [8] also noted that the use of three or four cyclones instead of two in their process only slightly increased the efficiency, while considerably increasing the static pressure drop.

Vegini et al. [4], on the other hand, used numerical CFD simulations with the CYCLO-EE5 code, which is the code used in the present optimization study, and compared the results to experimental data on cyclones in series used in the cement industry. The authors concluded that the code results showed good agreement with experimental data and thus the code has considerable potential for the prediction of the collection efficiency.

Among the first studies related to cyclone optimization found in the literature is that carried out by Gerrard and Liddle [9], who optimized the number of cyclones operating in parallel using the conventional Stairmand geometry and empirical modeling. It took a couple of decades until authors started publishing studies on the optimization of the cyclone geometry, with one of the first examples being the work of Ramachandran et al. [10], who aimed to increase the cyclone efficiency while maintaining a restriction on the pressure drop. Later, multi-objective studies aimed at maximizing the efficiency while simultaneously minimizing the pressure drop began to be reported [11].

Currently, in some cyclone optimization studies, the approach was still to select the best out of a few geometries (e.g. Refs. [12,13]). These studies are undoubtedly related to optimization, but in a minimalistic sense [14]. In the present study, the optimization is not limited to a simple improvement by choosing the best among three or four cases that were tested. Instead the best possible configuration within existing limitations is sought, usually requiring hundreds of evaluations.

Table 1
Stairmand and Lapple geometrical ratios.

Geometry	Ds/Dc	Dl/Dc	Le/Dc	Ls/Dc	Lc/Dc	Lco/Dc	b/Dc
Stairmand	0.50	0.37	0.50	0.50	1.00	2.50	0.20
Lapple	0.50	0.25	0.50	0.62	1.38	2.00	0.25

The solids collection efficiency and pressure drop are the most commonly evaluated parameters in optimization studies on cyclone performance. The collection efficiency is defined as the proportion of solids that is collected through the underflow in relation to the mass rate of solids that was fed into the cyclone. The pressure drop is the total energy loss of the flow from the inlet to the top outlet. Both of these performance parameters are dependent on the geometrical variables of the cyclone.

Ideally, a higher efficiency and lower pressure drop indicate a better geometry. However, in practice, the efficiency and pressure drop parameters are in conflict, and therefore optimization studies on cyclones focus on finding the best possible compromise (or compromises) between these parameters, in accordance to the design priorities.

In order to evaluate the numeric values of these parameters in optimization procedures, either accurate mathematical models or a large number of physical experiments are required. In reality, the costs associated with physical experimentation for optimization studies are prohibitive, and therefore authors use sufficiently accurate mathematical models in its place (e.g. Refs. [15–17]).

In this context, the empirical and semi-empirical mathematical models are relatively simple and computationally inexpensive. However, they mainly involve the mathematical regression of empirical data, which generally limits their extrapolation capacity. In addition, these models frequently consider only a portion of the variables that constitute the cyclone geometry and operating conditions, and they are limited to the type of geometry for which they were developed, hindering exploration of novel geometries. Nevertheless, due to its ease of use and low computational cost, empirical modeling is widely reported in cyclone optimization literature [10,18,19], and more recently [16,20,21].

There are also phenomenological models which describe the physical phenomena associated with fluid flow, generating a set of equations that can be solved by numerical approaches, such as the computational fluid dynamics (CFD) technique. CFD has the main advantage of accurately predicting important fluid flow characteristics and cyclone performance variables [22], without being restricted by empirical data ranges. This technique also considers all geometrical and operating variables, and can be used to evaluate unique and/or novel geometries (e.g. without a conical region). Its main drawback is the high computational costs compared to empirical modeling, which limits the extent to which it can be applied in optimization studies [14].

Several authors have used CFD techniques in cyclone geometry optimization. One of the earliest examples was described by Hoekstra et al. [23], who applied CFD techniques to obtain data which was used to build a polynomial meta-model. Meta-models, also known as surrogate models, are simplified models of actual models: CFD alone is a model or an abstraction of a phenomenon in the real word, and a meta-model adds another layer of abstraction.

Various recent investigations have used meta-modeling approaches in order to optimize the cyclone geometry. These approaches generally fit simpler models, such as polynomials, to the CFD or experimental data through response surface methodology [24–26] or artificial neural networks [21,24,27] techniques. Then, the optimization is performed with the simpler model effectively saving time and computational resources. The main drawback of the meta-modeling approach is that another error source is introduced into the calculations. Safikhani et al. [27], for example, encountered an error of up to 8.8% in their optimized result when comparing the previously regressed CFD meta-model with new CFD