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Optimization of the cyclone separator geometry for minimum pressure drop using mathematical models and CFD simulations

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A B S T R A C T

The response surface methodology has been performed based on the Muschelknautz method of modeling (MM) to optimize the cyclone geometrical ratios. Four geometrical factors have significant effects on the cyclone performance viz., the vortex finder diameter, the inlet width and inlet height, and the cyclone total height. There are strong interactions between the effect of inlet dimensions and vortex finder diameter on the cyclone performance. CFD simulations based on Reynolds stress model are also used in the investigation. A new set of geometrical ratios (design) has been obtained (optimized) to achieve minimum pressure drop. A comparison of numerical simulation of the new design and the Stairmand design confirms the superior performance of the new design compared to the Stairmand design.

1. Introduction

Cyclones are widely used in the air pollution control and gas–solid separation for aerosol sampling and industrial applications. With the advantages of relative simplicity to fabricate, low cost to operate, and well adaptability to extremely harsh conditions and high pressure and temperature environments, the cyclone separators have become one of the most important particle removal devices which are preferably utilized in scientific and engineering fields. Cyclones are frequently used as final collectors where large particles are to be caught. Efficiency is generally good for dusts where particles are larger than about 5 μm in diameter. They can also be used as pre-cleaners for a more efficient collector such as an electrostatic precipitator, scrubber or fabric filter (Swamee and Aggarwal, 2009).

1.1. Cyclone performance

In addition to separation efficiency, pressure drop is considered as a major criterion to design cyclone geometry and evaluate cyclone performance. Therefore, an accurate mathematical model is needed to determine the complex relationship between pressure drop and cyclone characteristics. The pressure drop in a cyclone separator can also be decreased or increased by varying the cyclone dimensions. For an accurate optimal design of a cyclone, it is quite necessary to use a reliable pressure drop equation for it.

Currently, the pressure drop models for cyclone separators can be classified into three categories (Zhao, 2009): (1) the theoretical and semi-empirical models, (2) statistical models and (3) computational fluid dynamics (CFD) models.

The theoretical or semi-empirical models were developed by many researchers, e.g. Shepherd and Lapple (1940), Alexander (1949), First (1949), Stairmand (1951), Barth (1956), Avci and Karagoz (2001), Zhao (2004), Karagoz and Avci (2005) and Chen and Shi (2007). These models were derived from physical descriptions and mathematical equations. They require a very detailed understanding of gas flow pattern and energy dissipation mechanisms in cyclones. In addition, due to using different assumptions and simplified conditions, different theoretical or semi-empirical models can lead to significant differences between predicted and measured results. Predictions by some models are twice more than experimental values and some models are even conflicted as to which models work best (Swamee and Aggarwal, 2009).

In the 1980s, statistical models, as an alternative approach, were used to calculate cyclone pressure drop. For instance, the models proposed by Casal and Martinez-Benet (1983) and Dirgo (1988) were developed through multiple regression analysis based on larger data sets of pressure drop for different cyclone configurations. Although statistical models are more convenient to predict the cyclone pressure drop, it is significantly more difficult to determine the most appropriate correlation function

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for fitting experimental data in this approach especially with the limited computer statistical softwares and robust algorithms available at that time.

Recently, the computational fluid dynamics (CFD) technique has presented a new way to model cyclone pressure drop. For instance, Gimbun et al. (2005) successfully applied CFD to predict and to evaluate the effects of temperature and inlet velocity on the pressure drop of gas cyclones (Zhao, 2009). Undoubtedly, CFD is able to provide insight into the generation process of pressure drop across cyclones but additional research is still needed to have a good matching with experimental data. CFD is also computationally expensive in comparison with the mathematical models approach.

1.2. Stairmand design

In 1951, Stairmand (1951) presented one of the most popular design guidelines which suggested that the cylinder height and the exit tube length should be, respectively, 1.5 and 0.5 times of the cyclone body diameter for the design of a high efficiency cyclone (Safikhani et al., 2010) (Fig. 1 and Table 1). In the Stairmand model for pressure drop calculation (Stairmand, 1949), the velocity distribution has been obtained from a moment-of-momentum balance, estimating the pressure drop as entrance and exit losses combined with the loss of static pressure in the swirl. The main drawbacks of the Stairmand model are: (1) neglecting the entrance loss by assuming no change of the inlet velocity occurs at the inlet area; (2) assuming constant friction factor; (3) the effect of particle mass loading on the pressure drop is not

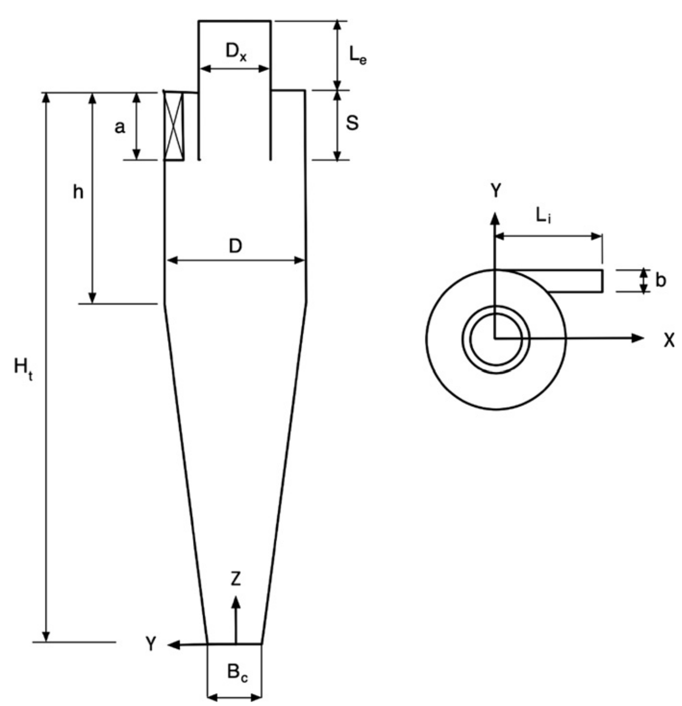

Fig. 1. Schematic diagram for Stairmand cyclone separator.

Table 1
The geometrical parameters values for Stairmand design (barrel diameter D=0.205 m).

Cyclone	a/D	b/D	D_x/D	H_t/D	h/D	S/D	B_c/D	L_i/D	L_e/D
Stairmand design	0.5	0.2	0.5	4	1.5	0.5	0.36	1.0	0.618

included. All these drawbacks are overcome in the *Muschelknautz method* of modeling (MM) (Hoffmann and Stein, 2008) introduced by Muschelknautz and Trefz (1990, 1991). The main benefit of MM over other models is its ability to take the following effects into account: (a) wall roughness due to both the physical roughness of the materials of construction and to the presence of collected solids; (b) the effect of mass loading and Reynolds number on cyclone performance; (c) the change of flow velocity throughout the cyclone (Hoffmann and Stein, 2008).

The present paper is an attempt to obtain a new optimized cyclone separator based on the MM model and to investigate the effect of each cyclone geometrical parameter on the cyclone performance using response surface methodology and CFD simulation.

1.3. The Muschelknautz method of modeling (MM)

Hoffmann and Stein (2008) stated that the most practical method for modeling cyclone separators at the present time is the Muschelknautz method (MM) (Muschelknautz and Kambrock, 1970; Muschelknautz, 1972; Muschelknautz and Trefz, 1990; Trefz, 1992; Trefz and Muschelknautz, 1993; Cortés and Gil, 2007; Hoffmann and Stein, 2008). The roots of the Muschelknautz method (MM) extend back to an early work performed by Barth (1956) as it is based on the equilibrium orbit model (Hoffmann and Stein, 2008).

1.3.1. The pressure loss in cyclone

According to MM model, the pressure loss across a cyclone occurs, primarily, as a result of friction with the walls and irreversible losses within the vortex core, the latter often dominating the overall pressure loss, $\Delta p = \Delta p_{body} + \Delta p_x$. In dimensionless form, it is defined as the Euler number:

$$E_u = \frac{1}{\frac{1}{2}\rho v_{in}^2}[\Delta p_{body} + \Delta p_x] \quad (1)$$

The wall loss, or the loss in the cyclone body is given by

$$\Delta p_{body} = f\frac{A_R}{0.9Q}\frac{\rho}{2}(v_{\theta w} v_{\theta CS})^{1.5} \quad (2)$$

where v_{in} is the area average inlet velocity, ρ is the gas density, Q is the gas volume flow rate, A_R is the total inside area of the cyclone contributing to frictional drag. The wall velocity, $v_{\theta w}$ is the velocity in the vicinity of the wall, and $v_{\theta cs}$ is the tangential velocity of the gas at the inner core radius.

The second contribution to pressure drop is the loss in the core and in the vortex finder is given by

$$\Delta p_x = \left[2 + \left(\frac{v_{\theta cs}}{v_x}\right)^2 + 3\left(\frac{v_{\theta cs}}{v_x}\right)^{4/3}\right]\frac{1}{2}\rho v_x^2 \quad (3)$$

where v_x is the average axial velocity through the vortex finder (for more details refer to Hoffmann and Stein, 2008).

1.3.2. Cut-off size

A very fundamental characteristic of any lightly loaded cyclone is its cut-point diameter or cut-off size x_{50} produced by the spin of the inner vortex. This is the practical diameter that has a 50% probability of capture. The cut size is analogous to the screen openings of an ordinary sieve or screen (Hoffmann and Stein, 2008). In lightly loading cyclone, x_{50} exercises a controlling influencing on the cyclone's separation performance. It is the parameter that determines the horizontal position of the cyclone grade-efficiency curve (fraction collected versus particle size). For low mass loading, the cut-off diameter can be estimated in MM